Comparative assessment of Digital Ecosystems

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CYNTHIA GIAGNOCAVO (UAL), ROSA MARIA HEREDIA HORTIGÜELA (UAL), ANDREA KNIERIM (UNI HOHENHEIM), BEATRIZ HERRERA (UNI HOHENHEIM), MICHAEL PAULUS (UNI HOHENHEIM), ALESSIO FERRARI (CNR), CHIARA MANNARI (CNR), MANLIO BACCO (CNR)

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D3.3 COMPARATIVE ASSESSMENT OF DIGITAL ECOSYSTEMS

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Authors	Cynthia Giagnocavo (UAL), Rosa Maria Heredia Hortigüela (UAL); Alessio Ferrari (CNR), Chiara Mannari (CNR), Manlio Bacco (CNR); Andrea Knierim (UNI HOHENHEIM), Beatriz Herrera (UNI HOHENHEIM)
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Project Coordinator	University of Pisa

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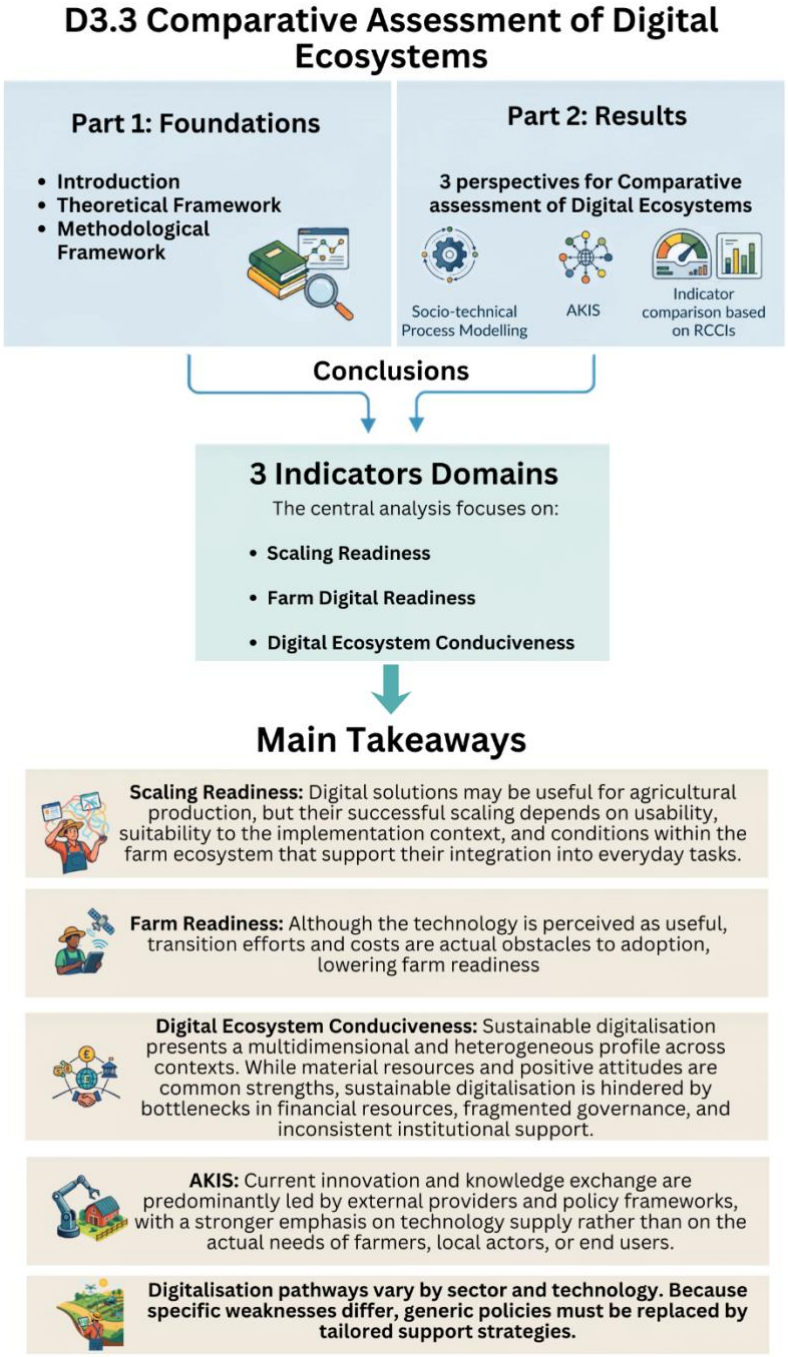
Executive infographic summary



This deliverable provides a comparative assessment of agricultural digital ecosystems, moving from theoretical foundations to an analysis structured around three complementary analytical perspectives: Socio-technical Process Modelling perspective, the Agricultural and Innovation Knowledge Systems (AKIS) perspective, and an indicator comparison based on a resources, capabilities, collaborations and innovations (RCCIs) perspective. These lenses converge to evaluate three indicator domains (farm digital readiness, scaling readiness, and digital ecosystem conduciveness).

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Part 1: Foundations

1 Introduction

Deliverable 3.3 Comparative Assessment of Digital Ecosystems (D3.3) builds on the previous work carried out within Work package 3 (WP3) *Analysis of Digital Ecosystems* and moves from the description of individual Living Labs[1] (LLs) towards a comparative analysis across LL cases. As seen in the infographic above a comparison has been carried out using three different analytical perspectives and three indicator domains which will be further described herein. Agricultural digitalisation does not take place in isolation, but within complex environments shaped by technologies, actors, resources, knowledge flows, governance arrangements and socio-economic conditions. Within the CODECS project (*Maximising the CO-benefits of agricultural Digitalisation through conducive digital ECoSystems*), these environments are analysed as Digital Ecosystems (DEs), defined as a dynamic system where digital, socio-economic, organisational, knowledge, and physical components converge to support the production, storage, communication, and utilisation of digital technologies and data.

The comparative assessment developed in this deliverable focuses on three complementary indicator domains:

- Scaling readiness; understood as the potential of a digital technology to be adopted by large numbers of farms in different contexts.
- Farm digital readiness; understood as farmers' ability to adapt to and effectively use digital technologies and tools in order to achieve their goals and objectives. This indicator domain contributes to a better understanding of farmers' motivations in relation to digital technologies and their adoption patterns.
- Digital ecosystem conduciveness; refers to the extent to which the environment supports the growth, success and adoption of digital activities, such as the development of new technologies, the creation of new businesses and the adoption of digital solutions. This indicator domain contributes to identifying the conditions under which digital technologies can deliver their best performance.

More specifically, D3.3 pursues the following objectives:

- To provide a comparative assessment of Digital Ecosystems across the CODECS LLs, categorising cases into different clusters (technology, sector, goal…) to identify drivers of digitalisation.
- To compare the current state of LLs across the indicator domains (farm digital readiness, scaling readiness and digital ecosystem conduciveness).
- To display comparative insights from different analytical perspectives (Process-modelling, AKIS, RCCIs), contributing to the identification of patterns that may inform future work within CODECS and support policy recommendations.
- In addition, this D3.3 will contribute to Policy Brief 13: Digital ecosystem conduciveness: concepts and indicators.

The structure of this deliverable move from conceptual framing and methodological explanation (Part 1: Foundations) to comparative results, discussion and conclusions (Part 2: Results and Conclusions). Section 1 introduces the purpose and objectives of D3.3. Section 2 presents the theoretical framework, framing Digital Ecosystems as multi-layer systems. Section 3 describes the methodological framework. Section 4 presents the comparative assessment results. Finally, Section 5 concludes the deliverable by summarising the main insights and their relevance for sustainable agricultural digitalisation.

[1] A LL is understood as a network of farmers, knowledge intermediaries, stakeholders, policymakers, technology providers, and other concerned actors, constituted around an emerging problem within a given application scenario, and willing to develop solutions through collaboration.

