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Who Benefits from Agricultural Digitalisation? Evidence on Farm Size and Technology Adoption Across Europe

Senour Ahmadi

snour.ahmadi@unifg.it

University of Foggia

Mariantionetta Fiore

University of Foggia

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Who Benefits from Agricultural Digitalisation? Evidence on Farm Size and Technology Adoption Across Europe

Abstract

The digitalisation of agriculture plays a major role in the EU strategy for its agricultural sector. This study focuses on inequalities in adoption of farm digital technologies, adoption gaps for advanced and basic digital technologies, as well as the effect of regional connectivity on these gaps. The analysis employs 2023 Eurostat data, and covers 814 economic-size units in 164 regions across 20 Member States for the farm economic size analysis. The farm regional connectivity analysis covers 577 units in 116 regions in 19 Member States. Adoption gaps for Internet, farm management information systems (FMIS), and livestock management technologies, were 22.97 percent, 33.88 percent, and 40.85 percent, respectively, for farm businesses with standard outputs of at least €100,000, as compared to farm businesses with standard outputs of less than €2,000. Similar adoption gaps for farm robotics and precision farming were observed. The results show that adoption gaps among farm businesses are larger for advanced digital technologies than for basic digital technologies.

More advanced technology presents bigger size gaps than basic Internet facilities. Regional household Internet access is positively associated with basic farm Internet adoption, but not with advanced technology adoption. The associations between basic farm Internet access and advanced technology adoption are not statistically significant in the adoption models. The moderation analysis also does not support the hypothesis that connectivity narrows farm-size adoption gaps. For FMIS, robotics and livestock management machinery, higher connectivity is associated with widening gaps, while the interactions with the farm Internet access and precision farming are not statistically significant. These results imply that in the presence of favourable digital environments, equitable adoption is unlikely.Recommended policies would be to integrate connectivity and financial subsidies, advisory services, ICT skills training and equipment, while assessing their impact using distribution-based indicators.

Keywords: digital agriculture; farm economic size; digital divide; precision farming; regional connectivity; European Union

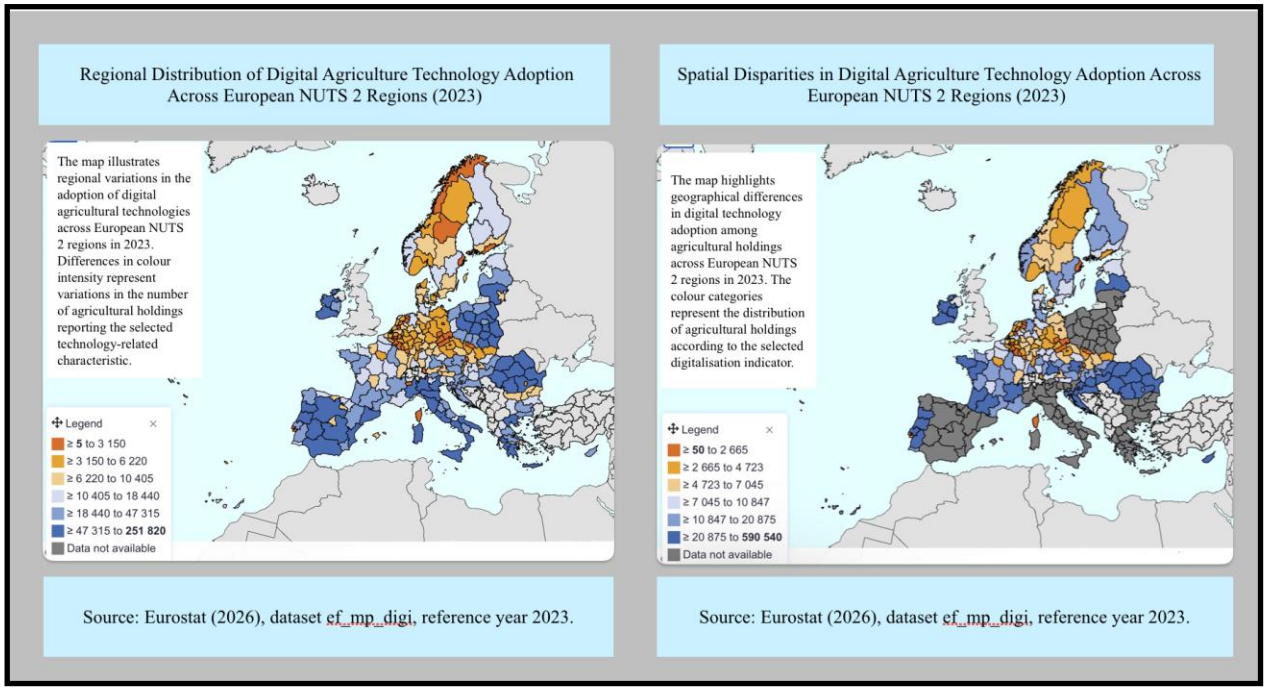
1. Introduction

The development and uptake of digital technologies have the potential to support the competitiveness and efficiency of European agri-food systems. The possibilities span the creation of new forms of aggregation, agricultural production and food processing, as well as transforming the ways in which products and services are bought and sold. Farmers are therefore positioned to take advantage of positive cross-sectoral spill-over opportunities by adopting new ways of working and employing new technologies. The CAP 2023-2027 specifically taps into the potential of the knowledge economy and the digital economy. It builds on the 2025 Vision of the European Commission for Agriculture and Food to modernise farming and sustainability. The 2026 European Commission's strategic framework on research and innovation also identifies digitalisation and robotics as top research and development priorities for agriculture. There is a gradual recognition of the importance of the role of digitalisation, including large scale data management and processing, towards improving the resource and environmental efficiency of food systems.

Recent Eurostat data make this distributional question hard to ignore. In 2023, around 43% of EU farms had access to the Internet, about 11% used a farm management information system (FMIS), and approximately 7% used robotics. Some 18% of farms with a utilised agricultural area (UAA) used some form of precision farming, but these farms covered approximately 44% of the UAA of the EU (Eurostat, 2026e). The difference between the level of farm adoption and the level of land covered by adopters illustrates that technological and farmer coverage are not the same. The economic size gradient is impressive too: Eurostat states that farms with a Standard Output of at least €100,000 had higher levels of Internet access, FMIS, and robotics compared to farms with a Standard Output of below €2,000 (Eurostat, 2026b). These statistics indicate a structural digital divide in European agriculture, during which a change that appears to be extensive, when measured by land, may in fact be considerably less inclusive when measured by the number of holdings.

Factors such as the size of the enterprise, the degree of education and training, experience and technical know-how of the farm managers, and the availability of financial and technical services,

Figure1. Regional distribution and spatial diparities of Digital Agriculture Technology Adoption Across European NUTS 2 Regions (2023)



Source : Eurostat (2026)

are of key importance to the adoption decision. Larger farms are generally more innovative in the adoption of technology (Žáková Kroupová et al., 2025). The JRC survey of 1,444 farms in nine EU Member States also revealed that large and better-connected farms (Internet) were more innovative in the adoption of farm management systems and precision farming technologies (Tur Cardona et al., 2025).

As reported by Fragomeli et al. (2025) for a case of Italian farmers, high up-front costs disproportionally affected the willingness of smaller farms to adopt Agriculture 4.0 technologies, indicating that high level of resources and physical infrastructure are critical to the adoption of advanced technologies for farm management. Therefore, a single aggregate measure of digitalisation of farms conceals an important hidden reality: the farm size divide may be narrow for low-level digital infrastructure, but widens for advanced and farm-specific technologies.

Territorial factors represent another dimension of the problem. Internet connectivity is a foundational element for providing digital services, exchanging data, and using cloud- and web-based applications and advisory systems. The EU digital policy of "never again leaving anyone behind" seeks to combine technology with adequate infrastructure, skills, and training, and to remove the digital divide between rural territories and users (European Commission, 2026b). While reducing digital divides is of significant importance, equal access to a digital environment does not mean the same level of capacity is available to exploit it. For the assimilation and use of digital technologies, there needs to be an integration of various elements, including an adequate skills base, advisory systems, and the supply-side institutions (Klerkx et al., 2019). Rural connectivity has the potential to provide a more level playing field to all farms, including smaller farms, or to provide an opportunity for larger, more resource-rich farms to adopt more advanced digital technologies.

Although a large body of literature on digital agriculture is rapidly emerging, three interconnected issues remain unresolved at the European level. The first is the lack of large-scale evidence on the degree of inequality of farm size in the adoption of digital agriculture. The second is the lack of evidence on whether the inequality of farm size in digital agriculture adoptions systematically differs for more advanced digital agriculture tools from less advanced digital tools. The third is the fact that connectivity is one of the most important enablers of the adoption of digital agriculture, however, there is little evidence to suggest whether improving connectivity and digital infrastructure would reduce the inequality of digital agriculture adoptions. The JRC survey and more recent Eurostat data document different farm sizes and different levels of digital and physical connectivity. However, they do not analyze the interaction of these elements.

