agriculture

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Enablers to Digitalization in Agriculture: A Case Study from Italian Field Crop Farms in the Po River Valley, with Insights for Policy Targeting

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Abstract: The prosperity of Po River Valley's quality agri-food system depends on the efficiency of its field crops, which are recently facing a crisis evidenced by cultivated areas decreasing and yields stagnating. Several factors, including EU policies and climate variability, impose an improvement in the use of production factors and adapted business models: literature shows how digitalization and Agriculture 4.0 can contribute to addressing these challenges. This paper aims to explore drivers and barriers in the adoption of digitalization among Po River Valley field crop farms, in a dynamic view. Using a case study approach to guarantee adequate consideration of context and conditions, three farms were studied. As one of the main outcomes, several drivers (digital skills, data management practices, and interoperability) that should be at the heart of policies were identified as demands to farmers in exchange for financial contributions, or as "innovation space" offered by EU institutions. Policies should not only focus on supporting mechanical/digital equipment acquisition but also on promoting the evolution of farmers' human capital. The framework developed paves the way for future research on the degree of farm digitalization in the same/similar territorial contexts: identified drivers of digital transition can be used as a basis for survey questionnaires, as well as tested in their validity.

Keywords: digitalization; agriculture; policy; Agriculture 4.0; field crops; geographical indication

Citation: Giorgio, A.; Penate Lopez, L.P.; Bertoni, D.; Cavicchioli, D.; Ferrazzi, G. Enablers to Digitalization in Agriculture: A Case Study from Italian Field Crop Farms in the Po River Valley, with Insights for Policy Targeting. *Agriculture* **2024**, *14*, 1074. https://doi.org/10.3390/agriculture14071074

Academic Editors: Claudio Bellia and Marcus Randall

Received: 27 May 2024
Revised: 26 June 2024
Accepted: 1 July 2024
Published: 3 July 2024

1. Introduction

The Italian agri-food system is among the best known in the world, and this notoriety stems from a set of products with Geographical Indication (GI): (PDO-Protected Designation of Origin; PGI-Protected Geographical Indication; GTS-Guaranteed Traditional Specialty). There are 326 GI Italian food products as of 30 November 2023; these numbers put Italy in first place in the European Union, followed by France, with 272 GI products [1]. While the value of production of all Italian GI products accounted for EUR 8.85 bn in 2022, 86% of this amount (EUR 7.61 billion) was generated by only 15 references [1]. Most of this value is represented by animal-based products, cheeses, and cured meats. In 2022, the first three GIs (Grana Padano, Parmigiano Reggiano, and Prosciutto di Parma) recorded a production value of EUR 4.39 billion, equal to 50% of the total [1]. Moreover, the production chains of these products are concentrated in the plain of Northern Italy (the Po River Valley) in the regions of Lombardia, Piemonte, Emilia-Romagna, and Veneto. In this area, field crops such as maize, soy, wheat, and barley, are the feedstock base for livestock farming supporting the most relevant animal-based GI supply chains. Such crops are usually reused as feed in livestock farms or sold on the market by field crop farms. Therefore, the viability and prosperity of the northern Italian agri-food system located in the Po River Valley depends on the productive efficiency of its field crops.

Although these feedstock crops play a fundamental role in the Italian agri-food system, their cultivated areas (including maize, soy, wheat, and barley) in northern Italy have decreased by 11% over the last 10 years (from 2014 to 2023) [2]. This was mainly due to the reduction in maize-cultivated areas by 41% in that period. In the same period, maize production fell to the same extent [2]. Furthermore, looking at yields in the same period, those of w wheat and maize do not vary (there is a variation of 1% for the first crop and none for the second). For soy, however, there was a decline of 17% (it must be said that 2014 was a particularly favorable year for the crop), while only barley saw a growth of 8% [2]. This seems to represent the fact that farmers struggle to produce, do not invest adequately in innovation, and are subject to weather anomalies, climate variability effects, and other external contingent events.

This crisis in cereals production is not the consequence of a crisis in demand, which, despite some difficulties in the livestock sector, remains sustained. Focusing on maize, from the 2013–2014 campaign, national imports rose from approximately 797 mln t to approximately 1.950 mln t recorded in the 2022–2023 campaign. Correspondingly, the level of national self-sufficiency fell to 41% in 2022–2023, or by 23 percentage points in 10 years. It is noteworthy that in 2022, the Italian import of maize and soy was equal to €4282 bn, which is almost equivalent to the value of the production of the first three GI products, or equal to 130% of the value of the export of GI cheeses and cured meats.

This particularly demonstrates a real crisis in maize, a crop that has received much attention in the past decade and which represents the basis of the livestock farming system of the Po River Valley. The context for farmers is one of great uncertainty: they seem to prioritize the short-term market logic and focus on crops with lower added value but relatively lower need for inputs, aiming to support profitability. In fact, the areas cultivated with soft wheat, soy, and barley have grown in the same regions by 12%, 21%, and 69%, respectively [2].

The decrease in maize acreage in favor of other field crops is also driven by the constraints imposed on farms by the Common Agricultural Policy (CAP). Since 2015, in order to receive direct payments, farms must adopt crop diversification and allocate 5% of arable land to environmental focus areas (EFA). In northern Italian regions, this obligation has led to a significant reduction in maize acreage [3] that has been replaced by other crops, with consequent drops in income for farms [4].

Other additional factors may have contributed to the decreasing trend of maize acreage:

- The effects of weather variability, which manifest themselves specifically with long dry periods and an increase in the frequency of localized extreme events and heat waves;
- Linked to the previous point, the introduction into the cultivation areas of new alien species of pests/harmful insects and related plant diseases (an example of this is the introduction and spread of *Diabrotica virgifera* in the maize cultivation areas of Northern Italy);
- A general decline in profitability is linked to the worsening of the terms of trade and an increase in the costs of production factors.

All these factors, therefore, threaten the competitiveness and profitability of field crop farms, which are urged to improve the efficiency of production factors and to adapt business models, organization, and processes to meet increasingly demanding economic and environmental standards imposed not only by agricultural policy [5] but also by the market demands (supply chain players and consumers).

In recent years, the literature has shown how digitalization in agriculture and the transition towards the so-called Agriculture 4.0 can contribute to addressing the fragilities and challenges faced by field crop farms. This is especially true in terms of more accurate decision-making based on a large amount of data and new innovative technologies, an improvement in the efficiency of agricultural activities, and the satisfaction of environmental sustainability requirements. The adoption of digital technology can provide farmers with benefits related to profitability, environmental sustainability, and other factors affecting people inside and outside the farm [6].

While a push towards digitalization is given by the evolution of technologies and the innovation market, it is also true that EU policies are driving the agriculture industry towards the adoption of new digital technologies in the field, not only through the CAP framework [7].

Therefore, digital transition is a key element for the agricultural sector, particularly for Italian field crop farms located in the Po River Valley, for addressing economic and environmental (and related social) challenges that they have been facing in recent years. In this sense, Agriculture 4.0 can be an enabler of survival and durable success for them in the next years. There is a lack of studies in the literature that evaluate the level of digitalization of large-scale field crop farmers in the Po River Valley, highlighting enablers and barriers to the digital transition, as well as proposing specific initiatives that policymakers could take to promote it. Moreover, in the studies on agricultural digitalization, there is a need for empirical research and an appropriate framework of the local context, equally keeping in mind a broader political economy perspective.

Therefore, this paper contributes to the current literature by exploring drivers and barriers to the adoption of digitalization among field crop farms in northern Italy, using a case study approach and, at the same time, aims to guarantee an adequate consideration of the local context and specific conditions of the arable crops farming in the Po River Valley. Moreover, the aim is to examine the interaction between enablers and digitalization policies in agriculture, by highlighting initiatives that policymakers can implement to obtain better results in promoting the digital path. Since our aim is to present an in-depth study of the digital transition, the focus will be on the dynamic process and its phases, rather than a binary decision [8], to capture the subtle nuances.