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2 Theoretical framework

2.1 Digital Ecosystem as a multi-layer system

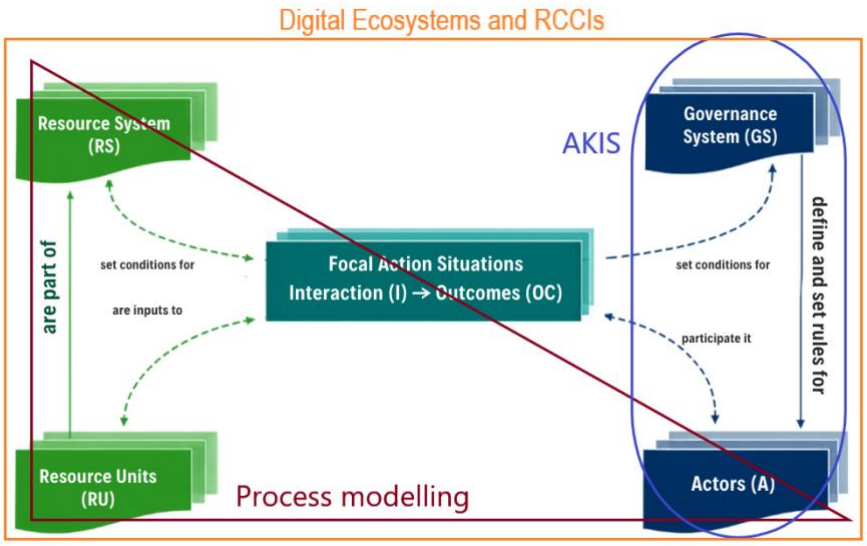

Figure 1. Positioning of the WP3 analytical perspectives within the socio-ecological system framework (SESF). The figure illustrates how the analysis of DEs and RCCIs connects the four SESF subsystems with the FAS and how socio-technical process modelling focuses on the transformation of processes at the FAS level focused on resources and actors. AKIS focuses on actors and governance. (Source: adapted from Mc Ginnis and Ostrom (2014)

WP3 general approach draws on Elinor Ostrom's Socio-Ecological System Framework (SESF) (McGinnis and Ostrom, 2014; Ostrom, 2009; supplemented by Ostrom, 1990; and Hess and Ostrom, 2007) to analyse the DEs and thus complex environments in which digitalisation processes take place. D3.1 established the initial conceptual and methodological basis for analysing DEs across CODECS LLs, introducing the SESF, RCCIs, AKIS and socio-technical process modelling as complementary analytical lenses. D3.2 expanded and refined this work by providing a more detailed and validated characterisation of each DE at individual LL level, whereas D3.3 explains the process of arriving at the indicators derived from that analysis, and then draws on them for the analysis herein. To achieve the project objectives and those of D3.3, the deliverable combines three complementary analytical perspectives (see Figure 1) carried out under *Task 3.2, Mapping the Socio-Ecological Context (T3.2)*, and *Task 3.3, Farm Socio-technical Process Modelling of Use Cases (T3.3)*, of WP3.

- First, under T3.3, it develops a comparative assessment of socio-technical process modelling (Section 4.1), focusing on how digital technologies transform farm-level processes and how these transformations differ across LLs.
- Second, under T3.2, it incorporates an Agricultural Knowledge and Innovation System (AKIS) perspective (Section 4.2)
- Third, also under T3.2, it applies the analysis of DEs derived from the SESF and resources, capabilities, collaborations and innovation (RCCIs) perspective (Section 4.3), which provides the basis for comparing farm digital readiness, scaling readiness and digital ecosystem conduciveness indicators across LLs.

At the core of the theoretical approach of WP3 is the intention to analyse agricultural digitalisation as a multi-layered process. In CODECS, digitalisation is not understood only as the introduction of digital technologies into farming systems, but as a transformation that depends on the complex interaction between technologies, actors, resources,

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and different socio-economic conditions, among others. This perspective is aligned with the project's emphasis on capabilities and sustainable digitalisation, understood as digitalisation that contributes to the resilience, wellbeing and adaptive capacity of individual, groups or rural communities and socio-ecological systems.

Figure 1 shows how the three analytical perspectives of WP3 are positioned within the SESF. The analysis of DEs and RCCIs frames the overall socio-ecological context, connecting the four SESF subsystems (Resource Systems, Resource Units, Governance Systems and Actors) with the Focal Action Situation (FAS). This perspective examines how the broader socio-ecological context enables, constrains or sets the conditions for the RCCIs that LLs need in order to address their problem statements. The layer acts as a mediating analytical layer between the SESF subsystems and the FAS, it helps translate wide systemic conditions into concrete elements that can be identified, compared and assessed across LLs. The AKIS perspective is a subjacent system that helps explain how knowledge is generated, exchanged and used, it is positioned around the Actor and Governance subsystems, focusing on knowledge flows and advisory structures. Farm socio-technical process modelling is located at the FAS level, where it analyses how farm activities, actors, resources and workflows change before and after the introduction of digital solutions. Together, these perspectives capture both the broader enabling conditions of digitalisation and how digital technologies reshape concrete processes within each LL.

2.1.1 Process Modelling perspective

The Socio-technical Process Modelling method adopted in Task 3.3 stems from two main areas of the information systems field, namely business process modelling and requirements engineering.

Business Process Modelling (BPM) (Aguilar-Savén, 2004) is a method used to create a visual representation of an organisation's workflows and activities. This technique involves using diagrams and flowcharts, i.e., models, to map out the steps involved in various processes of the organisation. Business process models serve as a common language between stakeholders, as they enable a shared understanding among IT experts, business analysts, social scientists and economy experts, facilitating collaborative analysis, discussions, and decision-making. By modelling and reasoning on their processes, organisations can analyse their workflows to identify bottlenecks, inefficiencies, and areas for improvement. Among the visual languages used in BPM, Business Process Model and Notation (BPMN, 2010) is the most prominent one, having a large diffusion among practitioners. BPMN models are means for information exchange between engineers and business analysts (Corradini et al., 2018). The language supports advanced techniques, even AI-based, for data analysis, such as process mining (Aalst 2011), or change impact analysis (Alam, 2015).

Requirements Engineering (RE) (Loniewski et al.; Horkoff et al., 2019) is a field of software and systems engineering that focuses on understanding and defining what a system must accomplish. It involves capturing the expectations and needs of stakeholders, detailing them clearly, and ensuring they are realistic and achievable. The process also includes handling any changes to these requirements over time, ensuring that the system being developed aligns with user needs and business goals. To facilitate communication with stakeholders and reason on their goals, RE also involves graphical modelling activities, similar to BPM. Common visual languages used in RE are iStar (Yu et al., 2011), and KAOS (Dardenne et al., 1993). iStar focuses on representing social relationships between stakeholders that are part of a socio-technical system, i.e., a system composed of human actors and technological elements, and in representing their goals. Instead, KAOS focuses on system's objectives to be achieved, and decomposition of the objectives into lower-level requirements. Another common notation used in RE is the Unified Modelling Language (UML, 2017), which is a comprehensive software engineering language including different types of structural diagrams (e.g., class diagrams) and behavioural ones (e.g., sequence diagrams). UML is widely used in industry for requirements representation, according to the survey by Wagner et al., 2019.

2.1.2 Agricultural Knowledge and Innovation System perspective

AKIS is defined as knowledge flows between persons, organisations and institutions who use and produce knowledge for agriculture and interrelated fields. By linking people and institutions, AKIS promotes mutual learning and generates, shares, and utilises agriculture-related technology, knowledge, and information. The concept of the AKIS has emerged as a way to systematically structure the complexity of actors, values and types of knowledge that have a role in the adoption of innovations. AKIS in the European Union (EU) context has moved from being an

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academic concept used to describe actors, networks and institutions (Knierim et al., 2015) to a policy instrument, guiding Research and Innovation interventions of EU Member States (MS) (Knierim and Birke 2023; Sutherland et al. 2023).

The process of digitalisation affects, and it is affected by, knowledge flows, e.g., through the emergence of new actors (Klerkx et al, 2019) or through a shift in knowledge relationships (Ingram and Maye, 2020). Digital innovations can enable or disrupt knowledge networks, allowing new actors to enter and changing preexisting roles (Ingram and Maye, 2020). For a digital transformation that creates value (e.g., that optimises the potential and creates a fair benefit for the farmer), the knowledge and skills of the actors beyond the digital domain need to be strengthened, in order to manage the new demands, relations, and tensions (Ingram and Maye, 2020). This relations and tensions can be analysed in CODECS LLs, as LLs are spaces that offer opportunities for testing, validation, development and co-creation at all stages of innovation processes among different actors (Compagnucci et al, 2020). Analysing how knowledge flows are present in LLs action situations can be studied using different analytical perspectives: infrastructural, procedural, and/or functional perspectives (Klerkx et al., 2012; Knierim et al., 2015). The AKIS concept is used to further specify the actor´s mobilisation and utilisation of knowledge and innovation support and further examine the composition, roles, and proximity of key actors, the extent of institutional pluralism, and the nature of coordination mechanisms that govern knowledge flows outside the region or local community, highlighting knowledge exchange and learning components relevant for the interactions around the development and application of digital technologies as studied with the FAS (Knierim, et al. 2023).