This study fills gaps in previous research by using the 2023 Eurostat farm-digitalisation module and regional household Internet access data. It studies digital agriculture adoption by farm economic-size class in different regions of the EU, differentiates Internet access, Farm Management Information Systems (FMIS), precision farming, and robotics and livestock management equipment, rather than combining them in a digitalisation index. The study assesses if the farm-size adoption gap is bigger for advanced technologies, compared to basic digital facilities. It analyzes if regional connectivity is positively related to the average adoption level of digital agriculture, and if regional Internet access helps diminish the digital adoption gap for smaller farms. A complementary analysis for the EU-27 for physical farm size and specific precision agriculture practices and practices provides an independent robustness test of the main structural hypothesis.

This study is based on four research questions. The first research question is: To what extent does digital agriculture adoption vary across farm economic size classes in the EU? The second research question is: Are farm size inequalities larger for advanced agricultural digital technologies compared to basic digital facilities? The third research question is: Is regional Internet access positively related to digital agriculture adoption, controlling for farm economic size classes and country level differences? The fourth research question is: Does regional Internet access help

diminish the digital agriculture adoption gap between smaller and larger farms? The second chapter formulates the above four questions as hypotheses.

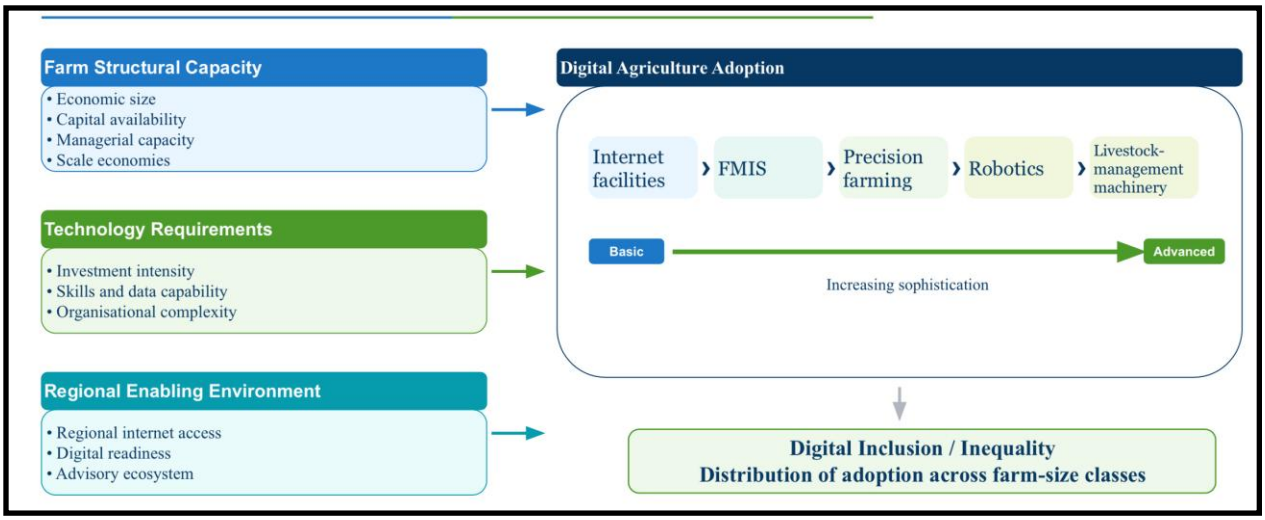
The authors makes three main contributions. First, instead of analyzing the average rate of digital adoption, the author focuses on how digital adoption is distributed across farm structures. This allows for an assessment of whether digital transformation is happening across the farm sector or occurring amongst larger, more economically powerful farms. Second, the authors uses the concept of digital technologies and the size divide to examine whether the farm-size divide increases when the level of digital infrastructure moves beyond basic digital facilities to more sophisticated agricultural technologies. Finally, the authors incorporates the territorial enabling environment to address the gap in structural connections by distinguishing the relationship between average adoption and connectivity from the more relevant case that connectivity closes structural gaps.

The remainder of the paper is organized as follows. Section 2 offers the main ideas and hypotheses. Section 3 provides an overview of the Eurostat data and presents the sample construction and empirical strategy. Section 4 analyzes the results, including case studies for size gradients and connectivity, and tests the robustness of the results. Section 5 discusses the results and offers some thoughts on the EU Digital Transition.

2. Theoretical framework and hypotheses

There are a number of opportunities for European Agriculture through digitization, including improvement in productivity and competitiveness, resilience and the achievement of environmental targets. The principles of the EU policy integrate a number of areas including, technology and infrastructure, and knowledge and training as well as advisory services (European Commission, 2026b). This integration recognizes the existence of digital divides at the farm and rural level. This integral policy framing is important, as the ability of a farmer to access a digital environment and their ability to use the access to the full potential of farm activities are two different things. Digital Agriculture is a socio-technical transition and the integration of digital technologies in farming restructures a farm, organizationally, socially and technologically (Klerkx

Figure 1. Theoretical framework of study



Source: Authors' elaboration

et al., 2019). Therefore, the focus of the study is to analyse the conditions of digitization to determine whether they lead to broad and inclusive participation of farm structures (Figure 1).

The framework combines three complementary ideas. First, the literature on the agricultural digital divide draws attention to inequalities in the control of data, as well as to differences in the skill and the resource base in relation to the use and access of digital technologies (Rotz et al., 2019). Second, smaller farm size and lesser financial resources tend to constrain the adoption of improved agricultural technologies (Acevedo-F ghost et al., 2021; Barnes et al., 2019; Dogbey et al., 2016). Larger farms and more financially endowed ones are, however, found to have a greater likelihood of adopting digital technologies (Žáková Kroupová et al., 2025). Third, regional digital infrastructures create an enabling environment, and the benefits accrue to those farms which have complementary resources. Hence, the framework considers farm size as structural capacity, connectivity of the region as the enabling environment, and the technology as the source of adoption gap heterogeneity.

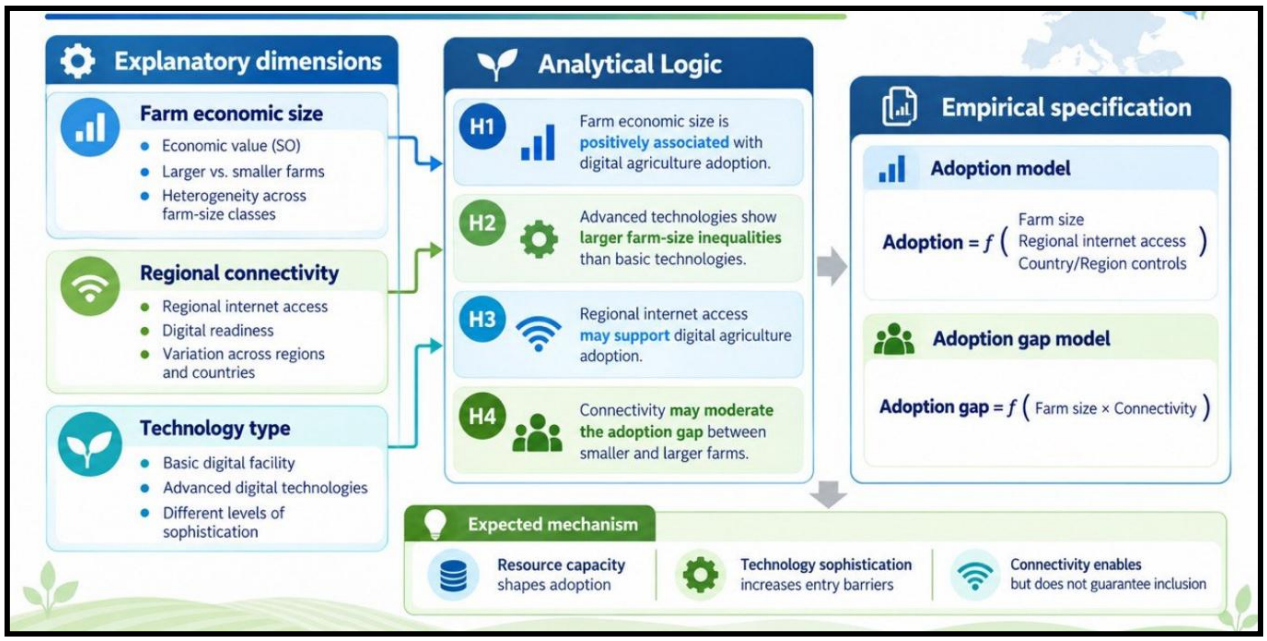
The size of the farm economy can provide clues for digital adoption due to several complimentary mechanisms. Most agricultural digital solutions include fixed costs, e.g. capital equipment and software, as well as services and infrastructure, maintenance, and training. For larger farms, the fixed costs of these digital solutions can be spread over more hectares. Larger farms also may have greater access to working capital and specialized farm labor. The acreage of a farm only poorly captures the scale of the farm economy. Farm economic size may also be associated with the farm's capacity to absorb larger investments and adapt to new organization. In the Eurostat farm statistics, size is often captured by the total Standard Output (SO), which is the total value of crops and livestock (Eurostat, 2026e).

It is generally accepted that larger farms have greater capacity to adopt digital solutions. Barnes et al. (2019) reported that larger farms with higher incomes adopted more of the advanced digital solutions in agriculture. Heterogeneous and often limited adoption of digital solutions in small-scale farming in Europe was also reported by Gabriel and Gandorfer (2023). The JRC (2025)

survey of 1,444 farms in nine EU Member States reported high costs and a digital divide, i.e. a lack of skills, as barriers to the adoption of digital farming. Thus, from the evidence, an association between economic farm size and the adoption of digital farming solutions is to be expected (Figure 2, Table 1).