In the following paragraphs, after a literature review on the topic, the *Methodology* followed by the research team will be illustrated, starting from the selection of case studies in the local context of interest. The next step will be the presentation of the *Results* through a model developed by the authors, and then find evidence of the case studies within the model of digital evolution presented by Munz et al., 2020 [8], (based on Porter and Heppelmann, 2014 [9]). Finally, in the *Discussion* sections, the most relevant themes emerging from our study and their meaning in the context of interest will be presented, focusing on the implications they have concerning EU policies on digitalization in agriculture. Recent and current EU and national policies activated in the Po River Valley will be highlighted: they will be analyzed considering the results discussed in the previous sections, highlighting limits and potential with respect to the objective of advancing farms on the digitalization path.

Literature Review

The literature review was conducted using the following research keys: Agriculture 4.0, Smart Agriculture, Digital Technologies, Digitalisation/Digitalization, Connectivity, Smart Farming, Farm Management Information System, and Enterprise Resource Planning. Priority was given to studies that addressed the topic of digitalization in a transversal way, including literature reviews as well as large-scale surveys of farms and the depiction of models of the digital evolution path; furthermore, they addressed the issues of benefits, drivers, and obstacles to digitalization.

Among the numerous definitions of Agriculture 4.0 present in the literature, some reported in a recent review by Da Silveira et al. (2021) have been selected [5]: in fact, these make understandable the advantages that digitalization can bring in managing the challenges field crop farmers face in the area under study.

- Kong et al. (2019) [10] focus on the issues of data management and decision-making in contexts of uncertainty: "Based on digital technologies and data advances (IoT, sensor data, and remote sensing technologies), Agriculture 4.0 improves the agricultural system's responsive performance with accurate decision making in response to operational uncertainties and real-time data updates";

- Zhai et al. (2020) [11] focus on the concept of digital transition towards improving efficiency: "Nowadays, the evolution of agriculture steps into Agriculture 4.0, thanks to the employment of current technologies like the Internet of Things, Big Data, Artificial Intelligence, Cloud Computing, Remote Sensing, etc. The applications of these technologies can improve the efficiency of agricultural activities significantly";
- Huh and Kim (2018) [12] focus on greater environmental sustainability and the demands of downstream actors in the supply chain, including consumers: "Supported by future technologies and environmental concerns, Agriculture 4.0 pursues eco-friendly but more efficient farming methods, which satisfy the requirements of the value chain as well as the demands of society, and especially those of consumers".

FMISs (Farm Management Information Systems) are a relevant component of the digital equipment made available by digital technologies in agriculture. An FMIS consists of "a planned system for the collecting, processing, storing and disseminating of data in the form of information needed to carry out the operations functions of the farm" [13].

FMISs represent a very frequent object of study in the literature since they enable the management and interpretation of the large amount of data that can be collected through agricultural machinery and sensors in the field and the agricultural environment, also thanks to advanced data connection technologies. Thanks to the ability of these systems to incorporate a large part of the farm's digital equipment, they are the subject of study by numerous researchers interested in evaluating aspects such as barriers, enablers, and levels reached in the digitalization path.

A part of the literature focuses on the in-depth study of current digital technologies' characteristics (such as the domain of application), the extent of adoption, their advantages and disadvantages, and the barriers and drivers in their diffusion [5,6,14,15]. Some reviews found that the main field of research is crop application, in particular, the in-field processes (those involving crop growing) [15] on the contrary livestock application is less studied [6]. The main domains of application are water management, crop management and monitoring, precision microclimatic prediction, and monitoring [6]. The technology most cited and explored is the Internet of Things (IoT) [6], which is extensively present in farms [15].

Giua et al. (2021) [14] analyzed the technology adoption's drivers and barriers according to three categories [16], namely the "technological features", "farm and farmer traits" and the "external environmental features". The latter does not seem to be relevant. Whereas da Silveira et al. (2021) [5] identified 25 barriers to the adoption divided into five categories: technological, economic, political, social, and environmental. Following the division of adoption's limitations, Abbassi et al. (2022) [15] associated the interconnected "roadblocks" that do not facilitate the implementation of technologies in the agricultural sector with the technical and socio-economic dimensions.

Additional barriers to agricultural digitalization were found in the literature. Schulze et al. (2022) [17] conducted a study in Germany on how to optimize and adjust FMISs to fulfil the needs of farmers, with a distinction among adopters and non-adopters based also on the intensity of use and perception. Among the obstacles presented, the adopters note the often-missing compatibility and the poor attractiveness of FMIS. Whereas, Munz et al. (2020) [8], in their survey, emphasized the fact that several persons adopt diverse isolated solutions [18] without the possibility of having functions from individual production processes or farm enterprises in one software application. Notably, universal data standards for information systems do not exist yet in agriculture for efficient data exchange [14,15,18]. The farmers expressed the need for flexible and user-friendly software with the ability to network among systems from different manufacturers [8,14,15].

Ensured compatibility and interoperation among different systems is of major concern [7]. Fountas et al. (2015) [19] reported the difficulty of integrating the data in FMISs and the lack of aids to promote interoperability between stakeholders and the services offered. Some studies' results clearly depict the necessity of farmers to experience smooth operability among the technologies adopted [14,15,20], resulting in automated data acquisition, avoiding multiple data entries, and all-in-one solutions [8].

The importance of the value added generated by the compatibility among machines and with FMIS is stressed [17]. Therefore, this interoperability across heterogeneous systems is fundamental to promoting and enhancing agricultural technology development [7]. In terms of an already adopted innovation, the technology characteristics and its interoperability play a crucial role [20]; in fact, a lack of interaction between software and hardware technologies leads to a reduction in the efficiency and the potential of their adoption [7].

One main barrier is the complexity of the solution: Junior et al., 2019 [20] found that complexity, defined as the perceived difficulty of an innovation, has a negative effect on the possibility of implementing an innovative technology. Instead, Roussaki et al. (2023) [7] highlight one key challenge in agriculture, namely the absence of adequate support for farmers. One argument is the need to control the knowledge derived from the high volumes of data gathered; this could foster the shift from a burdened farmer to the ability to exploit data to meet agricultural and economic needs, placing the end-user of the technology in better control [5,7,15]. Another connected issue reported is the complexity of technologies, often resulting in excessive features that exacerbate the difficulty of use and understanding; in this case, technologies are perceived as time-consuming in terms of learning how to use them and input data [14].

Finally, Da Silveira et al. (2023) [21] found that some of the barriers expressed by Brazilian farmers are the lack of infrastructure and accessible solutions, age group risk, and scarce efficacy in the data on the rural environment.

A fundamental component of a favorable road to digitalization lies in the need to adopt new working habits together with training due to the new information management concepts and designs [22]. Also, according to the results of Schulze et al. (2022) [17], higher education has a significant impact on the level of technological skills and use. Focusing on enhancing the capacity of a farmer to take advantage of the information and to fully use the services is of paramount importance [22]. The compelling documentation requirements, presented as positive drivers, due to the new agricultural regulations may encourage the use of FMISs as a complete management tool [8,17,20]. On the other hand, the demonstration of the solutions' benefits [20] and the possibility of testing the products positively influence their adoption [17], considering that technologies' performance expectancy highly influences the adoption decision [23].

A structural favorable factor is the farm dimension [8,17]. In particular, the economies of scale permit covering the cost of the investments in a brief period [17]. This is due to the necessity that more extended farms have in terms of complex production processes and additional data and information [14].