2.1.3 Analysis of Digital Ecosystem, Socio-ecological system framework and Resources, Capabilities, Collaborations and Innovations perspective

To bridge the Socio-Ecological Systems Framework (SESF) and the Focal Action Situation (FAS), WP3 uses the Resources, Capabilities, Collaborations and Innovations (RCCIs) approach as a mediating analytical layer. This approach draws on organisational and strategic management theory, including the resource-based view, dynamic capabilities, the knowledge-based view and the relational view (Barney, 2001; Teece, Pisano, & Shuen, 1997; Kogut & Zander, 1992; Dyer & Singh, 1998). In the context of CODECS, RCCIs help explain how the four SESF subsystems shape the conditions that enable or constrain digitalisation processes within LL.

Resources are understood as tangible and intangible assets owned, controlled or accessed by an entity, such as a farm, organisation or LL, which can be used to create value, achieve an objective or solve a problem. Tangible resources include physical and financial assets, such as equipment, infrastructure, digital devices or funding. Intangible resources include knowledge, motivation, organisational routines, networks and technological assets such as software or data-related tools.

Capabilities refer to the individual or collective abilities, know-how and routines required to use resources effectively and achieve specific goals. In digital ecosystems, capabilities are not only operational or technical, but also dynamic: they involve the ability to reorganise resources, skills and relationships in response to changing conditions. This is particularly relevant for assessing digital readiness and digital ecosystem conduciveness, since agricultural digitalisation requires adaptation, learning and coordination among different actors.

Collaborations and innovations are included in the RCCIs approach because digitalisation in agriculture often depends on relationships, networks, partnerships and new technological or organisational arrangements. Collaborations may provide access to knowledge, infrastructure, advisory support or market opportunities, while innovations may refer to new digital tools, practices, services or governance arrangements.

Overall, the RCCIs approach allows the analysis to connect the broader SESF subsystems with the practical and strategic needs of each LL at FAS level. It helps identify what each LL has, what it requires and how the surrounding digital ecosystem enables or hinders the acquisition, use and mobilisation of these elements. In D3.3, this approach provides the conceptual basis for comparing digital ecosystem conduciveness, farm digital readiness and scaling readiness across LLs.

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3 Methodological framework

3.1 Comparative assessment in Socio-technical Process Modelling

Digitalisation reshapes farm practices, leading to a transformation that can be analysed from multiple perspectives. In this respect, the comparative assessment of the CODECS LLs based on the socio-technical process modelling enables the analysis of three key aspects related to the introduction of digital technologies at the farm-process level:

- Process impacts: this analysis considers how the introduction of digital technologies modifies the process flow and configuration.
- Transition effort: this analysis complements the impact analysis by focusing on the effort required to the LLs to introduce the digital technologies, thereby accounting for the perceived organisational and operational effort necessary to support the digitalisation process.
- Technological maturity: this analysis assesses the degree of advancement and consolidation of the proposed technologies within real-world contexts.

3.1.1 Cross-case analysis

The synthesis of findings across the LLs has been conducted following the cross-case analysis methodology proposed by Miles and Huberman (1994). In this perspective, the LLs are treated as comparable cases and progressively grouped according to selected analytical dimensions, so as to enable both intra-category and inter-category examination. This made it possible to analyse commonalities and differences within clusters of LLs sharing relevant characteristics, while also identifying emerging patterns across groups. Through this cross-case synthesis, the analysis extended the understanding of individual cases developed in Deliverable D3.2 toward a broader and more comprehensive interpretation of agricultural digitalisation.

Following Miles and Huberman's framework, the analysis was structured around the three interconnected phases of data reduction, data display, and conclusion drawing and verification.

- Data reduction: This phase was mainly conducted within Task 3.3 (Farm socio-technical process modelling of use cases), in which a methodology for carrying out process modelling within the LLs was developed and applied. In addition, Task 5.3 (Technical and scientific support to demo farms) within WP5 provided complementary information on the technologies introduced within the LLs, particularly with regard to their characteristics, maturity, and readiness for adoption. Within these tasks, data relevant to process transformation and the technologies introduced in the LLs were collected through specific reporting templates filled by the LLs. Deliverable D3.1 provides detailed information on the data collected in Task 3.3. In addition, with regard to Task 3.3, the information contained in the process modelling reports was further analysed and formalised into the corresponding process models, thereby transforming qualitative information into structured and comparable representations. Deliverable D3.2 presents the resulting set of models produced through this formalisation process.
- Data display: in this phase, fully described in this deliverable, the LLs were clustered and the results were presented through tables and figures, while descriptive statistics were used to support cross-case examination of the LLs with respect to the three aspects under analysis, namely impact, transition effort, and technological maturity.
- Conclusion drawing and verification: this phase, also documented in this deliverable, was carried out by interpreting the patterns emerging from data display in relation to the objective of the analysis, checking the consistency of the findings across cases and analytical dimensions.

3.1.2 Clustering

The CODECS LLs represent a variegated catalogue of digital technologies introduced in diverse agricultural contexts. These include, among others, IoT-based systems, drones and UAVs (Unmanned Aerial Vehicles), and digital platforms, applied across multiple domains such as livestock farming, crop and grassland management, and

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farm marketing. As such, the cases reflect a broad spectrum of digitalisation interventions in agriculture, differing not only in the type of technology adopted but also in the sector the technology is applied.

In the cross-case analysis, the LLs were treated as representative of this heterogeneity in order to derive observations that could go beyond the interpretation of individual cases. Therefore, to support generalisation while preserving meaningful comparability across cases, the LLs were clustered. The clustering aimed to maximise internal coherence within groups and enable the identification of recurring patterns across different contexts.

Clustering has been performed along two dimensions, namely technology and sector. The cluster by technology groups the LLs according to the type of digital technology introduced to compare cases characterised by similar technological solutions. The cluster by sector groups LLs according to the agricultural sector in which the digital solutions introduced, thereby accounting for similarities and differences related to the context of application. The combined use of these two clustering dimensions provides a more nuanced analytical lens to examine process impacts, transition effort, and technological maturity across the LLs.

3.1.3 Impact analysis

The impact of digitalisation on farm processes was assessed by examining the changes occurring at the farm-process level in relation to the introduction of a new digital solution, with particular attention to variations in actors and tasks. This analysis is grounded in the Activity Transformation Models in BPMN, one of the model types proposed within the CODECS process modelling methodology. Figure 2 contains an excerpt of an Activity Transformation Model developed for the Italian LL Pecorino Toscano with a view to the tasks of the Veterinarian interacting with the Farm Management Information System (FMIS). This model depicts the overlap between the process as-is (before the introduction of the digital solution) and to-be (after the introduction of the digital solution) and makes it possible to identify the elements introduced, removed, or unchanged through digitalisation. This distinction is supported by a colour-coding scheme, where unchanged elements are shown in green, newly introduced elements in blue, and removed elements in red. We refer the reader to Deliverable 3.2 for a detailed description of all cases.

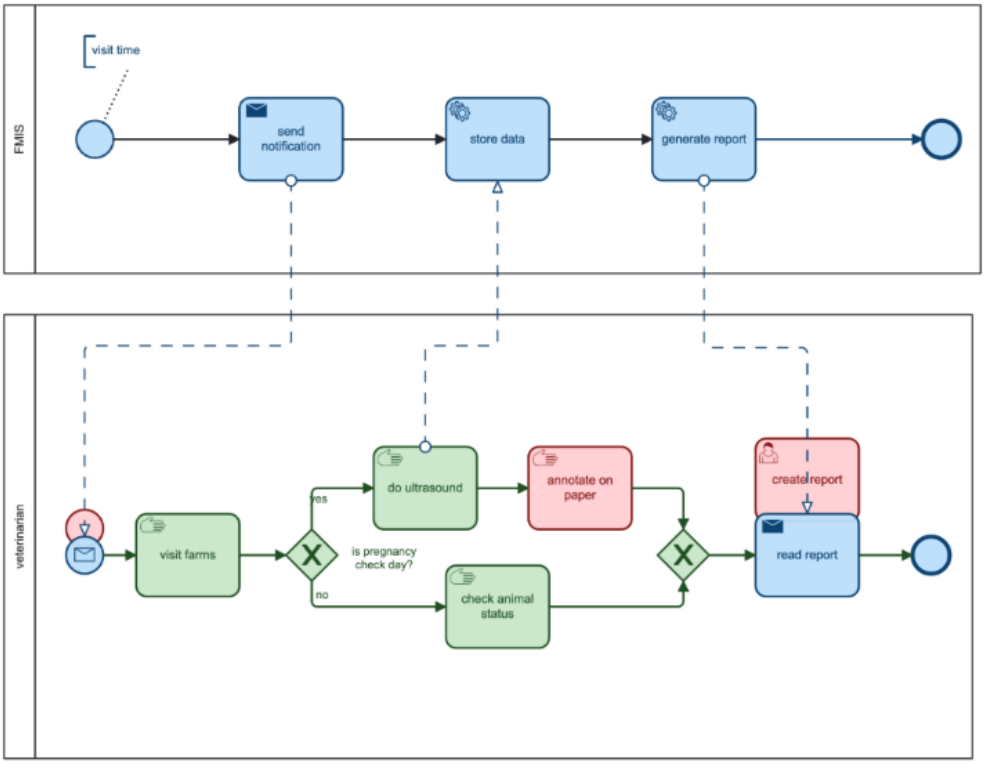

Figure 2. Part of an Activity Transformation Model developed for the Italian LL Pecorino Toscano