H1. Digital agriculture adoption increases with farm economic size.

Figure 2. Anayitical framework of digital agriculture adoption and inequality across farm economic-size classes.



Note: The figure was developed by the authors with AI assistance for visual design and formatting

2.2. Technology sophistication and unequal adoption

Not all digital technologies require the same level of complementary resources to be adopted. Basic levels of the Internet for example, require reasonable access and a limited level of equipment and skills. Other more integrated and farm-specific digital technologies, for example, farm management systems and precision farming, can require more integration, farm level skills and confidence in expected returns. Evidence from the EU indicate that general IT tools, including farm management systems, are more widespread than expensive farm-specific systems for crops and livestock (Tur Cardona et al., 2025). The distinction, therefore, is not to place all digital technologies on a strict ordinal ladder from least to most; rather, it would place basic levels of digitization from a farm's perspective, and more integrated digital technologies for the farm.

Advanced digital adoption, for the reasons explained above, should more heavily depend on complementary farm resources. Hence, structural differences between small and large farms should more visibly emerge as the level of digitalization and the required complementary farm

resources increase. This is substantiated by meta-research (Žáková Kroupová et al., 2025) which found more advanced digital technologies (Agriculture 4.0) were adopted by large, capital-intensive farms. Similarly, recent research shows high up-front costs on technologies associated with Agriculture 4.0 are a barrier especially for small farms (Fragomeli et al., 2025). Thus, the empirical hypothesis is that for more integrated digital technologies, an advanced farm-size technology gap is expected than for basic digital technologies (Figure 2, Table 1).

H2: Structural differences in farm size for adoption of integrated digital technologies in agriculture are greater compared to basic digital technologies.

2.3 Regional connectivity as an enabling digital environment

The regional connectivity dimension covers the territorial aspect of the framework. Households and businesses usually operate in a highly interconnected environment, thereby lowering basic barriers to accessing digital services. The European Commission identifies infrastructure as one of the core elements of its digitalisation policy for agriculture, along with skills and advanced-technology support (European Commission, 2026b). A recent JRC study, in the meantime, indicates that farm digital adoption is higher among respondents with a better Internet connectivity (Tur Cardona et al., 2025). A positive relationship between the regional digital environment and the level of farm digital adoption is therefore plausible.

The regional connectivity dimension of the framework is captured by the 2013 Eurostat indicator on the share of households with Internet access at home. This should be regarded as a proxy for the regional digital environment, rather than for broadband quality and speed on farms. According to Eurostat, there is large regional variation in household access to the Internet across the EU. Rural households remain less connected than urban households (Eurostat, 2024). It is, therefore, expected that in areas with a better digital environment, farm digital adoption would be higher, particularly after controlling for farm economic size and possible differences at the country level in the quality of institutions (Figure 2, Table 1).

H3. Better regional Internet access increases digital agriculture adoption.

2.4. Can connectivity reduce the farm-size digital divide?

The inclusion question requires looking beyond the average impact of connectivity. If inadequate connectivity is a binding constraint that disproportionately affects smaller farms, then improving regional connectivity should remove a key barrier to entry and allow smaller farms to catch up. Equalization logic is aligned to the EU policy goal to reduce digital divides through support and infrastructure. With this approach, the marginal association between farm size and adoption should weaken as regional connectivity improves.

A different logic is, however, plausible. Improving connectivity may create opportunities without making all farms equally able to take advantage of those opportunities. New or improved connectivity, in combination with investment or other policy interventions, can be used to bridge digital divides. The key, though, will be to couple the interventions in a manner that enables smaller and less integrated farms to effectively benefit from improved adoption of ICT. The underlying concern is that, without complementary policies or resources, improvements in digital connectivity may widen the digital divide.(Rotz et al., 2019). H4 therefore provides a direct empirical test of the stronger inclusion proposition: whether a better-connected regional environment actually narrows the farm-size adoption gap (Figure 2, Table 1).

H4. Higher regional Internet access reduces the digital adoption gap between smaller and larger farms.

Table 1. Conceptual framework linking farm structure, technology requirements and the regional digital environment.

Framework dimension	Empirical representation	Theoretical mechanism	Hypothesis
Farm structural capacity	Economic size (Standard Output)	Capital absorption, scale economies, specialised labour, ability to bear fixed costs	H1
Technology requirements	Basic Internet vs farm-specific advanced technologies	Greater complementary-resource requirements should magnify size-related inequality	H2
Regional enabling environment	Household Internet access at NUTS2 level	Lower territorial access constraints and greater digital readiness	H3
Inclusive transition mechanism	Farm size × regional connectivity	Tests whether connectivity operates as an equaliser across farm-size groups	H4

3. Data and methods

3.1 Research design

The study focuses on a cross-sectional and observational research design. It employs a quantitative approach. The secondary data used in the study is harmonized by Eurostat, and therefore it provides comparability across the EU member states. As stated earlier, the primary focus of the study is on the 2023 reference year (Table 2). . It is important to note that this study works on aggregate statistical cells, and therefore it does not work on individual farms. Thus, it is not possible to identify individual level causal effects. It is only possible to approximate associations between farm-size classes and regional conditions with the adoption of digital technologies on the farm. The study provides sufficient evidence to support the use of digital technology on the farm. The secondary data used in this study covers the agricultural sector in the EU at the regional and national levels. The data provided is broken down at the regional level and can identify associations with farm size.

Table 2. Data sources and their role in the empirical analysis.

Eurostat dataset	Year	Analytical level	Variables used	Role
ef_mp_digi	2023	NUTS2 × economic-size class	Internet; FMIS; precision farming; robotics; livestock-management machinery; holdings; UAA; Standard Output	Main H1–H4 dataset
ef_mp_digicr	2023	NUTS2 × UAA-size class	Any precision farming; robotics for plant protection; band spraying; variable-rate techniques; precision crop monitoring; soil analysis	EU-27 size robustness
isoc_r_iacc_h	2023	Primarily NUTS2	Households with Internet access at home (%)	Regional digital-environment proxy

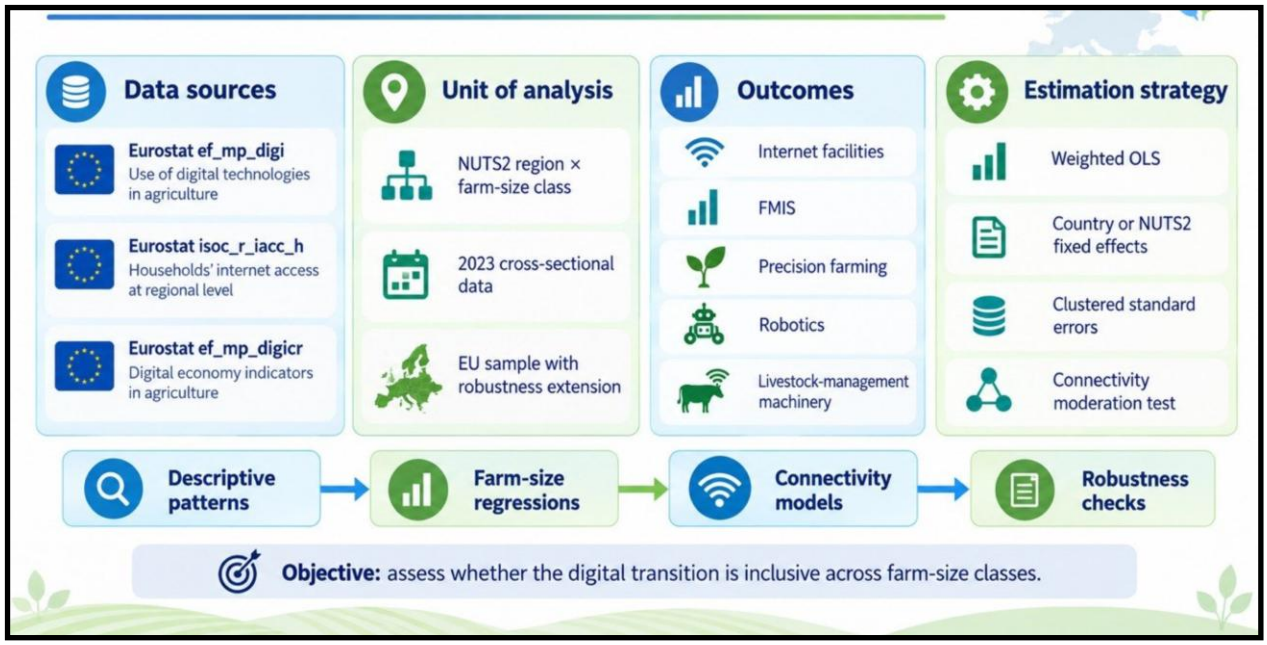
3.2 Outcome variables

For ef_mp_digi, for each region × economic-size cell, adoption rates are calculated for each technology by dividing the number of holdings reporting a given technology by the total number of holdings in that cell, and multiplying by 100. In the analysis, five different outcome variables are used: the availability of the Internet, FMIS, and precision farming; as well as the use of robotics and machinery for livestock management. Keeping the outcome variables separate avoids imposing an arbitrary, common scale on technologies with different requirements. It also permits a test of whether there is size-related inequality with respect to the basic and the more advanced forms of digitalisation (Figure 3).

$$\text{AdoptionRate}(i, r, t) = [\text{TechnologyHoldings}(i, r, t)] / [\text{TotalHoldings}(i, r)] \times 100 \quad (1)$$

3.3 Farm economic size

Figure 3. Empirical stategy and study design



Note: The figure was developed by the authors with AI assistance for visual design and formatting

Farm economic size is the main explanatory variable, and is measured by Eurostat Standard Output (SO). Standard Output is the average monetary value of agricultural output at the farm gate, and is summed for crop and livestock output to measure the economic size of a holding (Eurostat, 2026e). Economic size is preferred over land area (i.e. hectares) as the main structural variable, since farms with the same land area may vary in production and may differ in financial resources available for investment.