Giua et al. (2022) [23] argue that organizational facilitation conditions, namely commercial networks, are crucial in the adoption process of the entire supply chain and may also be favorable to promoting digital transition among less technological farms.

However, as stated by Benegiamo et al. (2023) [24], it must be considered that the specificity of the local context generates relevant differences in the drivers and effects of agricultural digitalization, where farmers adopt strategies including choices of digital innovation with the aim to manage endogenous as well as exogenous problems.

Regarding the benefits related to the application of Agriculture 4.0 in agriculture, Maffezzoli et al. (2022) [6] argue that the adoption of digital technologies can provide farmers with several advantages and that they can be categorized into the following three areas:

- Profitability of farming companies: in terms of cost reduction, enhancement of farm productivity, and improvement of product quality;
- Environmental sustainability of operations: in terms of reduction in environmental impact, enhancement of biodiversity, and reduction in land consumption;
- People inside and outside the company: in terms of pursuing food authenticity, reduction in time spent by farmers carrying out operations, and enhancement of social sustainability.

These results highlight the interplay between economic and environmental benefits: enhanced efficiency, decreased operational costs, and higher farm productivity are coupled with lower environmental impacts and increased sustainability [6].

Roussaki et al. (2023) [7] have argued how EU policies are driving agricultural industries towards the adoption of innovation in the digital technology field. This, on the one hand, happens with challenges for the agriculture technology development space, having an impact on the supply chain from—food production to the bioeconomy—via the EU Common Agriculture Policy. On the other hand, policies promote the digital single market strategy which drives requirements for "the right environment for networks and services" and "ensuring that the European economy takes full advantage of what digitization offers"; which is in line with the pressure towards common European data spaces [25–27].

The same authors underline how another push towards the digitalization of the agricultural sector is given by the evolution of the technologies applicable to it: they identify a whole series of technologies available on the market and accessible to farmers, such as the Internet of Things, artificial intelligence and robotics, enablers for Agriculture 4.0. At the same time, they report that their potential to collect, analyze, and interpret large volumes of relevant data has not been fully realized, leaving the market with several challenges to address, particularly in terms of data management. Some advanced technologies, in fact, are not implemented yet, due to the complexity and the costs, in fact in most cases technologies under study are still in the prototype phase [15].

2. Materials and Methods

2.1. Identification of a Specific Case

First, a pilot test was conducted to refine data collection and to develop relevant lines of questions. The selection of cases was based on convenience, accessibility, and proximity [28]; moreover, preliminary interviews took place to understand the gaps and the context.

Therefore, with a clear idea of the background, a multiple holistic [29] instrumental [28,30,31] case study was selected to gain an in-depth comprehension of digital development in the field of arable crop farming. The system in which the sample lays is bounded, that is farms specialized in field crop cultivation with a substantial size (at least 400 hectares), characterized by minimal digital technological equipment (beyond the mechanical equipment of agricultural machinery), feed crop producers in the Po River Valley and whose production is included within Italian quality supply chains. In this sense, a purposive selection strategy [28] was chosen based on accessibility and availability, still offering different perspectives on the issue under study. Through the assistance of local stakeholders, it was possible to contact the farmers. Three farms were finally selected for the study: their characteristics will be described in detail in the *Results* section.

Data collection was held from April 2023 to March 2024 through in-depth interviews and document analysis, completed by observations made by the research group.

A rigorous data collection protocol [32] was followed, to obtain homogeneous and comparable kinds of data.

2.2. Sections of the Protocol

For each of the selected farms, a semi-structured interview was conducted in the presence of at least two members of the research team. Each interview was conducted in the headquarters indicated by the farmers so that the researchers were able to observe the technological equipment (mechanical and digital equipment) for each case study, those available for viewing at the time of the interview. Table 1 shows the high-level outline followed by the research team during the interview performed with each selected farmer.

Table 1. High-level outline for the semi-structured interview.

1. Farm characteristics: location, organization, and activities
2. Agricultural machinery and related equipment
3. Public incentives used for the purchase of the equipment
4. Digital or digital-related equipment Weather stations/sensors Satellite systems on machinery Farm Management Information Systems/operative platform linked to machinery Irrigation systems Stable management system Other, if present These were investigated in terms of features, interfaces, users, benefits, frequency of use, accessibility, and integration with machinery and other tools/equipment.
5. Benefits of digitalization
6. Obstacles encountered in the digital transition

2.3. Data Analysis

The data gathered were analyzed in two distinct phases. The first phase comprehends a within-case analysis, through an individual case report [32] depicting the case's location, a detailed context description, and the recorded observations. The second phase involves cross-case analysis, namely the comparison of the different case studies that bring insightful conclusions. As a result of this second phase, relevant topics having implications in the definition of the digitalization level, transition enablers and barriers of each involved farm, as well as in the definition of possible effective policies for agriculture digitalization were highlighted. These will be illustrated and discussed in the *Discussion* section of this paper.

3. Results

3.1. Within-Case Analysis

As mentioned in the *Methodology* section, in this paragraph, the outcome of the analysis conducted within each case will be illustrated. For each of the involved farms, a short context description of the farm, including location, organization, activities, and technology equipment is presented.

As a second step, the results of the cross-case analysis are enumerated, illustrating:

- The main technology (mechanical and digital) equipment for each case, highlighting in detail those that are owned and used by the farm;
- A high-level data flow was observed in each case, considering the main processes of the field crop activity.

To conclude this section, each case study will be inserted within a model of digital evolution in agriculture proposed by Munz et al. (2020) [8,9]. This is with the aim of understanding which level each farm has reached at the current moment within the digital transition path. This will, in fact, have consequences in the subsequent *Discussion* section, particularly in understanding the enabling and hindering factors towards Agriculture 4.0 in the context of the study. In Table 2, a summary of the main characteristics of each case study is presented, including their indicative location, the utilized agricultural area (UAA) under management, the main crops grown, and the type of livestock.

Table 2. Main information of each farm.

Case	Location	UAA (in ha)	Main Crops Grown	Livestock
Case 1	Southwest from Milan	Over 600	Maize and soft wheat	Milk cows
Case 2	East from Milan	About 3000	Maize, soft wheat, soy, rapeseed	/
Case 3	Province of Alessandria	Over 400	Maize, soft wheat, forage (mainly alfalfa)	/

3.1.1. Case 1

Farm 1 manages over 600 hectares of land located in the southwest area with respect to Milan. The company also owns a stable with dairy cows located in the same province; the cattle are mostly fed with internal forage production. Referring to 2023, the land under management is mostly destined for the cultivation of waxy maize and wheat. A small part of the production is intended for feeding the dairy cows, the rest, is allocated to the external market.

Several machines were purchased taking advantage of European incentives. The farm avails of machinery and services from contractors, mostly for harvesting and fertilization. Some of the third-party machines are equipped with satellite systems aimed at the optimization of inputs.

Several weather stations are installed on the farm's land: they are supplied by XFarm Technologies® (Milan, Italy) and managed/displayed using the homonymous software (https://xfarm.ag/ accessed on 19 March 2024). The stations record data on rain, air temperature, air humidity, wind speed, and other parameters. Six satellite-guided systems are used in the farm, mostly supplied with RTK accuracy. Satellite systems are supplied by Topcon (Corporation Headquarters Tokio, Japan) and linked to the TAP® (Topcon Agriculture Platform) web platform (https://tap.topconagriculture.com/ accessed on 19 March 2024): this software collects, and store data registered in operations run during the agricultural cycle.

The company has a private account on the XFarm® web platform, with access to its basic features. These could be used for farm management activities.

The farm employs the traditional flood irrigation method due to the availability of water according to shifts defined by the local consortium.