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Drawing on this basis, model analysis can be conducted within the existing clusters of LLs to highlight variation and recurrent patterns across cases. The analysis is based on three steps:

1. Calculation of process change variables

These variables concern both actors and activities and consider:

- Actor removal rate, relative to the process to-be (after)
- Actor addition rate, relative to the process as-is (before)
- Task removal rate, relative to the process to-be (after)
- Task addition rate, relative to the process as-is (before)

From these rates, a derived measure, namely the change ratio, is calculated: it is computed as the sum of added and removed tasks, divided by the sum of unchanged and removed tasks, thus providing an estimate of the extent to which the original process is transformed by the introduction of the digital solution, by relating the number of changed tasks to the size of the initial process structure. In other words, it measures the intensity of the transformation between the process before and after the introduction of the digital solution. Added and removed tasks capture the extent of the change, while unchanged and removed tasks represent the process before digitalisation used as the reference baseline.

2. Cluster comparison

The variables resulting from Step 1 are compared across the identified clusters to examine similarities and differences in process transformations. This comparison is carried out by aggregating cases within each cluster and is repeated for both clustering dimensions, namely technology and sector, to identify both recurring tendencies and variations between clusters.

3. Discussion and takeaway lessons

The results of the cluster-based comparison are then discussed to interpret the main patterns emerging across the LLs. On this basis, a set of takeaway lessons is derived, highlighting the most relevant insights on process transformation and their broader implications for understanding digitalisation in the analysed contexts.

3.1.4 Transition effort analysis

The transition effort associated with the introduction of digital technologies was analysed through a thematic analysis (Braun and Clarke, 2008). Data were extracted from the final questions on transition included in the process modelling reports, i.e., *How is the living lab dealing with the transition to the new system?* (contained in the reporting templates following the procedure for Digitalising cases) and *How did the living lab deal with the transition to the new system?* (contained in the reporting templates following the procedure for Digitalised cases). Responses were structured as a sequence of progressive steps describing the transition process.

Based on qualitative data, the thematic analysis captures how the LLs describe the steps and effort required to support the introduction and use of the proposed digital solutions. The analysis is based on three steps:

1. Coding and themes extraction

In this phase, excerpts from the question on transition in the LL reports are coded and themes are extracted. The coding process is focused on the steps described, such as *technology acquisition* and *set up*, *training*, *infrastructural conditions*, *coordination requirements*, and other contextual elements shaping the effort perceived by the LLs. This step resulted in a set of themes capturing the main dimensions of transition effort emerging from the reports.

2. Cluster comparison

The themes identified in Step 1 are compared and ranked by frequency to highlight the most prominent dimensions of transition effort across the clusters in order to examine similarities and differences in how transition effort was characterised across the cases. In this way, the analysis made it possible to explore whether certain forms of transition effort are more frequently associated with specific technological solutions or with particular agricultural domains of application and whether a broader trend emerged.

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3. Discussion and final synthesis

The results of the cluster-based comparison are discussed and the main patterns emerging across the LLs are presented. On this basis, a final synthesis is developed to highlight the most recurrent forms of transition effort and the broader implications for understanding how digital technologies are introduced and supported in real-world agricultural contexts.

3.1.5 Technological maturity analysis

Technological maturity in digital agriculture is increasingly shaping as a concept that cannot be fully captured by the technical properties of a solution alone but needs to be considered in relation to its context of use, adoption, and integration into practice. While established indicators such as Technology Readiness Levels (TRL) provide a useful starting point for positioning technologies along a maturity scale, they tend to offer a partial view of how technologies are actually used within real agrifood systems. In addition, they provide limited support for analysing the wider drivers and barriers that shape digitalisation processes. This is particularly relevant in agriculture, where digital solutions often combine multiple technological components with different TRL levels, or involve technologies that are mature in other domains but still require adaptation to agricultural contexts and process configurations. In this sense, analysing technological maturity *in context* is especially relevant, as it allows maturity to be understood also in relation to adoption and integration into practice. This implies that maturity must be assessed not only from a supply-side perspective, but also by incorporating the perspectives of technology adopters and other stakeholders engaged in the process. Building on this understanding, within the CODECS project we conceptualise technological maturity in context as an enriched construct that integrates multiple perspectives and is analysed in relation to the socio-technical processes in which technologies are embedded.

On this basis, the technological maturity of the digital solutions introduced in the CODECS LLs was analysed through a mixed-method approach combining both qualitative and quantitative evidence. The analysis captures two complementary perspectives.

First, technological maturity is considered from the internal perspective of the farms introducing the technology. This perspective provides contextual insights into the conditions that may support or hinder the uptake of the technology directly from the adopters.

These perspectives make it possible to examine technological maturity as a multidimensional and context-dependent construct that can be self-assessed by the LLs. By combining qualitative and quantitative evidence, the analysis supports a broader understanding of how maturity is perceived in practice.

The analysis was based on three steps: data analysis, where data from the different perspectives were analysed through a mixed-method approach, including a thematic analysis and examining the positioning of each solution on the maturity scale.

Observations by cluster, where the results were examined across the identified clusters, namely by technology and by sector in order to analyse similarities and differences between groups of LLs. At this stage, triangulation was performed by relating the farm and LL perspectives, as well as the qualitative and quantitative findings. This made it possible to observe patterns emerging in relation to specific technological solutions or agricultural domains.

The results of the cluster-based comparison were then synthesised in order to highlight the main patterns emerging across the LLs. On this basis, a summary was developed to capture the most recurrent maturity profiles, the principal factors associated with higher or lower perceived maturity and adoption readiness, and the broader implications for understanding the introduction of digital technologies in real-world agricultural contexts.

3.2 Comparative assessment in AKIS perspective

The objective of the analysis is to compare the AKIS actor settings across the LLs and influencing the FAS of the LLs. The methodology is a continuation of the steps followed for the AKIS analysis presented in Deliverable 3.1 and Deliverable 3.2.

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Making use of selected data collected during the LL Workshops conducted in 2023 under T3.2, the overall approach for the analysis pursues two specific objectives:

1. To analyse the AKIS related results of LL workshops with respect to Actor and Governance subsystems with an AKIS infrastructural perspective and
2. To compare the AKIS related results according to different groups of LLs to identify patterns.

As stated in Deliverables 3.1 and 3.2, the analysis of AKIS infrastructures makes use of the infrastructural analytical perspective, which encompasses the *Actors* and the *Governance Subsystems*. The original data was collected under T3.2 and under the following questions:

- Q2. What are the main actors related to the LL FAS problem statement and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?
- Q5. Which governance mechanisms influence the LL FAS problem and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?

For the specific purpose of the AKIS analysis, the previously collected data were coded using the following research questions: (RQ1): Who are the actors related to the problems addressed within the Living Labs' FAS? (RQ2): Which governance mechanisms influence the problems addressed within the Living Labs' FAS? (Further details on the data collection methodology are provided in Section 3.3 and in Deliverables 3.1 and 3.2). The analysis involved three cycles of coding, which included developing a scheme of categories and subcategories to: a) identify salient ideas, b) structure and compare the categories with the AKIS analytical framework, c) recategorise the answers from the LLs according to the categories found and develop diagrams by LLs (Table 1).