The categories retained by Eurostat are five ordered classes: (1) €0-1,999; (2) €2,000-7,999; (3) €8,000-24,999; (4) €25,000-99,999; and (5) €100,000 and over. The smallest class is the reference category in the regression models. Treating size as a set of indicator variables allows the adoption gradient to be non-linear.

3.4 Regional digital connectivity

This indicator includes the percentage of households with internet access at home in 2023 from isoc_r_iacc_h. It captures part of the digital environment in which farms operate, but it is not a farm-broadband measure. Eurostat's regional documentation states that geographical reporting levels are not uniform in all countries: For instance, in 2023 Germany is reported at NUTS 1, while others are reported at broader or older regional classifications (Eurostat, 2024). For the main analysis (H3-H4), artificial spatial allocation was avoided by using only 2023 NUTS 2 level data for the farm and connectivity datasets.

The reported coefficients indicate a 10 percentage point difference in access to the internet among households in a given region. This is a mean-centered measure, which allows a better interpretation of the farm size coefficients in the presence of interaction effects.

3.5 Sample construction and geographic harmonization

The cleaned economic size dataset comprises 814 analysis eligible region × size observations for 164 regional units in 20 EU Member States (Table 3). Variations exist in outcome-specific sample sizes, due to absence or suppression of data. In the ef_mp_digi table, accessed data for economic size, was not available for Bulgaria, Greece, Spain, Italy, Lithuania, Poland and Slovenia. No values were imputed for these countries.

The strict regional-connectivity merge retains 577 region × size cells across 116 directly aligned NUTS 2 regions, in 19 member states, prior to outcome-specific missingness. Matching is according to Eurostat regional geography, and only compatible regional observations are used in the main specification. Incompatible geographic levels or vintages are left un-matched and uncollapsed. For instance, in the strict regional connectivity scenario, household Internet access is available at the NUTS 1 level rather than NUTS 2 for Germany in the 2023 regional table, and so Germany is left out of the analysis.

The ef_mp_digicr robustness dataset contains 948 analysis-eligible region × physical-size observations across the 27 EU Member States, and four unadjusted area classes: below 5 ha, 5-29.9 ha, 30-99.9 ha, and 100 ha or more. This second size measure provides an independent check to assess if the dominant structural feature in the economic size coverage is driving the main pattern.

Table 3. Analytical samples used in the study.

Analytical sample	**Geographic coverage**	**Cell count**	**Key rule**
Economic-size analysis (H1–H2)	20 Member States; 164 regional units	814 eligible region × size cells	N varies by outcome; no imputation
Strict connectivity analysis (H3–H4)	19 Member States; 116 directly matched NUTS2 regions	577 cells before outcome-specific missingness	Exact NUTS2 matching only
Physical-size robustness	EU-27	948 eligible region × UAA-size cells	Four UAA classes

3.6 Empirical Strategy

As described above, percentage-point adoption rates are estimated by weighted least-squares (WLS) regressions. In each aggregate cell, weights are equal to the number of agricultural holdings. This ensures a cell that contains only a few agricultural holdings does not affect the estimation as much as a cell that represents a large number of agricultural holdings. Using percentage points helps us to interpret the coefficients in more easily understandable terms for policymakers. The standard errors are clustered at the NUTS 2 level to allow arbitrary correlation among observations of the same size class within the same region.

We estimate H1 separately for each technology using NUTS 2 region fixed effects. Through the fixed effects, we control for all observed and unobserved regional characteristics that are similar

across all economic-size classes within the same region, including e.g. broad regional infrastructure, the climate and the regional institutional setting. H1 therefore applies to within-region difference across economic-size classes (Table 4).

$$Y(i, r,t) = \alpha(r,t) + \Sigma\, j=2\ldots5\ \beta(j,t)\ SizeClass(i,j) + \varepsilon(i,r,t) \quad (2)$$

In (2) Y(i,r,t) denotes the adoption of technology t by economic-size class i in region r; α(r,t) denotes the region fixed effect; and β(j,t) denotes the difference in adoption compared to the smallest economic-size class. H1 is supported if the estimated coefficients for the size classes are positive and the adoption gradient is increasing with respect to the largest economic-size class.
A stacked technology model allows for size-class effects to vary by technology, and fixed effects by region and technology absorb baseline regional differences for each outcome. The main focus of this hypothesis is the largest versus smallest economic-size gaps for each of the selected technologies relative to the gaps for Internet facilities. Linear Wald tests are performed with the full clustered covariance matrix.

$$\text{H2 test: } \beta(Large,t) - \beta(Large,Internet) = 0;\ t = FMIS, Precision, Robotics, Livestock\ machinery \quad (3)$$

This formulation intends to test an inequality hypothesis of an advanced technology versus a basic technology. It does not require the selected four advanced technologies to create a strict ordinal sophistication ladder.
The main association of connectivity and adoption is the focus of H3. NUTS2 fixed effects are not possible in this case because the 2023 connectivity measure is the same for all economic-size classes in a region and thus would be perfectly absorbed by region fixed effects. The H3 specification uses country fixed effects, farm size indicators, and variation in connectivity within countries.

$$Y(i,r,c,t) = \alpha(t) + \Sigma\, j=2\ldots5\ \beta(j,t)\ SizeClass(i,j) + \gamma(t)\ Connectivity(r) + \mu(c,t) + \varepsilon(i,r,c,t) \quad (4)$$

Connectivity is scaled by 10 percentage points. The coefficient γ (t) therefore measures the association of a 10 percentage point increase in regional household Internet access and the farm adoption level, conditional on the economic size of the farm and other country level factors.
With regard to farm size gaps, hypothesis H4 seeks to determine whether the change in adoption gaps is associated with different levels of regional connectivity. Since the main effect of connectivity is not required for the identification of this moderation, the fixed effects for NUTS2 region can be included again. The interaction of connectivity is then included with the different non-reference farm size classes and the parameter of interest is the interaction of the ≥€100,000 class.

$$Y(i,r,t) = \alpha(r,t) + \sum j=2\ldots5\ \beta(j,t)\ SizeClass(i,j) + \sum j=2\ldots5\ \delta(j,t)\ [SizeClass(i,j) \times Connectivity(r)] + \varepsilon(i,r,t) \quad (5)$$

Hypothetically, a negative δ parameter of the largest class would mean that the adoption gap for the large-small farm size class would decrease as regional connectivity increases, supporting H4.

In addition to the largest-class interaction, a joint Wald test is also conducted for the four size by connectivity interactions for each technology.

Table 4. Empirical specifications and identification logic.

Hypothesis	**Model**	**Key parameter**	**Identification logic**	**Inference**
H1	WLS + NUTS2 FE	Size-class coefficients	Within-region economic-size differences	Holdings; SE clustered by NUTS2
H2	Stacked WLS + region×technology FE	Technology-specific large–small gaps	Advanced vs basic inequality	Holdings; Wald difference tests
H3	WLS + country FE	Regional connectivity main effect	Within-country regional variation	Holdings; SE clustered by NUTS2
H4	WLS + NUTS2 FE + interactions	Size×connectivity interactions	Whether connectivity changes the size gap	Holdings; joint Wald test

The main WLS models utilize analytical weights that are based on the number of holdings within each Eurostat cell. Missing data and confidentiality related suppressions are handled outcome by outcome . In the case of a zero technology count, this represents an observed case of non-adoption. A missing cell, however, implies that information is unavailable. The study does not address missing values of technology and connectivity adoption and/or connectivity.
Cluster-robust standard errors are calculated at the regional level. Statistical tests of significance are two-sided. Exact p-values are reported, if available. Confidence levels are reported at 95%. Model robustness is assessed through alternative specifications, since the outcomes of the model are bounded percentages.

3.8 Robustness and sensitivity analyses

Five robustness checks are performed. First, the farm size models are re-estimated without analytical weights to verify that the main results are not driven by large cells mechanically. Second, a balanced-region sample keeps only the regions which possess all the five economic-size classes. Third, grouped-binomial models are performed using observed technology and total holding counts to preserve the bounded adoption structure. Since Eurostat counts are aggregated and may be rounded, these models are performed as robustness checks. Fourth, the EU-27 ef_mp_digicr analysis replaces economic size with physical size of the farm and estimates the gradient of precision agriculture using NUTS2 fixed effects. Fifth, connectivity analysis is performed after the

exclusion of Corse and under a broader geographic matching rule in which higher level values are used only for sensitivity analysis. The direct NUTS2 merge is preferred.