3.1.2. Case 2

Farm 2 has a peculiar configuration since the company owns over 400 hectares, but it also has a contractor agency offering machinery and management services to landowners, adding over 2500 hectares to the operating area. The managed area is in the east area with respect to Milan. The land owned and managed is mainly intended for producing maize, wheat, soy, and rapeseed. The productions are destined for animal and human food supply chains. The company handles the harvesting, drying, storage, and sale of the product also for the managed land productions. The farmer is currently renovating a stable to rear hundreds of dairy cows. Therefore, part of their production will be conveyed for internal use.

All machineries are equipped with a satellite system, using RTK precision; all tractors are provided with an Isobus connection. Only a few machineries were purchased using public incentives.

Two weather stations are installed in the owned land area: they measure and report rain, temperature, humidity, wind, solar radiation, and leaf wetness. Furthermore, various soil sensors are installed throughout the area to measure soil humidity.

The farm management information systems used are supplied by the machinery providers: the main platform is John Deer Operations Centre® (https://operationscenter.deere.com/ accessed on 19 March 2024), provided by John Deere & Company (Moline, IL, USA), coupled with AFS Connect® (https://caseih.afsconnect.com/ accessed on 19 March 2024), powered by My Case IH®, (Case IH, Racine, WI, USA). Considering the completeness of the mentioned platforms, the company does not adopt any other FMIS.

Irrigation is carried out through machinery provided by third parties, not equipped with digital support.

3.1.3. Case 3

Farm 3 manages over 400 hectares, partly owned by the farmer. The land is distributed around the province of Alessandria. The cultivated land is designated for cereals (maize and wheat) and forage (including alfalfa).

Six tractors from the fleet are provided with Isobus and satellite system (RTK precision) provided by John Deere: the latter is the main producer of machinery and digital equipment employed by the farm. Satellite systems are also embedded in the seed drill, in the sprayer, and in two fertilizer spreaders. The seed drill and fertilizer spreaders were purchased taking advantage of public incentives.

A weather station and several soil humidity sensors are installed on the farm; they are provided by XFarm Technologies. Data gathered are like those of Cases 1 and 2. The systems are accessible through the XFarm® web platform.

The farm management information system used is John Deere Operations Centre®, supplied by the main machinery provider; therefore, the farm does not employ any other FMIS, since all needed features are already covered.

Irrigation is carried out through machinery equipped with digital systems, i.e., irrigation remote setting and control application (hose-reel irrigation machines).

3.2. Cross-Case Analysis: A Model to Define the Level of Digitalisation

3.2.1. Farms' Equipment: Owned and Used

Table 3 illustrates the main equipment of the farms of the 3 case studies: they are categorized as agricultural machinery, hardware digital equipment, and software digital equipment. For each piece of equipment, it is indicated whether it is owned and if it is used by the farmer. There are cases in which the equipment is owned but not used, and cases in which the equipment is used but not owned: in these cases, it is provided by a third party. In these cases, the cell is colored grey.

Table 3. Equipment owned and used by the farm in each Case study (Cases are indicated as 1, 2, and 3).

		Owned			Used		
Type	**Product**	**1**	**2**	**3**	**1**	**2**	**3**
Machinery	Tractor	•	•	•	•	•	•
	Harrow	•	•	•	•	•	•
	Seed drill	•	•	•	•	•	•
	Fertilizer spreader	•	•	•	•	•	•
	Sprayer	•	•	•	•	•	•
	Harvester		•	•	•	•	•
	Machinery for hay and forage		•	•		•	•
	Hose-reel irrigation machine			•		•	•
Hardware	Satellite antenna and display	•	•	•	•	•	•
	Isobus link	•	•	•		•	•
	Weather station	•	•	•	•	•	•
	Soil sensor		•	•		•	•
Software	Satellite navigation system (onboard)	•	•	•	•	•	•
	TAP® (Topcon Agricultural Platform)	•					
	X-Farm®	•					
	X-Farm® (weather station)	•		•	•	•	•
	John Deer Operations Centre®		•	•		•	•
	AFS Connect®		•			•	
	Field Climate® (https://www.fieldclimate.com/ accessed on 19 March 2024), Pessl Instrument (Weiz, Austria)		•			•	
	ELCOS Smart Control® (https://www.elcos.it/ accessed on 19 March 2024), ELCOS (Parma, Italy)			•			•

The dots indicate if the equipment is owned and/or used. The grey colour represents if equipment is owned but not used and vice versa.

From the table, it can be seen that, in all cases, farmers own the machines for carrying out all the main cultivation processes, except in Case 1: here, in fact, the farmer uses harvesting machines supplied by third parties and, therefore, does not store or manage data collected by these machines, unlike the farmers in Cases 2 and 3. A similar situation is that of Case 2, which uses irrigation machines supplied by third parties; for this reason, it does not have digital equipment connected to such machines and does not store or manage data relating to this process.

Regarding the hardware equipment to support the digital systems, it is possible to note that in all cases farmers are equipped with on-board satellite systems and tractors with Isobus connection, even if in Case 1 there are only 2 tractors with Isobus. In any case, it is important to note that in Case 1, this connection is not commonly used. Consequently, there is no dialogue between operating machines and tractors, although these are equipped with satellite control and guidance systems. Therefore, their potential is not completely exploited.

Regarding Case 1, the same consideration can also be made in relation to the software equipment: in fact, the farmer does not commonly use the platform for storing and analyzing data detected by the satellite systems mounted on the machines. Moreover, the XFarm® platform is commonly used for the observation of data detected by weather stations.

Instead, in Cases 2 and 3 farmers profitably use the operating platform that stores and analyzes data collected by the machines, albeit with a different level of functionality. More specifically, the farmer in Case 3 decided to equip his farm with machinery from a single brand (Jonh Deere), to be facilitated in the choice and use of accessory equipment, i.e., the satellite and on-board connection systems, and the John Deere Operations Centre® software platform. The farmer in Case 2 made the same choice but, when purchasing a machine of significant economic value, he turned to the Case manufacturer due to the specificity of the machinery; for this reason, he also equipped his farm with the AFS Connect® platform (powered by My Case IH). This has required important software customization such that the two operating platforms (from John Deere and Case) are aligned in terms of database.

Note, then, how the farmers in Cases 2 and 3 own and use soil moisture sensors which they exploit for irrigation decisions. Moreover, the farmer in Case 3 owns and uses irrigation machinery, in particular a hose-reel irrigation machine: a software package (Elcos Smart Control®) useful for remote setting and control is connected to the latter.

In the next section, these considerations will be resumed to illustrate how each of the case studies can be described in terms of the flow of data collected and archived by the equipment illustrated here.

3.2.2. Data Flow through Agricultural Processes

Figure 1 represents a simplified diagram of the cultivation processes followed by the farms in the case studies: this diagram was designed by the research team to understand how each farm uses the data collected by/through the technological equipment (mechanical and digital) within their production processes. This method allowed us to understand how the equipment owned and/or used is exploited and what type of impact they have on agricultural activity. In this way, emerging aspects of similarity and difference determine the level reached by each farm within the digital transition path. Likewise, they are relevant to the issues raised in the cross-case analysis that will be presented in the *Discussion* section.

First, it can be noted that the data flows of Case 1 relate only to the processes from tillage to protection, while the irrigation and harvesting processes do not involve any detection, collection, storage, or analysis of data. Furthermore, the data collected are used by the operator directly on the field, to make contingent decisions; they are archived but not commonly analyzed and interpreted to make decisions on subsequent cycles, or other processes of the same cycle. Case 1, therefore, lacks integration between data containers and between processes of the same cycle or different cycles. For example, during a cultivation operation, fuel consumption or speed data are observed by the operator in real time through the onboard display and used to modulate the pace of the contextual tractor operation. Furthermore, satellite guidance is used to avoid overlapping in fertilizers or pesticide distribution, and to reduce the inputs used and soil compaction.