Table 1. Steps followed for the analysis of Agricultural Knowledge and Innovation System around the LLs

Step	Description	Outcome	Theoretical Reference
1	Inductive coding based on answers from the LL about actors and governance subsystem 1. For the Actor Subsystem, we identified and counted the types of actors, classified by the LLs according to the closeness to the FAS 2. For the Governance Subsystem, we identified and categorized the types of rules, norms, and regulations related to AKIS governance mechanisms and AKIS' coordination components as identified by LLs	Codes from different LLs for *Actor Subsystem* and *Governance Subsystem*	Saldana, 2016
2	Review of literature, review of categories and subcategories grouping the codes: 1. Identification of typology of actors according to the framework of AKIS 2. Identification of levels and governance mechanisms relevant for knowledge flows as identified by TAP and SCAR -AKIS literature	Framework of categories, subcategories and codes for *Actor Subsystem* and *Governance Subsystem*	FAO 2022, SCAR-AKIS 2023 Kok et al 2023

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Step	Description	Outcome	Theoretical Reference
3	Development of diagrams representing actors and their perceived closeness to the FAS as a conceptual model of knowledge systems around the LLs, using the categories, subcategories and codes determined in step 2	Living Lab diagrams	Ison, 2017
4	Comparative analysis according to groups of LL	Comparison between groups of LLs	Table 5

As a result of the analysis and according to the categories and codes, we identified 17 different types of actors that are recurrently mentioned around the LL, influencing the FAS. We grouped those types of actors into the seven main categories used in AKIS analysis literature (Table 2).

Table 2. Actors mentioned by LL Workshops participants, according to AKIS categories

Categories	Type of actor (subcategories)	Description (codes)
1. Farmers		
1.1	Farmers	Farmers: winegrowers, sheep farmers, beef farmers, family farms, demo farms, industrial scale farms, farm workers, informal economy farmers, farmers selling directly to consumers
1.2	Farmers associations, farmers organisations	Chambers of agriculture, farmers groups (women, fruit growers, viticulture), farmers associations, agricultural consortiums, cooperatives, trade associations, farmers unions, farmers federations, machinery cooperatives
2. Education and research		
2.1	Research	Research projects, research institutions, universities, research associations, research centres, laboratories, scientists
2.2	Education	Educational institutions, universities, training institutions, high schools specialized in agriculture, vocational schools, vocational training farms, technical schools, teachers
3. Bridging institutions-knowledge exchange (formal)		
3.1	Advisors (public, private, NGOs)	Public advisors, agronomists, consultants, consulting companies, veterinarians, public health advisors, advisory networks, digital academies for agriculture, experts, veterinary association, research institutions providing advice, research projects including advice, input suppliers providing advice, training centres providing advice, extension or advisory system in general.

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Categories	Type of actor (subcategories)	Description (codes)
3.2	Networks: other LL, hubs, platforms, Local Action Groups	Advisory networks, hubs, agricultural fairs, laboratory networks, LLs, industry organizations, projects including networking activities, soil associations, local action groups
3.3	NGOs	Non-governmental organisations working with local environment, animal rights, fund for nature
4, Public actors, authority		
4.1	Public/authority	Ministries and authorities (agriculture, science, trade, economy, tourism, planning), European level institutions, policy makers, local governments, public agencies and offices (regional, local), national extension services, regulations
4.2	Funding institutions	LEADER program, public institutions or agencies managing projects providing funding, tenders, agencies for financial support
5. Value Chain-Business		
5.1	Companies Agtech	Service providers, telecommunication companies, dashboard editors, software developers, technology developers, specific professionals (data analysis, technicians), technology vendors, internet providers
5.2	Companies (supply chain)	Input providers (energy, seeds, fertilizers, irrigation, feed), equipment or machineries manufacturers, supply stores, contractors, cooperatives
5.3	Companies (downstream)	Intermediaries, exporters, dealers, retail chains, distributers, marketing consultants, slaughterhouses, supermarkets, traders, tourists, processors
5.4	Certification/audit bodies	Auditing organisations, certification bodies, certification companies, accredited laboratories, standards norms organisations
5.5	Financial/investment institutions	Banks, financial institutions
6. Non-formal knowledge exchange		
6.1	Family, friends and neighbours, community, fairs	Family, neighbours and peers, community member, employees, local fairs
6.2	Consumers	Final consumers, consumers associations
7. Media		
7.1	Media	Influencers, opinion makers, mass media

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As a result of the analysis, we also identified and categorised the type of rules and norms that are relevant to the definition of AKIS and to those related to the definition of rules for access, extraction, management, exclusion and alienation of knowledge and information resources. The results reflect norms, rules and regulations for the coordination of AKIS components with two main levels of coordination mechanisms: global and macro level and local level (Table 3).

Table 3. Categories, subcategories and description of codes in Governance Subsystem

Category and sub-category	Description of the sub- category (codes)
1. Global and macro perspective	
1.1 Global macro-trends	Aspects mentioned are the global crises, the interest in the environment and in general the negative perspective about agriculture
1.2 EU level public policies and regulations	The coordination mechanisms at EU level such as the CAP; the GDPR; the EU organic regulation, EU guidelines on plant protection products, information systems such as FADN, regulation on frequencies
1.3 Public policies and regulations	The participants identified those public actors and policies relevant for the FAS. A long list of regulations and normative were mentioned: accounting, drones, young farmers, exports, environmental protection, fertilizers regulation, food legislation, health and safety regulations, land use, water management, manure management, education, technological innovations, livestock, GDO, nitrates, working time, spray regulatory framework, knowledge transfer strategies, subsidies, taxes, phytosanitary regulation. Some other aspects mentioned were the role of regions and municipalities, the participation on the policy making process, and the enforcement of those regulations. Finally, support instruments such funding grants, subsidies for specific innovations (precision agriculture) or entrepreneurs were included here
1.4 Education related guidelines	Available normative with regard to curricula on digitalisation in technical schools, vocational schools or vocational training farms
1.5 Private companies and market rules	Aspects included here are related with markets, farmers consumers and companies involved in the development of rules: some of them are large inputs (seed, planting materials or plant protection products) but also companies which implement rules such as insurance services or in control of geospatial analysis. It also includes norms dictated by certification mechanisms within the value chain, for example Biosert, monitoring social and environmental impact, quality certification bodies, impact certification bodies, food labels, GAP and PDO schemes
2. Local and regional perspective	
2.1 Social rules or norms	Rules that are present in the community that supports or limit the adoption of innovations. For example, the approach of meetings or the visions on the social system
2.2 Networks rules	Those are groups are networks of producers (AG Porc / GT porc, data providers or users, LLs or activities (tourism or animal production) that have their own norms

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Category and sub-category	Description of the sub- category (codes)
2.3 Local associations norms	Statements describing norms and rules determined by groups of persons, associations) soil, trade, irrigation, GDOS; producers, communities and cooperatives)
2.4 Farm objectives incentives expectations	This reflects those norms or rules that are seen as pursued by farms, for example improvement on the efficiency in the use of resources, generation renewal (succession) at farm level or those norms that takes into account the farmer as the user of the innovation

The comparative analysis is built upon the framework of dimensions, categories, and variables outlined in Table 2 and 3. Dimensions, variables and descriptions to be used for the comparative analysis is described in Table 4.

Table 4. Dimensions and variables for the comparative analysis of AKIS around the LLs

Dimension		Variables	Description
A. Actors			
1	A.1 Presence of actors	A.1.1 Number of actors in Level 1 (part of the LL) A.1.2 Number of actors in Level 2 (potential collaboration) A.1.3 Number of actors in Level 3 (influential, with little potential for collaboration)	Number of actors mentioned by the participants, with the level of proximity to the Focal Action Situation
2	A.2 Type of actors in the LL	A.2.1 Farmers A.2.2 Farmers associations, organisations A.2.3 Research A.2.4 Education A.2.5 Advisors A.2.6 Other LL, hubs, platforms, fairs, local action groups A.2.7 NGOs A.2.8 Public/authority A.2.9 Funding institution A.2.10 Companies (private) A.2.11 Companies IT A.2.12 Companies (supply chain) A.2.13 Companies (downstream) A.2.14 Certification/audit bodies A.2.15 Financial/investment institutions A.2.16 Family, friends and neighbours A.2.17 Consumers A.2.18 Media	Type of actor mentioned by the LLs workshops participants

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Dimension		Variables	Description
3	A.3 Pluralism of actors in the LL	A3.1 Number of type of actors in the LL	Average number of type of actors by LLs
4	A.4 Innovation support activities in the LL	A4.1 % of farmers on the total amount of actors (user involvement in the LL) A4.2 % research institutions in the LL A4.3 % of advisory service institutions in LL A4.4 % IT enterprises in LL	The relative presence of type of actor signals the innovation activities present in the FAS
B. Governance			
1	B.1 Presence and type of policies	B.1.1 Global macro-trends about food system B.1.2 EU level public policies and regulations B.1.3 Public national policies and regulations B.1.4 Private companies' rules B.1.5 Education related guidelines	Perceived coordination mechanisms that influence knowledge flows and innovation activities
2	B.2 Presence and type of other governance mechanisms	B.2.1 Local networks rules B.2.2 Local associations norms B.2.3 Social rules or norms B.2.4 Farming objectives, incentives or expectations	Perceived coordination mechanisms at local or regional level that influence knowledge flows and innovation activities

The CODECS LLs differ considerably one from the other in terms of objectives, actor composition, technologies studied and their socioeconomic and political environment (Deliverable 8.1). In order to take these differences into consideration within the AKIS related analysis, we propose to structure the LLs along four dimensions which are: type of digital technology studied, type of objective addressed in the Living Lab, technology readiness level of the digital technology to be used in the Living Lab and type of configuration of the advisory service in national AKIS (Table 5).