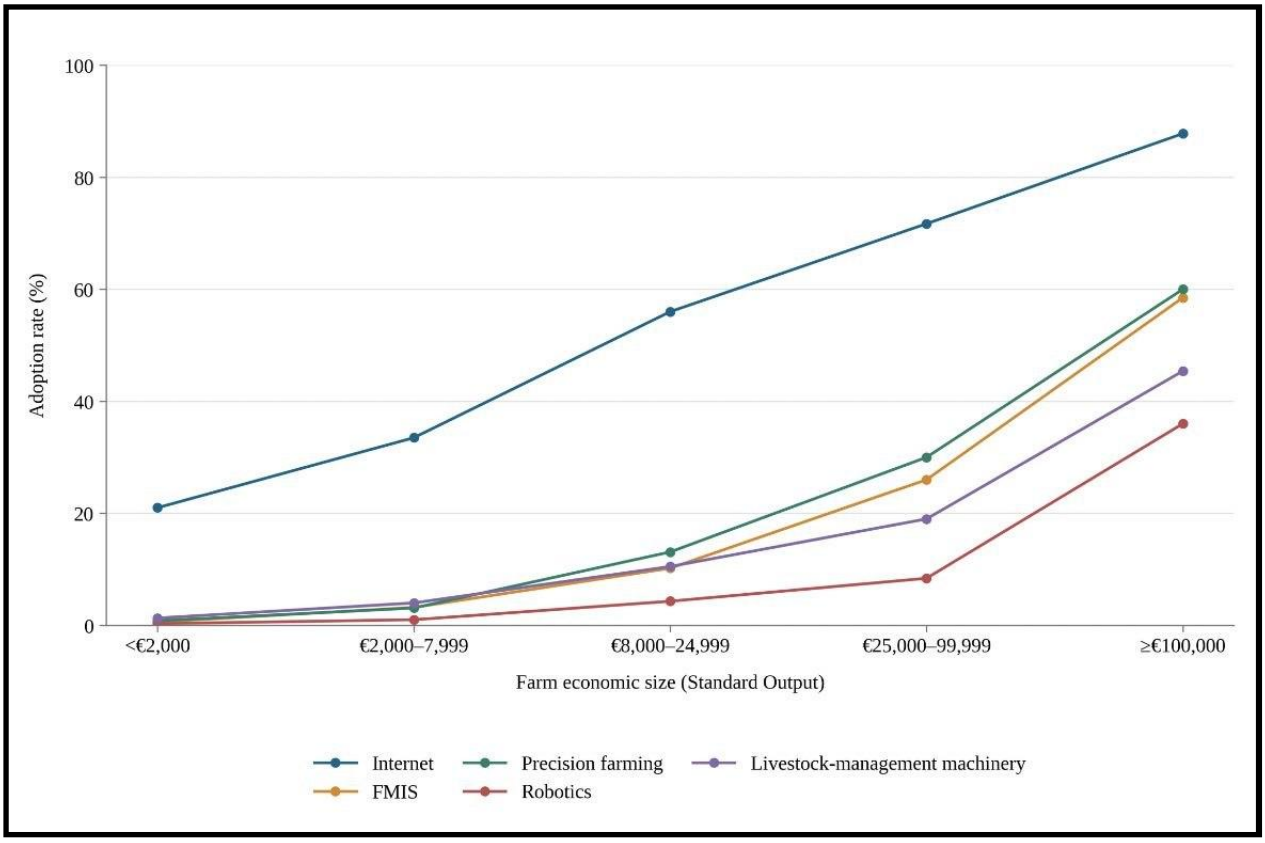
4. Results

4.1 Descriptive evidence of a farm-size digital divide

For all the technologies covered, the size of the farm's business economy influenced the extent of digital technology adoption. For farms in the smallest class of farm economy, holdings-weighted adoption rates were: 20.8% for Internet access; 0.85% for FMIS; 0.62% for precision farming; 0.37% for robotics; and 1.32% for livestock-management machinery (Figure 4, Table 5).

For farms in the largest class of farm economy (Standard Output ≥ €100,000), the adoption rates

Figure 4. Digital technology adoption by farm economic size.



Source: authors' calculations from Eurostat ef_mp_digi (2023)

were: 87.8% for Internet access; 58.4% for FMIS; 59.8% for precision farming; 35.9% for robotics; and 45.3% for livestock-management machinery. The described gradient is not limited to a single technology. It is clearly evident from the basic infrastructure-related technologies to more capital- and labor-intensive technologies.

Table 5- Conditional adoption based on economic-size classes

Economic-size class	Internet (%)	FMIS (%)	Precision farming (%)	Robotics (%)	Livestock machinery (%)
<€2,000	20.84	0.85	0.62	0.37	1.32
€2,000–7,999	33.54	2.78	2.86	0.94	3.88
€8,000–24,999	55.93	10.28	13.10	4.25	10.50
€25,000–99,999	71.62	25.85	30.03	8.34	18.91
≥€100,000	87.76	58.38	59.76	35.90	45.34

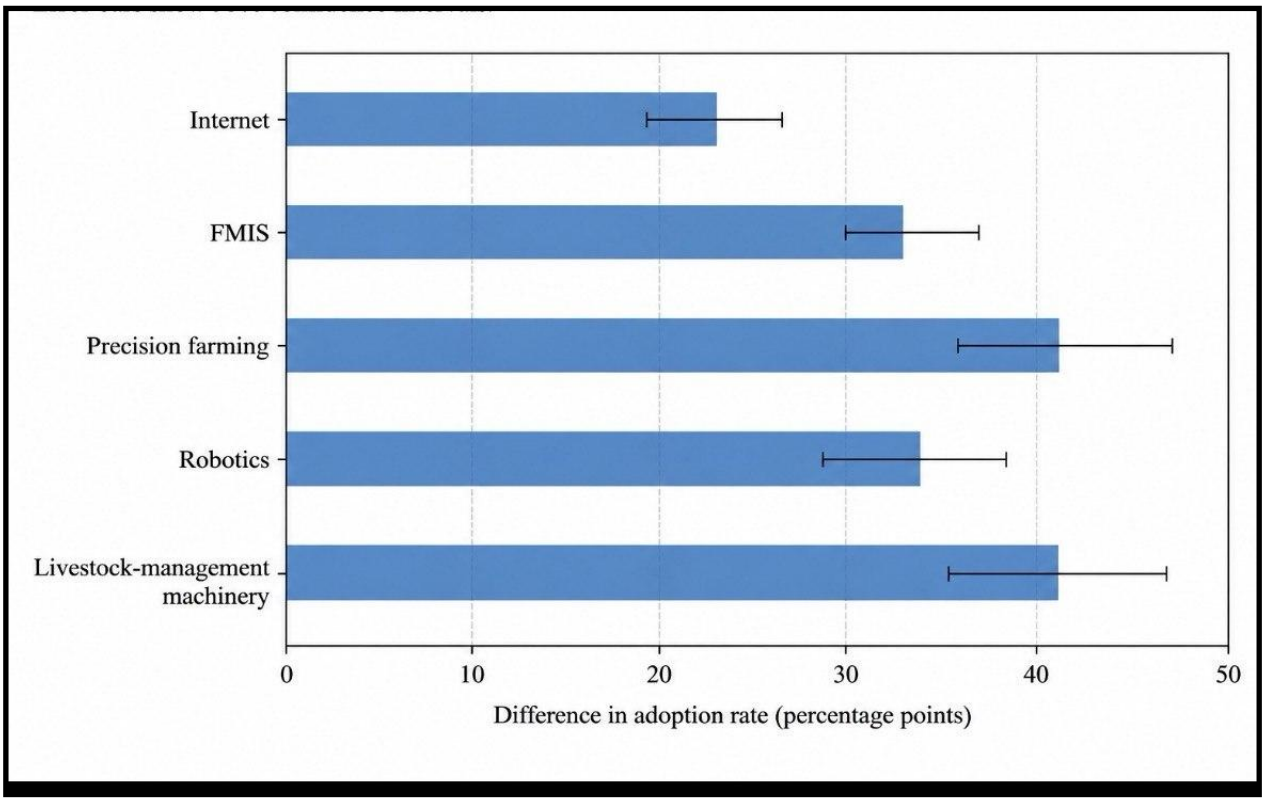
4.2 Farm economic size and digital adoption (H1)

The results of the regression analyses showed that the described pattern was also evident after the time-invariant characteristics of the farms were controlled for, which are common to farms belonging to the same NUTS2 region. Farm businesses in the largest class of farm economy (Standard Output ≥ €100,000) had much higher levels of adoption compared to farm businesses in the other classes of farm economy for the five technologies studied. The estimated differences were: 22.97 percentage points for Internet access; 33.88 percentage points for FMIS; 41.37 percentage points for precision farming; 33.37 percentage points for robotics; and 40.85 percentage points for livestock-management machinery. All these differences were statistically significant at $p < 0.001$. H1 is therefore supported (Figure 5, Table 6).

Table 6. Largest-versus-smallest economic-size differences from holdings-weighted OLS models with NUTS2 fixed effects and NUTS2-clustered standard errors.