In Cases 2 and 3, however, the data collected during the operations are archived, analyzed, and interpreted through the tools of the operating software platform. In this way, they are used to make operational and tactical, as well as strategic, decisions to be used in subsequent crop cycle operations and subsequent operations of the same crop cycles. For example, in fertilization and crop protection operations, in which the inputs used are traced from a historical and prospective perspective, it is also possible to employ variable rate techniques. This is performed through the Isobus connection between the operating machine and the tractor under satellite control.

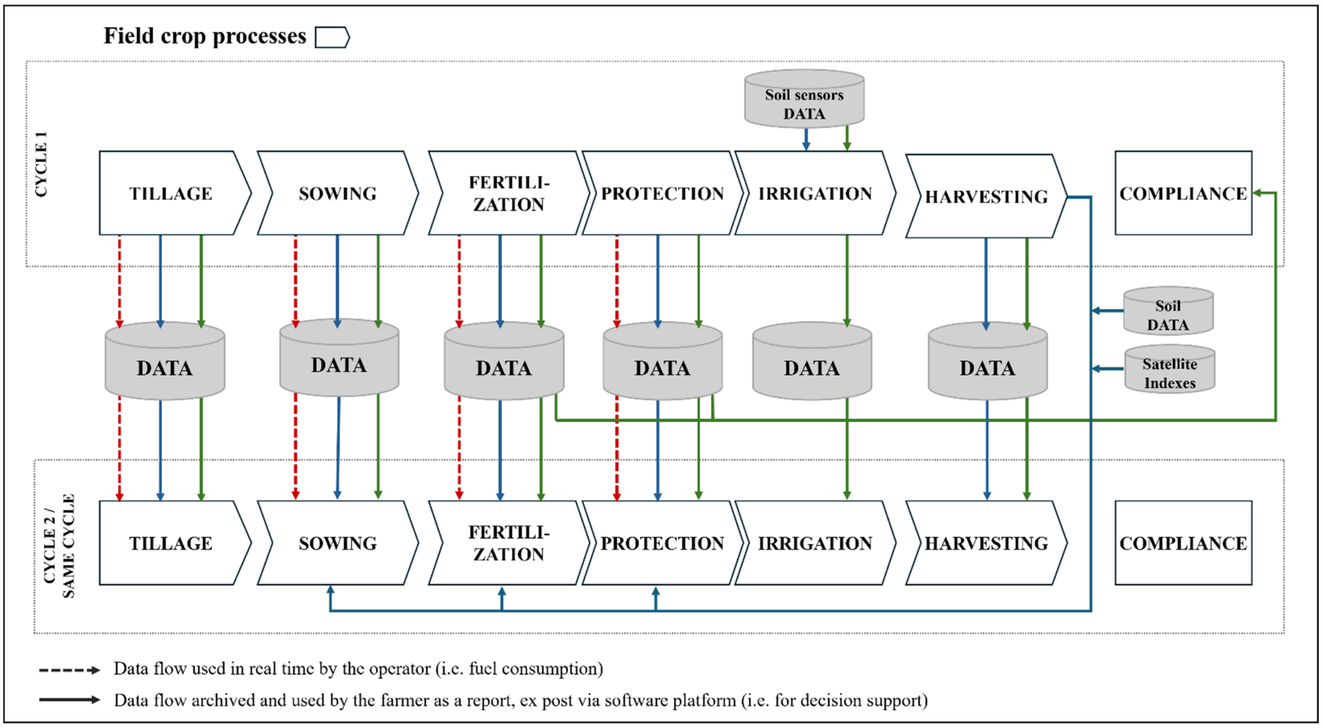

Figure 1. Simplified diagram showing the flow of data collected through technological equipment owned/used by each farm, as part of processes in the blocks. Processes in Cycle 1 refer to a hypothetical crop cycle; processes in Cycle 2/Same Cycle refer to a hypothetical subsequent crop cycle or repeated processes in the same crop cycle. Red: Case 1; Blue: Case 2; Green: Case 3.

As also emerges from the diagram, the data collected by the technological equipment can be enriched by external inputs deriving from field observation carried out by farmers as well as by workers authorized to input data on the mobile interfaces of the operating platform. There is, therefore, an integration of data sources within the same process: the data collected in the field from various sources are analyzed ex-post, typically through desktop interfaces in the office or on the move, as said before. This also demonstrates how workers on the field are trained to use digital tools, alongside farmers.

Furthermore, it can be noted that in Case 3 the farmer also uses the data collected in cultivation operations for regulatory compliance processes, to draw up reports on the use of crop protection chemical products. The same process, therefore, can have outputs used for different purposes.

Moreover, Case 3 presents a further uniqueness as already mentioned in the previous paragraph. The data collected by the soil humidity sensors are used to make irrigation decisions, as in Case 2. In addition, here the irrigation machines are set and controlled digitally through an operating web application. The data flow from the sensors, however, is not yet automated, as there is no integration between the two applications (XFarm® for the sensors and Elcos Smart Control® for the irrigation machine). In any case, the manual input of the settings on Elcos Smart Control® is a routinely carried out activity, the costs of which are vastly repaid by the benefits of remote control of irrigation interventions.

Regarding the irrigation process, it should be noted that the farm in Case 1 would have no way of automating/digitalizing operations, this is because the infrastructures and the shape of its land imply the implementation of flow irrigation. This practice, among the most traditionally used in the Po River Valley, is based on the availability of water granted in shifts by the local water resource management consortium. Furthermore, it is carried out through the overflow of water from channels located along the fields; therefore, no type of mechanical equipment within the scope of the farm is used.

A final consideration must be made on the data flows characteristic of Case 2. As can be seen from the diagram, data from the harvesting process, current and historical, are integrated with data and information from other sources for the definition of prescription maps. As an example, historical yield maps are integrated with data and information from soil maps and satellite indexes. These maps are used to make cultivation decisions to be carried out in future processes (typically those in subsequent cultivation cycles). This is particularly concerning for fertilization, crop protection, and irrigation processes; for example, for site-specific nitrogen fertilization to enhance the site-specific potential to maximize the yield and quality of production. The process of defining the prescription maps is not completely automatic but involves an intervention by the farmer on the operating platform interface. This intervention takes the form of both the manual integration of some external data and the processing/discussion by the farmer team. This is strongly based on knowledge about the land and the market, and of course on agronomic skills.

This consideration confirms that in Case 2 the farmer has set up an integration of technological equipment and data flows between different processes. This farm also adopts a dynamic perspective in digital and data management in the sense that it goes beyond the current cultivation cycle. This type of evolution is also in the works for the farmer of Case 3; specifically, he is currently working with the machinery supplier to implement the process of defining and using prescription maps. To reach this level, the farmer will have to acquire further skills (supported by the machinery supplier) and will have to evolve his digital equipment, as well as equip himself with an adequate maintenance system for the mechanical data collection parts. As an example, the flow sensors mounted on the harvesting machines perform operations fundamental for the correctness of the yield maps, at the basis of the prescription maps.

3.2.3. Advantages and Obstacles

Table 4 shows the benefits brought by digitalization and the obstacles encountered in the digital transition path, which were declared by the farmers of the 3 case studies.

Table 4. Benefits from digitalization perceived and declared by the farmer in each case; obstacles in the digital transition perceived and declared by the farmers in each case.