Table 5. Dimensions for the grouping of LLs

Dimension		Groups in each dimension	Rational for their linkage with AKIS
A	Type of digital technology	A1 IoT and UAV- A2 Platforms	The type of technology influences the configuration of actors and governance mechanisms involved
B	Objective of the Living Lab	B1 Human/social capital B2 Natural resources management B3 Productivity and efficiency B4 Value creation	The objective of the Living Lab, to what the digital technology is intended to contribute influence the range of actors present in the LLs and the coordination mechanism of AKIS actors in place

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Dimension		Groups in each dimension	Rational for their linkage with AKIS
C	Technology readiness level of the technology	C1 TRL 1 to 4 (concept) C2 TRL 5 to 6 (prototype) C3 TRL 7 to 9 (dissemination)	According to the technology readiness level of the digital technology, different innovation support activities are required, therefore numbers and constellation present in the LL can be influenced by this variable
D	Type of national predominant advisory service subsystem in which the Living Lab is embedded	D1 Firm-led advisory services D2 Pluralistic advisory services D3 Policy-driven advisory services	The national advisory service subsystem structure and conditions influence the presence of actors of the LLs, considering all the factors described in ABC

3.3 Indicator framework for Comparative assessment in Farm digital readiness, Scaling readiness and Digital ecosystem conduciveness

This section presents the methodology used for the comparative assessment of farm digital readiness, scaling readiness and digital ecosystem conduciveness across LLs. This assessment represents the final comparative output of WP3 derived from the four-step methodology developed under Task 3.2 *Mapping the Socio-Ecological Context*. While D3.1 and D3.2 mainly covered the first two steps of this methodology, focused on identifying the FAS, mapping the socio-ecological context of each LL and analysing the RCCIs required to address each LL problem statement, D3.3 addresses the subsequent comparative steps (see Figure 3). Further details about methodology are described in D3.1 and D3.2.

The methodology established for mapping the socio-ecological context begins with each LL identifying a clear problem statement within its FAS.

In Step 1, LLs identified the current RCCIs they already had and the necessary RCCIs they needed to address their FAS problem statement.

In Step 2, the four core subsystems of the Socio-Ecological Systems Framework (Actors, Resource Units, Resource Systems and Governance Systems) were analysed to understand how they enable or set conditions for the RCCIs needed to address the FAS.

Steps 3 and 4 provide the basis for the comparative assessment developed in D3.3. In Step 3, specific and common characteristics were identified from the individual analyses. These characteristics informed the development of indicators related to digital ecosystem conduciveness, farm digital readiness and scaling readiness.

In Step 4, the indicators were reviewed and validated through consultation with LL coordinators and stakeholders, ensuring that they were sufficiently meaningful across the diverse contexts represented in CODECS. The validated indicators were then used as the common framework for the comparative assessment presented in this deliverable.

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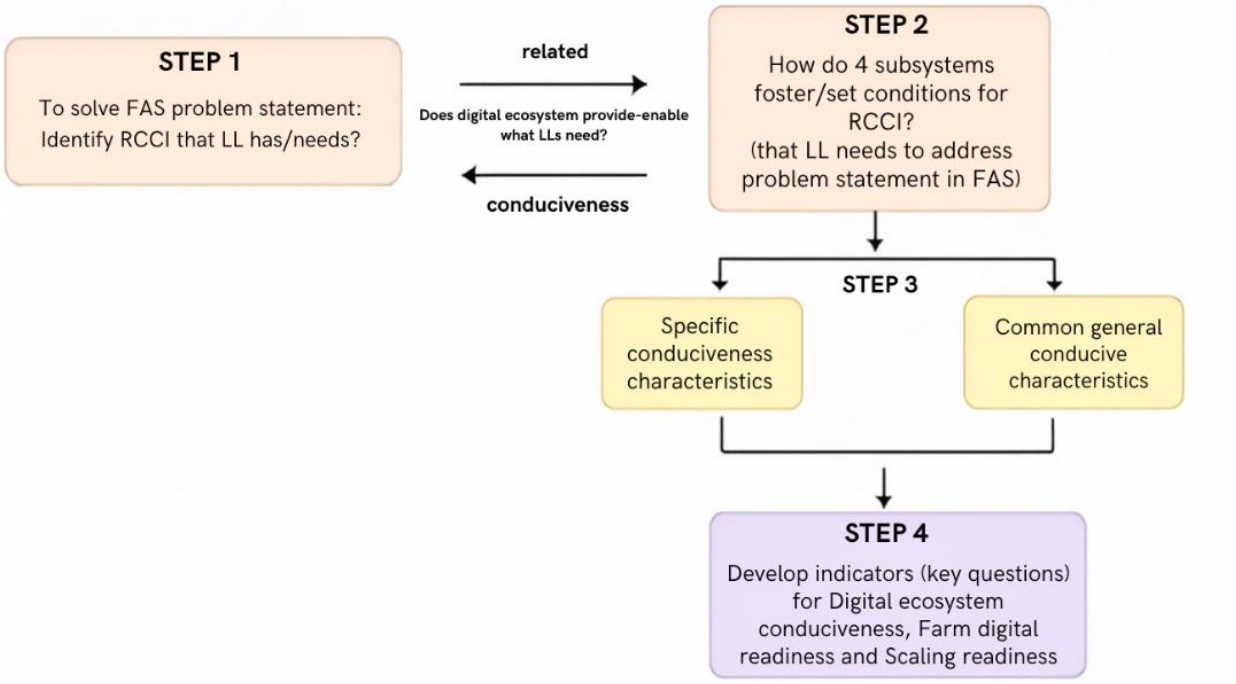

Figure 3. Four step methodology for mapping the socio-ecological context and developing the comparative indicator framework (UAL)

3.3.1.1 Data collection

The data supporting this comparative assessment were collected as part of the LLs Workshops, which were conducted between October 2023 and March 2024. The participatory workshops were designed to facilitate discussion between participants, with the objective of characterising and analysing the DEs within Ostrom's SESF and using the RCCIs approach (please see D3.1 and D3.2 for further details in methodology and data collection). The following questions asked during the workshops guided the mapping of the SESF involving the four "subsystems": actors, resource units, resource systems and governance:

- Q1. What resources, capabilities, collaborations and innovations do the LL have and need to address the LL FAS problem statement?
- Q2. What are the main actors related to the LL FAS problem statement and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?
- Q3. What resource units have an influence on the LL FAS, and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?
- Q4. What resource systems have an influence on the LL FAS problem and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?
- Q5. Which governance mechanisms influence the LL FAS problem and how do they enable or hinder the RCCI needed for addressing the LL FAS problem?

During this stage, each LL identified its FAS problem statement and mapped the RCCIs it had and needed in relation to the four SESF subsystems. These workshops provided the qualitative basis for understanding how actors, resource units, resource systems and governance arrangements enable or constrain digitalisation in each LL context.

The workshop data were compiled by LL coordinators using the templates provided by WP3 and were subsequently analysed to identify recurrent RCCIs, enabling and constraining conditions, and potential characteristics of digital

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ecosystem conduciveness and readiness. This analysis supported the extraction and homogenisation of an initial list of indicators.

3.3.2 Indicator framework and analytical hierarchy

For clarity, the indicator framework is structured hierarchically into four levels:

1. Indicator domains, which represent the overarching elements examined through the comparative assessment (farm digital readiness, scaling readiness, and digital ecosystem conduciveness).
2. Thematic areas, which organise related aspects within each indicator domain.
3. Indicator dimensions, which represent the main analytical areas used to interpret the results.
4. Indicators, which constitute the most specific level of analysis and are directly assessed by the LL coordinators.

The comparative assessment covers three assessment domains:

- Farm digital readiness, understood as the ability of farmers to adapt to and effectively use digital technologies and tools in order to achieve their goals and objectives;
- Scaling readiness, understood as the potential of a digital technology to be adopted by a larger number of farms across different contexts; and
- Digital ecosystem conduciveness, understood as the extent to which the surrounding environment supports the development, successful implementation and adoption of digital activities.