Technology	≥€100,000 vs <€2,000 (pp)	95% CI	p-value	N	NUTS2
Internet	22.97	19.76 to 26.18	<0.001	810	164
FMIS	33.88	30.03 to 37.73	<0.001	755	163
Precision farming	41.37	36.50 to 46.23	<0.001	711	164
Robotics	33.37	28.51 to 38.22	<0.001	620	162
Livestock-management machinery	40.85	35.37 to 46.33	<0.001	712	160

Figure 5. Conditional adoption gap between the largest and smallest farm economic-size classes



Source: authors' calculations from Eurostat ef_mp_digi (2023)

4.3 Technology sophistication and the magnitude of inequality (H2)

H2 was interested in the difference in the extent of farm-size inequality associated with the use of advanced agricultural digital technologies as compared to basic digital technologies. Taking the Internet as the benchmark of the basic technology, the largest-versus-smallest gap was 10.91 percentage points for FMIS, 18.40 points for precision farming, 10.40 points for robotics and 17.88 points for livestock management machinery. All the difference tests across technologies were significant at $p<0.001$. H2 is therefore supported in the advanced-versus-basic technology form. The results do not indicate a strict monotonic technological ladder as the gap for robotics is less than that for precision farming and livestock management machinery (Figure 6, Table 7).

Figure 6. Association between regional household Internet access and farm digital adoption

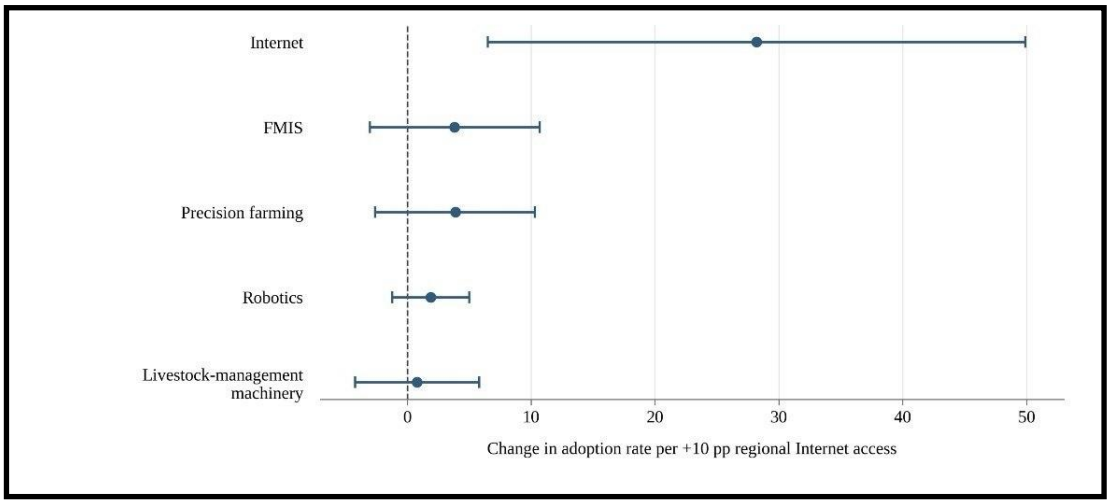


Table 7. Formal comparison of farm-size inequality across technologies.

Technology	**Large–small gap (pp)**	**Additional gap vs Internet (pp)**	**p-value of difference**
Internet	22.97	Reference	—
FMIS	33.88	10.91	<0.001
Precision farming	41.37	18.40	<0.001
Robotics	33.37	10.40	<0.001
Livestock-management machinery	40.85	17.88	<0.001

4.4 Regional connectivity and digital adoption (H3)

H3 relied on the strict NUTS2 connectivity sample, with country fixed effects and farm size controls. An increase in regional household Internet access by 10 percentage points, was associated with a 28.21 percentage point increase in farm Internet access, (significant at p=0.011). The coefficients for FMIS, precision farming, robotics and livestock management machinery were positive but statistically not significant. H3 is therefore only partly supported. Favorable regional digital environment is strongly associated with the basic farm connectivity; however, the evidence does not support the same for the use of advanced farm technologies (Figure 7, Table 8).

Table 8. Regional connectivity and digital adoption (H3): holdings-weighted OLS with farm-size controls, country fixed effects and NUTS2-clustered standard errors.

Technology	Connectivity coefficient per +10 pp	95% CI	p-value	N	NUTS2
Internet	28.21	6.54 to 49.88	0.011	575	116
FMIS	3.85	-3.00 to 10.71	0.271	550	115
Precision farming	3.88	-2.52 to 10.29	0.235	505	116
Robotics	1.91	-1.15 to 4.97	0.221	440	115
Livestock-management machinery	0.80	-4.19 to 5.79	0.754	507	112

4.5 Does regional connectivity narrow the farm-size gap? (H4)

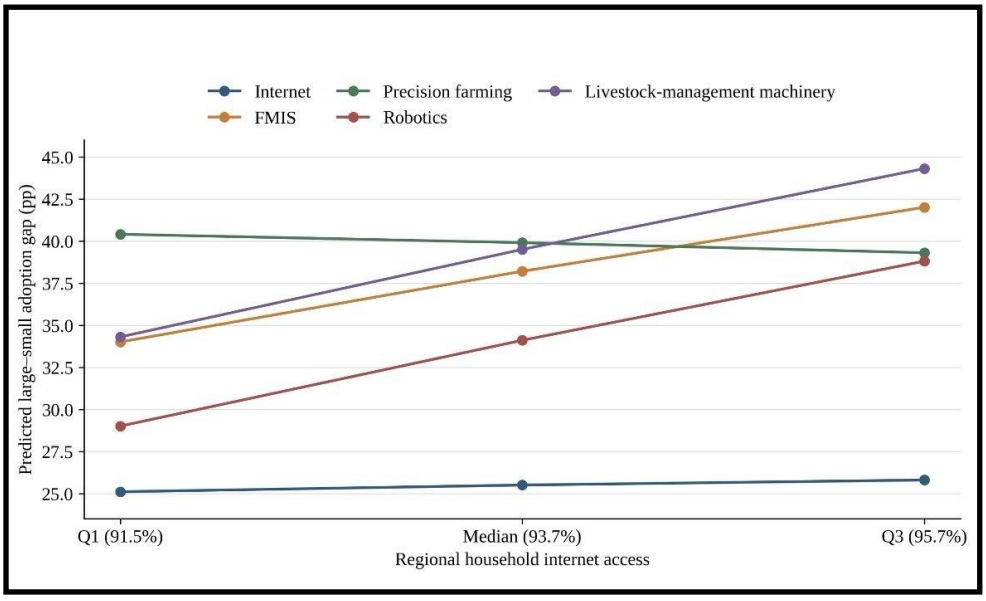
The results of the moderation analysis do not support H4. Statistically significant evidence that higher levels of regional connectivity are associated with a smaller adoption gap between the largest and smallest economic-size classes is not found for any of the technologies assessed. The interaction estimate for farm Internet access is small and not statistically significant (+1.76; $p = 0.819$), and the same holds true for precision farming (−2.59; $p = 0.840$). On the other hand, the interaction estimates for FMIS (+19.25; $p = 0.005$), Robotics (+23.42; $p = 0.017$) and livestock-management machinery (+23.96; $p = 0.030$) are positive and statistically significant. This suggests that the adoption gap between the largest and smallest economic-size classes is greater in regions with higher levels of connectivity and the technologies assessed, which goes against the prediction of H4. This is the case even if the estimated interaction effect is small. The negative and not statistically significant estimates for farm Internet access and precision farming provide no evidence of an increasing or decreasing gap. Also, these do not show that there is no difference in the gap with respect to connectivity. These are cross-sectional relationship and should not be interpreted as positive or negative impact of improvement of connectivity (Table 9).

Table 9

Table 9. Connectivity moderation of the farm-size adoption gap (H4). Interaction coefficients are scaled to a 10-percentage-point increase in regional household Internet access.