	Case 1	Case 2	Case 3
Benefits			
Increased environmental sustainability	•	•	•
Increased efficiency in the use of inputs	•	•	•
Increased time and cost savings	•	•	•
Less hard work	•	•	•
Less soil usage	•	•	•
Higher yields	•	•	
Higher products’ quality	•		
Obstacles			
Reduced interoperability	•	Managed	Supported
Excess of features vs actual needs	•	•	
Reduced digital competences	•		Supported
Presence of competitive/alternative consulting services	•		
Low trust in digital solutions	•		
Excessive cost of technologies			•

Regarding the benefits, one can immediately notice how there is almost total homogeneity about the perceived factors; only the farmers of Cases 2 and 3 did not declare "Higher products' quality" (in both cases) and "Higher yields" for Case 3. But those benefits of digitalization linked to greater environmental and economic sustainability are therefore confirmed, thus supporting hypotheses reported in the literature [6]. It is important to notice how those benefits can be seen as enabling factors supporting the agricultural sector in dealing with contingent challenges.

Notably, a broad picture of the benefits is also perceived by Farm 1, the one that owns and uses a smaller number of digital equipment, and which does not have advanced data flows integrated into its processes. This seems to demonstrate that even basic levels of digitalization can offer substantial benefits that are clearly perceived by farmers.

Regarding the obstacles, greater heterogeneity emerges as Farm 1 claims to face the greatest number of obstacles, among which the reduced interoperability of digital solutions and low trust in digital solutions were detected as the most relevant during the interview. Only the high cost of technologies is not perceived as a barrier.

In Case 2, however, there is the least number of perceived obstacles. Essentially, only the excess of features vs actual needs emerges, while the reduced interoperability, although it was initially perceived as a barrier, was managed positively thanks to the profound digital skills of the farmer (and his team). An example of this is the need for integration between the John Deere platform and the Case platform, without which the Case machinery would not have been purchased. This integration was created as software customization by the manufacturers' parent company team, thanks to the relevant economic investment afforded by the farmer.

The farmer in Case 3 is the only one to have declared the high cost of technologies as an obstacle, adding that it is the factor that has determined a slower pace in the digital transition path. Furthermore, reduced interoperability and reduced digital competencies have been defined as barriers that can be overcome through adequate support from the machinery supplier. Indeed, the farmer has signed a support and consultancy contract with his supplier, whose object is the maintenance and management of digital equipment (hardware and software).

3.2.4. The Path towards Digitalization: A Level for Each Farm

The presentation of results described so far is the basis of the considerations that lead to placing each farm of the case studies along an ideal continuum, representing the digital transition path. To facilitate the interpretation, the "five steps digital evolution model" developed for the agricultural industry by Munz et al. (2020) [8] was employed, based on the model proposed by Porter and Heppelmann (2014) [9]. The model envisages the transition from the "single product" to the "system of systems" through the adoption of digital solutions, depending on the level of integration between solutions and processes, as well as the level of variety and complexity of the technological equipment, including digital ones. Figure 2 is a graphical explanation and representation of the model. Specifically, the five steps of the model are the following: 1. Single product; 2. Smart product; 3. Smart, connected product; 4. Intelligent product system; 5. System of systems.

Therefore, with reference to the case studies and based on what emerged during the interviews with the farmers, the following considerations can be made.

The farm in Case 1 can be placed at level 2, or "Smart Product". The farmer, in fact, equipped the tractors with satellite systems that detect and collect telemetry data and support contingent operations. The tractor, therefore, becomes "smart" during the operation. However, there is no routine connection with operating machines and the data are not used ex-post, through the operating platform. The data collected by the weather stations are also used in real time to make contingent decisions; they are not used to make decisions on irrigation interventions or crop protection treatments.

The farm in Case 3 can be placed at level 3, or "Smart, Connected Product". The farmer activated the connections between tractors and operating machines under satellite guidance, being able to digitally set and control not only the action of the tractor but also the operation, in a specific and variable way throughout the field. Telemetry and cultivation data are collected, archived, and interpreted for subsequent use and decision support. The data collected by the soil sensors are also used to decide on irrigation interventions, which are also digitally controlled. There is, therefore, an integration driven by a flow of data within a single cultivation process, enabled not only by smart equipment but also by the connection among them.

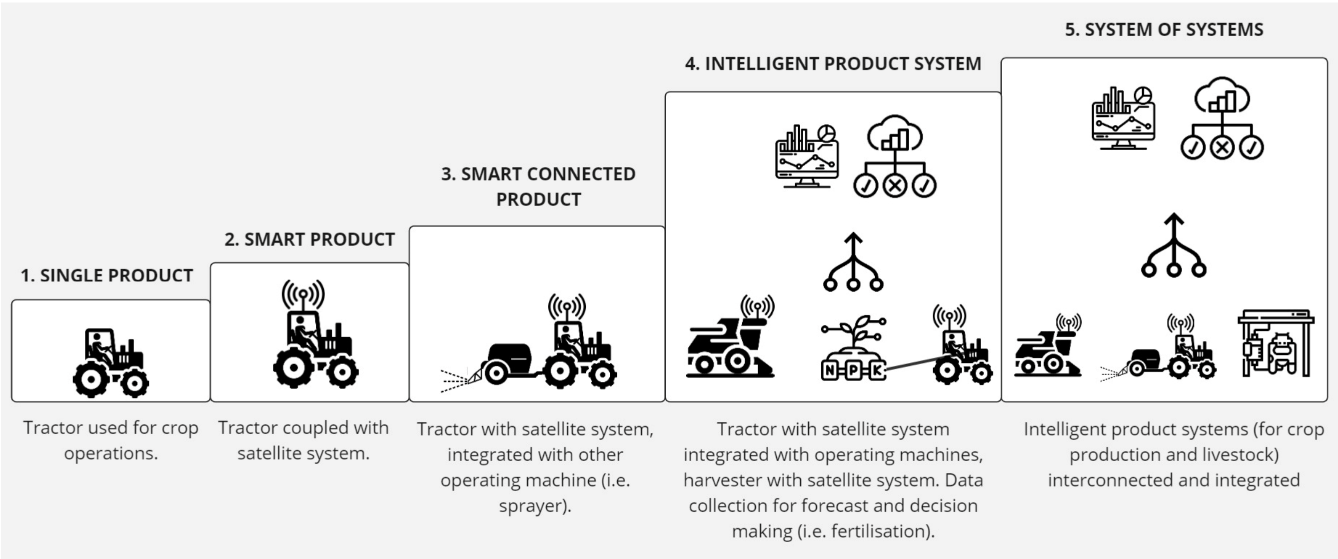

Figure 2. The five steps of digital evolution in farms. Source: authors' reinterpretation of the model based on [8,9].

The farm in Case 2 can be placed at level 4, or "Intelligent Product System". The farmer has set up the same system as in Case 3 in terms of smart and connected equipment. In addition, however, it has also activated a data flow that integrates different cultivation processes, even among subsequent cultivation cycles. The definition of prescription maps indicates maps based on historical yield maps, soil characteristics, and satellite indexes. For this reason, it is possible to affirm that the farm created an intelligent system that represents, in the selected sample, the most advanced level of digital evolution.

4. Discussion

4.1. Drivers of the Digital Transition

Through the performed within-case and cross-case analysis, several characteristics emerged that allowed us to place the three farms covered by the study along the digital transition path. From the study of the similarities and differences among cases, as well as from the observation of how the three farms are positioned along the digital transition path, the following relevant themes emerged:

1. Digital skills of the farmers;
2. Data management practices;
3. Interoperability of digital solutions.

a. First, digital skills of the farmers represent a key factor among those enabling digital evolution [7,17,20,22], also related to the solutions' complexity of use, users' education level, and the need for training [33]. This trait also emerges in our study.