The three assessment domains comprise a total of 56 validated indicators. These indicators are distributed across 18 dimensions, as summarised in Table 6.

Table 6. Structure of the indicator framework used in the comparative assessment

Assessment domain	Indicator dimensions	Number of indicators
Farm digital readiness	• State of digitalisation • Transition effort • Intention to use technology	10
Scaling readiness	• Technology usefulness • Technology ease of use • Technological maturity • Adoption feasibility	7
Digital ecosystem conduciveness	• Knowledge and training • Infrastructure • Financial resources • Human resources • Material resources • Governance • Institutional support • Functional skills • Attitudes • Collaborative structures • Innovation	39
Total	**18 dimensions**	**56 indicators**

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The framework allows the analysis to retain the level of detail provided by the individual indicators while also supporting a more synthetic interpretation at dimension level. The comparative assessment presented in this deliverable focuses primarily on results at the dimension level in order to facilitate the identification and communication of broader patterns across the LLs.

3.3.3 Indicator methodology

The indicators included in the comparative assessment were identified and refined through a progressive process. The objective of this process was to establish a common set of indicators that could be applied across the diverse agricultural, technological and territorial contexts represented within CODECS LLs.

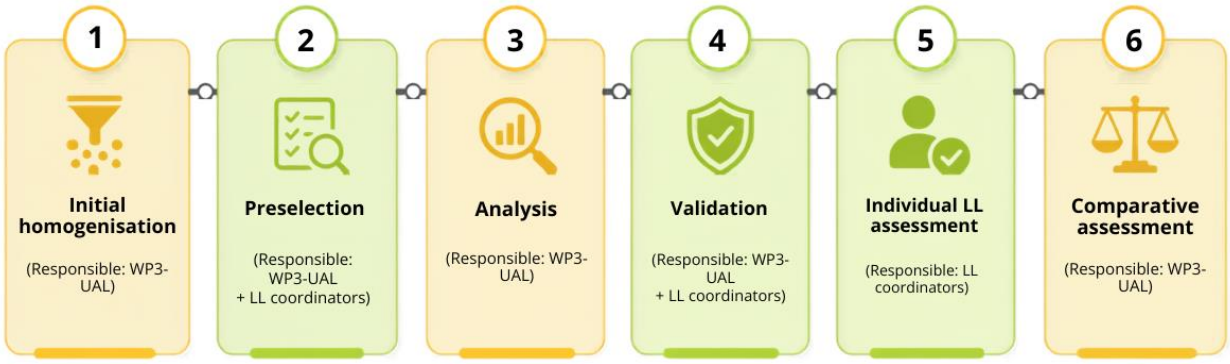

Figure 4. Methodology for the extraction and consolidation of indicators in relation to Digital Ecosystem Conduciveness, Farm Digital readiness and Scaling readiness (UAL)

First, from data collected under the T3.2 Mapping the Socio-ecological context, an initial homogenisation and extraction process based on previous project work and data analysis presented in Deliverable 3.1 and 3.2 was carried out. This resulted in a preliminary list of indicators covering the three assessment domains. The initial list was designed to capture a broad range of factors potentially relevant to agricultural digitalisation and to allow the LLs to assess their applicability in relation to their specific digital ecosystems and agricultural realities.

Second, the preliminary indicators were preselected through a consultation process with stakeholders. Then, LL coordinators were provided with the supporting materials required to conduct the consultation, including presentation materials, instructions and survey templates. Each LL collected at least ten responses from relevant stakeholders. Respondents assessed the relevance of the proposed indicators using a five-point Likert scale and a total of 149 answers were collected.

Third, the responses were analysed and the results organised by assessment domain and indicator dimension. The analysis supported the identification of common indicators that were considered sufficiently relevant across the different LL contexts. Indicators that did not meet the selection criteria were discarded or further reviewed. This iterative process was particularly relevant for digital ecosystem conduciveness, for which an initially broad set of indicators was progressively refined to a final list of 39 indicators.

Finally, the resulting common list was reviewed and validated with the LL coordinators during a dedicated validation session. The validated framework provided the basis for the subsequent comparative assessment.

Following the preselection and validation process, the LL coordinators applied the validated indicator framework to their respective LLs during the final CODECS workshop held in 2026. Each coordinator provided one consolidated score per indicator and per LL using a five-point Likert scale.

The LL therefore constitutes the unit of analysis. The final dataset does not contain individual stakeholder responses, but a consolidated LL evaluation reported by the corresponding coordinator. A total of 19 LLs were initially considered. Two LLs were excluded from the comparative assessment because the corresponding report was not

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available. The analysis therefore includes 18 LLs with valid data. Where an indicator was classified as “not applicable”, the value was excluded from the corresponding calculation.

3.3.4 Data preparation and analysis

The analysis was conducted at two complementary levels: indicator level and dimension level. At indicator level, the original scores assigned by the LL coordinators were retained in order to preserve the granularity of the information collected. At dimension level, the corresponding indicators were aggregated to provide a synthetic measure that facilitates interpretation and comparison across cases.

For each LL, the score of a given dimension was calculated as the arithmetic mean of the applicable indicators included within that dimension. The analysis does not combine the dimensions into a single overall index. This approach avoids introducing implicit weighting effects, as the dimensions contain different numbers of indicators. It also preserves the analytical value of the distinct dimensions and supports the identification of specific strengths, constraints and bottlenecks.

Descriptive analysis

The comparative assessment is descriptive and exploratory. For each indicator dimension, the analysis reports: the mean; the median; the standard deviation; the minimum and maximum values.

The median provides a robust measure of central tendency for the ordinal Likert-scale data, while the mean is reported as a complementary summary statistic that facilitates comparison between indicator dimensions and groups of LLs. The standard deviation and range provide information on the degree of variation across the analysed cases.

Graphical representations are used to support the interpretation of the results. Boxplots facilitate the examination of distributions, dispersion and potential outliers across indicator dimensions. Comparative charts support the identification of patterns across LLs and analytical groups.

Cross-case comparison by clusters

To extend the general descriptive analysis, the results by indicator dimension are compared across groups of LLs sharing relevant characteristics. These groups are referred to as clusters. The clusters are not generated through a statistical clustering algorithm but are predefined on the basis of the characteristics of the technologies, contexts and objectives represented in the LLs.

Following the previous sections 3.1 and 3.2, this comparative assessment considers the complementary clustering criteria:

1. Technology clusters, which group LLs according to the type of digital technology introduced.
2. Sector clusters, which group LLs according to the agricultural or commercial activity in which the intervention is situated.

For each cluster, the results by indicator dimension are aggregated and compared in order to identify similarities and differences between groups. The comparison supports the examination of whether certain indicator dimensions tend to be more or less developed in relation to specific types of technologies and agricultural sectors.

Interpretation and methodological scope

The results should be interpreted as an exploratory comparative assessment of the CODECS LLs. The analysis provides a structured overview of the patterns emerging across the cases and enables the identification of indicator dimensions that may require further attention in the design, implementation and scaling of agricultural digitalisation initiatives.

Several methodological considerations should be acknowledged. First, the analysis covers the LLs included in the CODECS project and is not intended to provide statistically representative conclusions for the broader population of European farms or DEs. Second, the final scores are consolidated assessments reported by the LL coordinators and do not capture the internal variation of stakeholder perceptions within each LL. Third, the number of LLs included in some clusters may be limited or unevenly distributed. Consequently, differences between clusters should be interpreted cautiously and as patterns that may inform subsequent analysis.

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Despite these limitations, the use of a validated common indicator framework provides a consistent basis for cross-case comparison. The combined examination of farm digital readiness, scaling readiness and digital ecosystem conduciveness offers a multidimensional perspective on the conditions shaping agricultural digitalisation across the diverse contexts represented within CODECS.

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Part 2: Results

4 Comparative assessment of Digital Ecosystems analysis

4.1 Socio-technical process modelling

The results presented in this section are the outcome of the analysis described in Section 3.1. The section follows the order introduced in the methodological framework, presenting in sequence the results of the clustering, the impact analysis, the transition effort analysis, and the technological maturity analysis.

4.1.1 Clustering

Clustering was carried out along two dimensions, namely technology and sector, based on the information reported by the LLs in the process modelling reports (Task 3.3). In particular, the positioning of each LL within the clusters was derived from how the technology and its application context were described in the reports, thus considering both the type of digital solution and the way it was embedded within the farm process.