Technology	Largest×Connectivity interaction (pp)	95% CI	p-value	Interpretation
Internet	1.76	-13.27 to 16.78	0.819	No significant moderation
FMIS	19.25	5.89 to 32.62	0.005	Gap widens
Precision farming	-2.59	-27.80 to 22.61	0.840	No significant moderation
Robotics	23.42	4.14 to 42.71	0.017	Gap widens
Livestock-management machinery	23.96	2.27 to 45.66	0.030	Gap widens

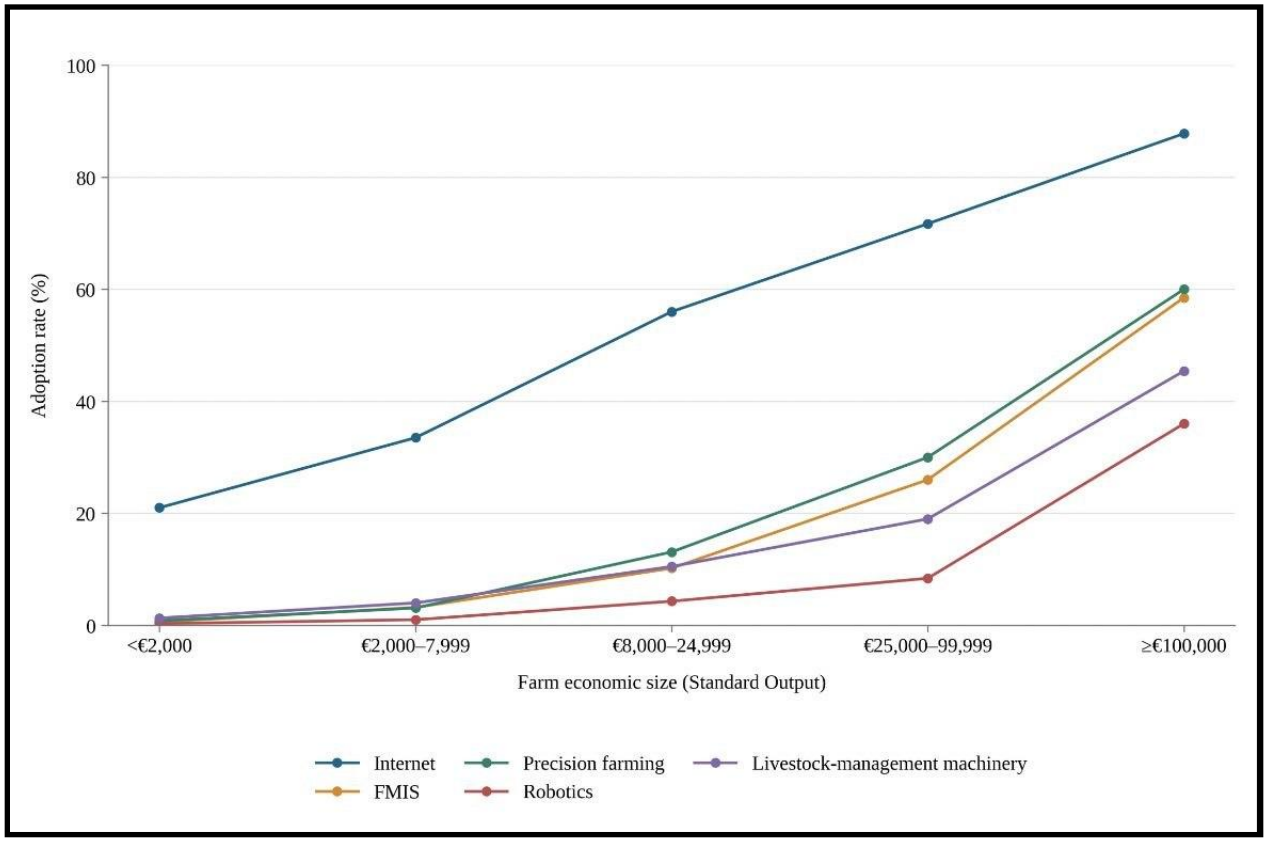
Figure 7. Predicted large–small adoption gap at the first quartile, median and third quartile



4.6 Physical size of farms across the EU-27

The economic size analysis did not include size-class data for seven Member States in the Eurostat dataset. To assess if this impacts the main conclusions, the analysis was repeated using the separate EU-27 precision-agriculture data set classified by utilised agricultural area. After NUTS2 fixed effects, farms of at least 100 ha had 35.72 percentage points higher adoption of any precision farming compared to farms less than 5 ha. Positive and significant gaps were also observed for

Figure 8. Precision-agriculture adoption across physical farm-size classes in the EU-27.



robotics for plant protection, band spraying, and soil analysis. Based on this independent size definition and broader country coverage, the focus of this study on the larger farms supports the conclusion that advanced digital agriculture is disproportionately found on larger farms (Table 10).

Table 10. EU-27 robustness analysis using physical farm size (UAA). Models include NUTS2 fixed effects and clustered standard errors.

Precision-agriculture outcome	≥100 ha vs <5 ha (pp)	95% CI	p-value	NUTS2
Any precision farming	35.72	31.19 to 40.24	<0.001	242
Robotics for plant protection	12.36	9.01 to 15.71	<0.001	227
Band spraying	6.48	4.79 to 8.17	<0.001	235
Variable-rate techniques	15.13	12.36 to 17.89	<0.001	233
Precision crop monitoring	13.67	11.20 to 16.13	<0.001	238
Soil analysis	29.45	25.02 to 33.87	<0.001	242

5. Discussion

The results of this study underscore the importance of taking a critical, structural perspective to the inequalities present in the digital transformations of European agriculture. Acknowledging that not all approaches to digitalisation are equal and producing evidence that characterises the ongoing European digital divide, along the lines of Gabriel and Gandorfer (2023), would be a helpful starting point. Digitalisation is increasingly advocated for improving the productivity and sustainability of the agricultural sector. The adoption of digital technologies, however, is characterised by substantial inequities across farms of different financial means. In this study, farm size (economic scale) was the primary driver of the degree of adoption of digital technologies. Other studies have also suggested that the digitalisation of agriculture is primarily driven by the availability of farm-level financial resources, along with the farmers' managerial skills (Gabriel and Gandorfer, 2023; John et al., 2023). More recent meta-analytic studies on the uptake of precision agriculture reinforce the relevance of the main drivers of digitalisation of farming, which are mainly economic (Žáková Kroupová et al., 2025). The Joint Research Centre of the European Commission has also recently analysed continuing inequities in the adoption of digital technologies among European farms (Tur Cardona et al., 2025).

This study highlights how size differences on farms can vary across farm technology domains. There is a clear difference in adoption gaps when it comes to farm management information systems, precision farming, and livestock-management machinery as compared to gaps for basic Internet facilities. Agricultural digitalization is a complex process involving multiple technologies with different levels of investment, complexity, and integration. Improvements in overall digitalization can mask differences in access to more advanced applications. High investment costs and costs associated with complexity and integration are key barriers to adoption of digital farming technologies (John et al., 2023; Addorisio et al., 2025; González-Vivar et al., 2025). As a result, it

is possible that improvements in the overall digitalization of the agriculture sector may not necessarily ensure equitable access to digital agricultural technologies.

This further distinction is reinforced by the relationship between regional connectivity and technology adoption. Positive and significant correlations are noted between regional household Internet access and basic farm Internet connections, demonstrating that under certain enabling conditions, farm enterprises are prepared to undertake their first steps towards digital participation. Elsewhere, no statistically significant relationships were recorded, even after controlling for country-level differences and the farm's economic size. This may imply that while digital connectivity serves as the backbone of various digital applications, it may, however, not be sufficient to explain the adoption of complex digital technologies. The digital transformation of the agri-food system relies on the inter-relations of various pillars, including ICTs, finance, human capital, and organisational structures (Klerkx et al. 2019). Gabriel and Gandorfer (2023) and other recent studies identify lack of adequate finance, inadequate digital skills, and uncertainty about the economic returns of digital technologies as the main barriers to the adoption of digital technologies.

One important finding addresses the relationship between regional connections and gaps in farm-size classes. Positive and statistically significant interaction terms suggest that, for the adoption of farm management information systems (FMIS), robotics, and livestock management machinery, the difference in adoption between the largest and smallest farms is larger in regions with higher household Internet access. Hence, H4 is not supported. The relationship is in the opposite direction of that expected. For farm Internet access and precision farming, the interaction terms are not statistically significant. Convergence or divergence cannot, therefore, be ascertained. Also, these relationships cannot be interpreted as causal. Overall, these results provide evidence that a better regional digital environment does not necessarily result in more equitable adoption of higher-end technologies. One of the reasons may be the complementarity between connectivity and farm-level resources. Since larger farms may be better positioned to benefit from a better digital environment as they are better placed to spread the fixed costs of investment over a larger production, and may have access to more financial and specialized resources, it may be assumed that smaller farms lack the necessary investment, organizational and technical resources. These may be plausible reasons for the observations made in the study. Other studies have also provided evidence to suggest digital agricultural and related technologies may widen social and economic inequalities (Rotz et al., 2019; Klerkx et al., 2019). The findings also align with economic and institutional barriers to technology adoption recently documented (Addorisio et al., 2025; Žáková Kroupová et al., 2025).

These results do not provide evidence for a cumulative-advantage mechanism. There is scope for various effects to be at play. For example, a positive regional digital economy may enable farm businesses of different sizes to expand. Larger and more economically robust farm businesses may, however, have greater capacity to take advantage of the digital opportunities offered by the regional economy. The observations are, therefore, consistent with a combination of positive regional conditions and different capacities to use those conditions. They do not reflect that increasing connectivity always intensifies inequality. The strong interaction effects for FMIS, robotics, and livestock-management systems suggest this may be the case particularly for technologies that require substantial investment and the integration of farm equipment and systems. The interaction effect for precision farming is not statistically significant. The intersection of one technology with a positive interaction and the other with a negative interaction does not, by itself, reflect a significant difference in their interactions. Precision farming, by its nature, is a

broad church. Within it are technologies with varying degrees of investment and operational integration. Some of these may allow more flexibility in the integration and use of the technology, compared to systems that require a more integrated and substantial approach. Possible differences in the degree of integration may also explain differences in farm businesses' level of acceptance of, and engagement with, these technologies.