In Case 2, the farmer has an excellent level of skills and can transmit them to all operational staff, at least in a useful way for the features that they must use. Digital skills, in fact, paved the way for the digitalization process and allowed it to evolve rapidly. Furthermore, they made it possible to avoid obstacles and barriers such as the lack of interoperability between digital solutions. As already mentioned, the integration between the farm's operational platforms was key at a turning point in the path. If the farmer had not advanced digital skills, he would not have been able to see this integration as a possible solution to the interoperability problem.

In Case 3, however, the farmer and his team do not have advanced digital skills but rely on the machinery supplier for support and consultancy services. This service also takes the form of continuous training which, in effect, is progressively increasing the skill set of the farmer and his team. Even in this case, therefore, skills represent a fundamental enabler, although not necessarily an endogenous factor of the farm. It can be validly implemented by third parties but with the effect of a slower transition path. Furthermore, the support for skills and the dissemination of the same within the farm also seem to be able to break down the barrier of the high costs of acquiring technologies, a problem that is very much felt by Farm 2.

Finally, in Case 1, the lack of digital skills is an obstacle to digital evolution, above all because it hides a lack of trust in digital solutions, which undermines the continuation of the evolution path. In fact, the simplest and most widespread solutions on the market are applied in Farm 1: although there is no perceived economic barrier, any further progress on the path is precluded.

b. Data management practices are a key factor in supporting the quality of digitalized processes and digital data flows. The enormous amount of data available in Agriculture 4.0 must be adequately managed, both in terms of data quality verification and in terms of adequate data interpretation, aiming at increasing the functionality for farmers [7,22]. Evidence and validation of this in the analyses of the present study were found.

In Case 2, the attention and ability to manage data is considered a very delicate and relevant element, which is why human, and economic resources are specifically allocated for the maintenance of data detection and storage equipment (i.e., on-board sensors on harvesting machines). Data quality, in fact, is the basis for making correct and effective decisions in the management of the agricultural business; this is particularly true in the production of yield maps for the definition of prescription maps.

The farmer in Case 3, however, recognizes the relevance of data management but does not yet have the adequate tools to manage it correctly. He is progressively acquiring awareness of the importance of this activity, also through the perception of the consequences of errors made in the data collection or interpretation phase. In fact, he declared that he will soon invest more resources in the maintenance of on-board sensors for harvesting machines, for example.

Finally, the farmer in Case 1 does not yet have an awareness of the importance of interpreting the data collected; therefore, he does not commonly carry out selection and interpretation activities of the reports. It is also possible that the lack of trust in digital solutions is one of the underlying reasons for the lack of confidence in the quality of the data collected.

c. Lastly, interoperability between digital solutions is often cited as one of the main obstacles encountered on the digital transition path in agriculture [7,8,17,19,20]. There are several public initiatives taken to overcome this problem, like European pilot projects underway [7]. At the same time, a wide number of private producers are developing and launching digital operating platforms open to other manufacturers, albeit following market logic. What emerges from our study, however, is that the interoperability barrier is an obstacle that stands between farmers and digital evolution, but that it can certainly be overcome through various strategies.

The farmer in Case 3, for example, strategically decided to rely on a single manufacturer of agricultural machinery, having this manufacturer also a good ability to integrate with other smaller producers through hardware and software solutions. Furthermore, this connection allowed the farmer to take advantage of a support and consultancy service that increases the farm team's digital skills.

The farmer in Case 2 also relied on a single manufacturer; when, however, he decided to purchase a large machine from another producer, he perceived the problem of the lack of interoperability and was able to solve it by requesting a software customized integration. As already mentioned, this solution was supported first and foremost by a high investment capacity and equally important, by internal advanced digital skills that allowed the farmer to guide the customization operations according to his needs.

Finally, in Case 1, the lack of interoperability is not strategically managed. The choices to purchase technological equipment seem to be guided by price levels and other market opportunities, thus resulting in the perception of non-interoperability problems in the middle of the activities. The issue, therefore, seems to be addressed by the farmer as a superficial motivation, maybe hiding once again a low trust in digital solutions and reduced digital skills.

Our study has therefore highlighted these issues as fundamental drivers in the digital transition path: they act in a positive or negative sense, therefore facilitating or hindering the evolution towards the digitalization of farms.

More specifically and originally with respect to other studies, the digital skills of the farmers appear to act above all as an enabler, also capable of accelerating the speed of traveling along the path. When they are missing, however, they are even capable of blocking digital evolution, leading the farmer into a spiral of lack of trust in digital solutions and a sort of self-exclusion from the innovation market. Finally, it is important to note that when skills are not an endogenous factor within the farm, they can be acquired from outside in an equally valid way, albeit at the expense of a higher speed of the evolution path.

Data management practices also appear to act as an enabler because they guarantee the quality and integrity of the data circulating within the company flow. When they are missing, the digitalization path risks slowing down or taking the wrong direction: for this reason, from the present study, it emerges that they can be considered as a "second level enabler", i.e., one that intervenes at an already advanced level of digitalization. For example, when the farm is already equipped with instruments for detection and archiving large amounts of data there is a desire to interpret them as decision support. Farms that do not implement data management practices, however, interrupt the evolution path and cannot unlock the benefits offered by a more advanced level.

The interoperability among digital solutions is often presented as an obstacle, a limiting factor because it is usually depicted as lacking; however, according to our experience, it can be interpreted in a broader and more positive sense. The present study shows how this factor if adequately managed, can be an enabler in the digital evolution path. That is, a valid interoperability management strategy is a key factor for leaping digitalization. Among the strategies identified, there is certainly the choice of a single supplier, but integration through software customization was also found, supported by investments and skills, if the economic opportunity is validated. Therefore, starting from the assumption that technological and digital solutions lack complete interoperability, it is not possible to stop here. Farms motivated in the digital transition are able to overcome this obstacle, through careful and thoughtful strategies, supported by an adequate use of tangible and intangible resources.

Furthermore, how the theme of digital skills is recurrent and how these are relevant in the digitalization process was noted. In any case, our study shows that they are not a sufficient factor, in themselves: there must be a will shared within the Farm organization, setting the strategic objectives within the digital evolution path. Without this, little progress can be made.

Lastly, it is important to note that investment capacity, also supported by the presence of public incentives, plays a peculiar role in the digitalization path. It is interesting to note how it can represent a factor that is not sufficient to move the farm towards more advanced levels, but able to increase the pace of the route. In other words, farms with a greater investment capacity (also facilitated by public incentives), are faster in achieving digitalization objectives, also because they can break down obstacles along the way if the necessary requirements have been met. The fact that there are essential technical elements without which the path cannot be started needs to be stressed. Those can be defined as the minimum technological equipment necessary to undertake digitalization in agriculture. However, as Case 1 also depicts, possessing these minimum requirements does not imply advancement in digital evolution. They must be commonly used and correctly employed in operational routines, as part of a strategically set path.

4.2. Policies for the Digital Transition

Policies can help to make digitalization in agriculture more widespread; in the context of agricultural policies, precision farming techniques are the most frequent subject of interest when referring to support for digitalization. Fingers et al. (2019) [34] highlight three aspects where policies can contribute to (i) promotion of adoption; (ii) provision of infrastructure and legal frameworks, and (iii) information sharing generated by the adoption of precision agriculture.

In recent years, Italy has allocated increasing financial resources to promote the uptake of precision agriculture among farmers. However, the public interventions have mainly focused on supporting the purchase of machinery and equipment by farmers, while less emphasis has been placed on the creation of public platforms for data collection and sharing, as well as on the training of operators. For instance, a portion of the national revolving funds, known as the Sabatini Law, was specifically earmarked for farmers purchasing precision agriculture equipment. Additionally, in 2020, significant tax credits of up to 50% of the equipment value were introduced for the acquisition of machinery compatible with Agriculture 4.0 standards. To qualify for the Agriculture 4.0 tax credit, assets had to be interconnected, sharing data with other internal and external systems using recognized standards. Thus, farmers were responsible for documenting continuous monitoring of operational conditions, interconnecting machinery with farm management information systems, and presumably utilizing gathered data in production processes. While this requirement, self-certified for investments below EUR 300.000, aimed to deter analog machine usage, it did not inherently ensure the implementation of a comprehensive precision farming system. Additionally, it is important to note that machine interconnection needed to be proven only for the three years post-purchase.