These results have important implications to promote an inclusive digital transformation of agriculture in Europe. Improving farm connectivity is still crucial, but combined with measures to address financial, technical and organizational constraints faced by small and medium farms. Undoubtedly, there are barriers to advanced technology adoption. These barriers may be overcome through the provision of advisory services and affordable and easily accessible financing, as part of the next CAP. A combination of different approaches may also be effective. These could include shares of agricultural machinery and contracts, as well as cooperatives and shared digital infrastructures. An integrated approach may enable farmers to reach optimal technology adoption decisions. Such an approach may include measures to strengthen digital skills and knowledge among farmers on various aspects of technology adoption. Other reviews point out that effectiveness of technology adoption strategies is largely dependent on the extent to which the financial, technical and institutional constraints are addressed (John et al., 2023; Addorisio et al., 2025; González-Vivar et al., 2025). With respect to the CAP, digitalisation measures should take account of the economic situation of each farm rather than assuming that uniform support results in equitable outcomes.

This research also indicates the need to assess agricultural digitalisation using distribution-sensitive indicators. Frequently, measures of connectivity are used to evaluate progress. However, if advanced technologies remain in the hands of economically stronger farms, aggregate adoption rates or connectivity measures may give a false sense of progress. To understand the consequences of public policy on inequality, it is important to monitor adoption differences across farm-size categories and technology domains. Farm size alone should not dictate the extent to which public policy aims to improve digital inclusion. The focus should be on providing the farming sector with the digital technologies it needs to increase farm production, and on alleviating digital divides amongst different farming systems. This should be based on equitable opportunities to access and effectively use suitable technology, rather than equity in farm-level technology ownership (Rotz et al., 2019).

There are several limitations. First, the nature of Eurostat data, which is aggregated and cross-sectional, limits analysis to farm-level adoption mechanisms. Second, the economic-size dataset does not include all EU Member States, although evidence from EU-27 (based on utilised agricultural area, UAA) provides additional analysis. Third, regional household Internet access is a proxy for the digital economy. It does not include farm-level broadband Internet access, quality and reliability. Fourth, geographical harmonization is restricted to NUTS2 due to differences in NUTS classifications. Finally, differences in farming systems can also impact observed patterns in adoption of these technologies. Ultimately, the future of agricultural innovation will require the integration of multiple data sources and longitudinal, farm-level analysis, digital skills and financial resources to analyze the costs, benefits and impacts of information and advisory services.

This study extends the literature on agricultural transformations by showing that digital expansion, advanced technology adoption and digital inclusion are conceptually distinct yet related dimensions. Farm size remains an important source of inequality in the farm sector, and the relationship between farm size and technology adoption varies across the technologies and regional digital environments. Adoption gaps for more-advanced technologies, especially for

more-integrated regions, suggest that more favorable digital environments do not always guarantee equitable participation in agricultural technologies. These findings add to existing literature on digital inequalities in the agriculture sector (Rotz et al., 2019; Klerkx et al., 2019; Tur Cardona et al., 2025) and underscore the need to integrate digital and other types of infrastructure, financial support, and digital skills in the agricultural sector. Such a combination is essential to foster structural inclusion and not just digital inclusion in agricultural sectors.

6. Conclusion

The aim of this study was to assess the inclusiveness of the digital transition in the agriculture of the European Union by bridging the farm economic size, technology type and digital connectivity of the region. Results show the farm size digital divide is real and pervasive. Large farms show higher adoption of all farm-related technologies and the disparity is larger with respect to adoption of advanced farm-related technologies compared with the basic farm-related Internet services. Using EU-27 robustness analysis based on physical farm size, we showed that the same structural pattern holds true for other precision agriculture technologies.

6. Conclusion

In the adoption models, the presence of regional connectivity was positively associated with the adoption of basic farm Internet access. There were no similar statistically significant associations for the other information and communication technology (ICT) adoption models. This does not mean that connectivity is not important for the other ICT adoption models. The moderation analysis showed that, for the ICTs that constitute the Integrated Farm Management System (FMIS), and for livestock management and farm machinery, there is a significant association between increasing regional connectivity and the adoption gap between the largest and smallest economic size classes, indicating widening gaps. For access to farm Internet and for precision farming, the interactions were not statistically significant. Therefore, H4 is not supported. The results showed no statistically significant evidence of closing gaps and showed gaps for the three advanced technologies, especially for farm machinery and for the Integrated Farm Management System (FMIS). This divergence between the levels of digital access and higher-order outcomes reflects the evidence discussed by Bahadori et al. (2020). Improved broadband and e-commerce were not associated with improved turnover and profitability of traditional businesses. In the agricultural context, the combination of complementary knowledge, financial resources and organisational capacity may contribute to explaining why, in the presence of favourable digital infrastructure, the gap for access to and use of advanced digital agricultural services is not reduced.

The policy implication of this research is that improving connectivity in a region is not in itself adequate proof of an inclusive agricultural digital transition. Considerable gaps remain in the adoption of FMIS, robotics, and livestock-management machinery, especially among the smallest classes of the economy. More engagement and targeted measures are warranted to address the gaps through integrated investments in ICT infrastructure and the strengthening of advisory services, the digital skills of beneficiaries, as well as digital, financial and other forms of services and technologies to facilitate/enable agricultural entrepreneurs, including farm workers and smallholders, to engage in agricultural production. While improving connectivity and related services, it is important to consider the needs of the smaller farms, especially on how the services improve the adoption gaps, and address both the ‘willingness’ and ‘ability’ to use ICTs.

7. References

Addorisio, R., Spadoni, R., & Maesano, G. (2025). Adoption of innovative technologies for sustainable agriculture: A scoping review of the system domain. Sustainability, 17(9), Article 4224. https://doi.org/10.3390/su17094224

Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T., & Gómez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. Land Use Policy, 80, 163–174. https://doi.org/10.1016/j.landusepol.2018.10.004

European Commission. (2025). A vision for agriculture and food: Shaping together an attractive farming and agri-food sector for future generations. Directorate-General for Agriculture and Rural Development.

European Commission. (2026a, September 8). New strategic approach to research and innovation for competitive, resilient and sustainable agriculture, forestry, rural areas and food systems. Directorate-General for Agriculture and Rural Development.

European Commission. (2026b). Digitalisation of agriculture and rural areas in the EU. Agriculture and Rural Development. https://agriculture.ec.europa.eu/vision-overview/digitalisation_en

Eurostat. (2024). Eurostat regional yearbook: 2024 edition. Publications Office of the European Union.

Eurostat. (2026a, July 24). 43% of EU farms with internet access. Eurostat News. https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20260724-1

Eurostat. (2026b). Internet facilities, robotics, precision farming and machinery for livestock management in farms by economic size of farm, farm type and NUTS 2 region [Data set]. European Commission. [Dataset code: ef_mp_digi]

Eurostat. (2026c). Precision farming by age and training of manager, size of farm and NUTS 2 region [Data set]. European Commission. [Dataset code: ef_mp_digicr]

Eurostat. (2026d). Households with access to the internet at home [Data set]. European Commission. https://doi.org/10.2908/isoc_r_iacc_h

Eurostat. (2026e). Glossary: Standard output (SO). Statistics Explained. European Commission.

Fragomeli, R., Zawadzki, W., Czajkowski, M., Annunziata, A., & Punzo, G. (2025). Italian farmers' preferences for adopting agriculture 4.0 technologies: A choice experiment analysis. Journal of Cleaner Production, 525, Article 146601. https://doi.org/10.1016/j.jclepro.2025.146601

Gabriel, A., & Gandorfer, M. (2023). Adoption of digital technologies in agriculture—An inventory in a European small-scale farming region. Precision Agriculture, 24, 68–91. https://doi.org/10.1007/s11119-022-09931-1

González-Vivar, J., Sobczyk, R., Romero-Frías, E., et al. (2025). Adoption and perception of precision technologies in agriculture: Systematic review and case study in the PDO wines of Granada, Southern Spain. Agriculture, 15(23), Article 2468. https://doi.org/10.3390/agriculture15232468

John, D., Hussin, N., Shahibi, M. S., Ahmad, M., et al. (2023). A systematic review on the factors governing precision agriculture adoption among small-scale farmers. Outlook on Agriculture. https://doi.org/10.1177/00307270231205640

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS: Wageningen Journal of Life Sciences, 90–91, Article 100315. https://doi.org/10.1016/j.njas.2019.100315

Rotz, S., Duncan, E., Small, M., et al. (2019). The politics of digital agricultural technologies: A preliminary review. Sociologia Ruralis. https://doi.org/10.1111/soru.12233

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R. C., Neufeld, H. T., Nixon, A., Pant, L. P., Shalla, V., & Fraser, E. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. Journal of Rural Studies, 68, 112–122. https://doi.org/10.1016/j.jrurstud.2019.01.023

Tur Cardona, J., Ciaian, P., Antonioli, F., Fellmann, T., Rocciola, F., Ierardi, I., Crimeni, R., & Anastasiou, E. (2025). The state of digitalisation in EU agriculture: Insights from farm surveys. Publications Office of the European Union. https://doi.org/10.2760/4688498

Žáková Kroupová, Z., Aulová, R., Rumánková, L., Bajan, B., Čechura, L., Šimek, P., & Jarolímek, J. (2025). Drivers and barriers to precision agriculture technology and digitalisation adoption: Meta-analysis of decision choice models. Precision Agriculture, 26, Article 17. https://doi.org/10.1007/s11119-024-10213-1