More recently, in 2023, the Italian government renewed public support for Agriculture 4.0, within its post-pandemic National Recovery and Resilience Plan (NRRP) financed by Next Generation Europe funds. NRRP allocated EUR 400 mln for the modernization of agricultural machinery to enable the introduction of precision farming techniques. The requirements for applying for the contribution on investments, this time provided in a capital account, were like those for the previous tax credit, although the number of eligible investments was smaller. In fact, regarding self-propelled machines, these could only be financed if they were powered by electricity or biomethane, technical solutions that are not yet widely available on the market, or still uneconomical for farmers. This fact, together with lower co-financing rates, has considerably discouraged farmers from participating in this new policy, the first calls for which were poorly attended.

In addition to national policies, farmers interested in investing in Agriculture 4.0 can also apply for funds from EU Rural Development (RD) policies, the second pillar of the CAP, particularly focusing on traditional measures for co-financing agricultural investments. However, it is important to note that this budget is not exclusively reserved for precision farming investments and applies universally to all investment types.

Notably, the new RD programming period 2023-2027 introduces in Italy an innovative measure [35] specifically dedicated to precision farming (SRA24). This RD intervention is categorized under the ‘Environmental and climate-related commitments’ framework (EU reg. 2021/2115 [36]) and differs from previously described policies. It entails a yearly per-hectare payment to support farmers adopting precision agriculture for a minimum period of 5 years. The payment primarily focuses on environmental objectives such as reducing the chemical and water inputs in agriculture, aligned with EU Farm to Fork strategy goals [34]. Participants in the scheme must fulfil two requirements: (i) collection and digitization of farm data, and digitization of the register of treatments, fertilization, and irrigation inputs, by joining digital service platforms and DSS in agriculture, open and interoperable with the public administration; (ii) to respect precision farming practices related to fertilization and/or phytosanitary treatments and/or irrigation. For instance, the measure mandates variable rate fertilization (VRF) based on prescription maps and/or variable rate irrigation (VRI) utilizing soil moisture sensors. Moreover, applicants may be required to undergo training in precision agriculture or utilize advisory services, both of which can be co-financed by the RD program (RDP).

The introduction of a policy measure (SRA24) focusing on the implementation of precision farming practices, rather than solely providing related investments, marks a novelty in Italian RD programs. This promotes a sustainable intensification farming option within the set of agro-climatic-environmental schemes, which predominantly favor agricultural extensification solutions. The practices encouraged are certainly ambitious, but also highly desirable to improve agricultural sustainability, even if likely feasible for farms with already established expertise in precision agriculture. The rather modest minimum and maximum eligible areas or degressivity thresholds established for payments do not support the development of economies of scale crucial for Agriculture 4.0 technologies.

Instead, mandatory training requirement goes in the right direction of promoting knowledge and strengthening human capital, essential for transitioning to precision agriculture alongside material assets. Data sharing with the public administration is also a mandatory condition, mainly intended for compliance checks, although uncertainties remain regarding the feasibility of creating public data-sharing platforms, a concept mentioned in some RDPs without technical details as the policy is still in the activation phase.

However, it is worth noting that SRA24 was activated in only 9 out of 21 regional RDPs in Italy, with very limited financial resources allocated, constituting only 0.21% of the national RD budget (approximately EUR 34 mln) for the 2023–2027 programming period. In comparison, organic farming RD measures have a budget of around EUR 2.100 mln. The exiguity of the allocated resources clashes with the interest shown in the SRA24 measure by farmers. For example, the Piemonte region, activating the SRA24 scheme in its RDP, has exhausted the resources allocated to this scheme since the first call, managing to satisfy only 15% of the applications submitted [37].

5. Conclusions

The present work aimed to explore drivers and barriers in the adoption of digitalization among field crop farms in northern Italy, using a case study approach and taking into consideration the local context of the Po River Valley. This has been achieved by illustrating the complexity of equipment systems and process data flows in the farms. Another goal was to investigate the interaction between enablers and digitalization policies in agriculture, presenting initiatives for policymakers to effectively promote the digital transition. For this purpose, three farm case studies varying in their level of digitalization were examined. These case studies were chosen as examples of the progression towards digitalization, by adapting a pre-existent model to the specific context. In doing so, the most relevant advantages and challenges faced by farms during this transition have been identified and generalized as "drivers of digital transition": (i) Digital skills of the farmer; (ii) Data management practices; and (iii) Interoperability of digital solutions.

Farmers' digital skills act as a mediator to digital transition: below a certain threshold, they may slow down or even block the process, while above they act as an enhancer. Such skills may also be acquired outside the farm, even if at the cost of a lower transition rate.

Data management practices represent a step forward, compared to digital skills, pertaining to accuracy in data acquisition, storage, and integration in the farm data flow. A minimum level of data management is a necessary condition to enjoy the benefit of using data as a decision support.

Interoperability is intended as the integration and data exchange among machinery and devices of the farm management information systems, even when from different manufacturers. One of the key results is certainly having presented interoperability not as a mere barrier to digitalization, but as a fundamental key to development that can be exploited through the implementation of the most appropriate strategies for the context. Indeed, a full degree of interoperability guarantees flexibility to farmers, allowing them to choose the most efficient technical solution within each farm decision-making area.

This paper indicates the steps on the path to achieving full farm digitalization. Since this path cannot be totally the responsibility of farmers, this analysis also provides guidance to all stakeholders involved in modernizing the agricultural sector (farmer associations, policymakers).

Policies aiming at promoting digitalization in agriculture should take into account the peculiar role played by drivers (digital skills, data management practices, and interoperability). The bulk of policies aimed at fostering digitalization in agriculture rely mainly on supporting the acquisition of mechanical and digital equipment. However, such a step is a necessary but not a sufficient condition for full-path digitalization. Such a target requires also a general (human capital) and specific development of farmer's skills in digitalization. In particular, farmers' acquisition of digital and data management skills should be a condition for subsidies on both investments and per-hectare payments for precision farming payments.

While such analysis has relied on current literature, the specificity of the context from which data have been gathered confines the validity of finding the same and/or similar territorial contexts.

Under the above-mentioned limitation, this paper paves the way for future research on the degree of farm digitalization in the same/similar territorial contexts. In particular, the identified drivers of digital transition (digital skills, data management, and interoperability) can be used as the basis for survey questionnaires and, at the same time, tested in their validity.

Author Contributions: Conceptualization, A.G. and G.F.; methodology, A.G. and L.P.P.L.; investigation, A.G., L.P.P.L. and D.C.; data curation, A.G. and L.P.P.L.; writing—original draft preparation, A.G., L.P.P.L., G.F., D.B. and D.C.; writing—review and editing, G.F., D.B. and D.C.; supervision, G.F., D.B. and D.C.; funding acquisition, D.B. and D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the European Union Next-GenerationEU: (Call PRIN 2022-Italian Ministry of University and Research (MUR)-RECIPE-cod. 20224ZHNXE).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy restrictions.

Acknowledgments: We want to thank the farmers for dedicating their time and opening their farms. We also want to acknowledge UNI and UNINFO for important knowledge support during the first phases of the work. The authors acknowledge support from the University of Milan through the APC initiative.

Conflicts of Interest: The authors declare no conflicts of interest.

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