4.1.1.1 Clustering by technology

With regard to technology, the analysis showed that the CODECS cases encompass a variety of digital solutions but also revealed recurring similarities that made it possible to aggregate them into two main clusters: IoT and UAVs and Platforms. The IoT and UAVs cluster include cases in which the description is more strongly centred on physical devices, sensors, drones, and other technological tools directly embedded in field operations, thus reflecting a stronger *agritech* and hardware-oriented focus. By contrast, the Platforms cluster includes cases in which the description places greater emphasis on software systems, data management, interoperability, and the relationships among the different actors involved. In several cases, platform-based solutions may also incorporate IoT components, but the focus lays on the central role of digital platforms as a coordination and integration layer. Figure 5 provides a visual representation of the clustering by technology.

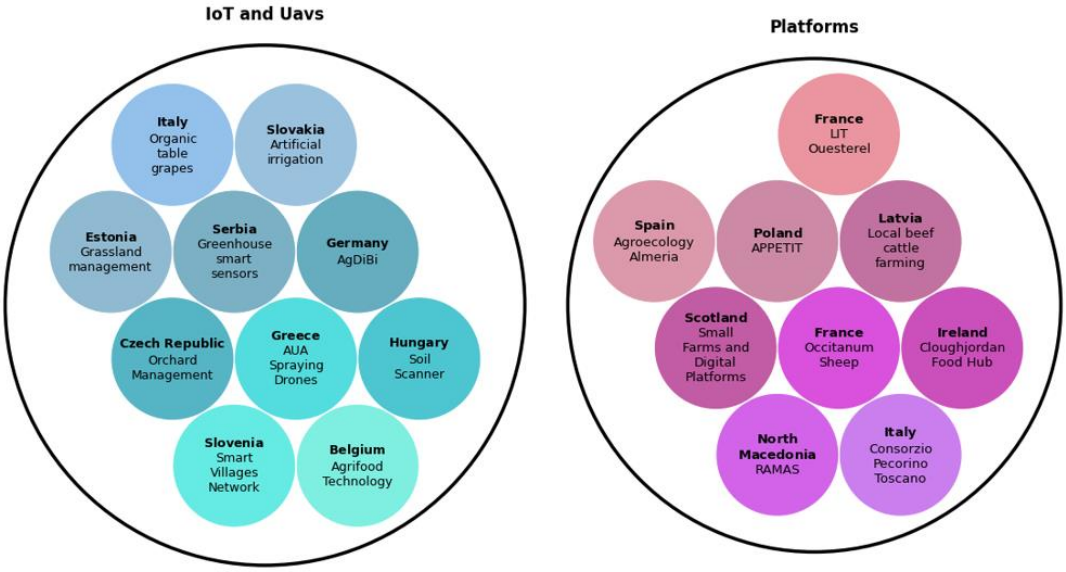

Figure 5. Clusters by technology

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Based on the above illustrated criteria, the positioning of the LLs within the clusters by technology is as follows:

1. The IoT and UAVs cluster includes: Agrifood Technology (Belgium), Orchard management and digitisation (Czech Republic), Grassland Management (Estonia), AgDiBi (Germany), Spraying drones (Greece), Innovative Soil Scanner technology for sustainable farming (Hungary), Organic table grapes (Italy), Greenhouse smart sensor (Serbia), Smart villages Network (Slovenia), and Artificial Irrigation Management System (Slovakia).
2. The Platforms cluster includes: LIT OUESTEREL (France), Occitanum Sheep (France), Cloughjordan Food Hub (Ireland), Pecorino Toscano (Italy), Local beef cattle farming (Latvia), RAMAS (North Macedonia), APPETIT (Poland), Scottish Small Farms and Digital Platforms (Scotland), and Almería Agroecology (Spain).

4.1.1.2 Clustering by sector

Clustering by sector aggregated the LLs according to the agricultural domain in which the digital solution was applied. The Crop and Grassland cluster groups cases concerned with crop production and land management, which share similar challenges related to monitoring field conditions and supporting agronomic decisions. The Livestock cluster includes cases centred on animal farming, where the process descriptions focus more specifically on breeding and animal monitoring. The Marketing cluster cuts across both livestock and crop production contexts, but groups cases in which the process description is primarily centred on commercialisation, transactions or advertising activities rather than on production itself.

Based on these criteria, the positioning of the LLs within the clusters by sector is as follows:

- The Crop and Grassland cluster includes: Agrifood Technology (Belgium), Orchard management and digitisation (Czech Republic), Grassland Management (Estonia), AgDiBi (Germany), Spraying drones (Greece), Innovative Soil Scanner technology for sustainable farming (Hungary), Organic table grapes (Italy), Greenhouse smart sensor (Serbia), Smart villages Network (Slovenia), and Artificial Irrigation Management System (Slovakia), RAMAS (North Macedonia) and Agroecology Almeria (Spain)
- The Livestock cluster includes: LIT OUESTEREL (France), Occitanum Sheep (France), Pecorino Toscano (Italy) and Local beef cattle farming (Latvia).
- The Marketing cluster includes: Cloughjordan Food Hub (Ireland), APPETIT (Poland), Scottish Small Farms and Digital Platforms (Scotland).

Figure 6 provides a visual representation of the clustering sector.

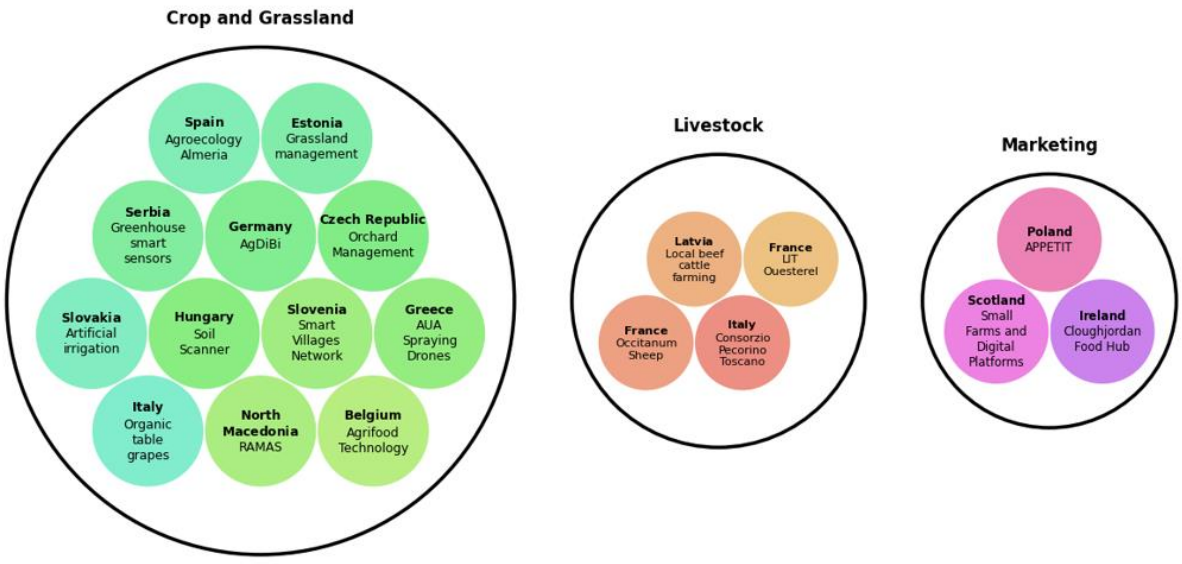

Figure 6. Clusters by sector

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Although cluster assignment was based on the specific process and technology represented through the modelling activity, the overall positioning reflects the focal action situation described by the LLs at the project level. The main exception is the German LL AgDiBi: although its broader focus concerns education, the process modelling activity was centred on a soil scanner technology, and the case was therefore positioned according to that description.

The identified clusters serve as the analytical basis for the cross-case analyses presented below.

4.1.2 Impact analysis

As described in Section 3.1, the analysis is conducted at two levels: (i) changes in tasks and actors, in terms of elements added and removed when comparing the process before and after the introduction of the digital solution; and (ii) the intensity of change, expressed as the sum of added and removed elements in relation to the overall process structure, thus enabling comparison across individual LLs.

4.1.2.1 Change impact

The change impact matrices presented in Figures 7 and 8 synthesise the extent to which digitalisation affects tasks and actors by comparing the process before and after the introduction of the digital solution and aggregating the results by cluster.

The comparison by technology cluster depicted in Figure 4 shows that both clusters are characterised primarily by change at the task level, while changes in actors are more limited. However, the Platforms cluster shows a stronger overall change with a higher proportion of both added tasks and removed tasks compared to the IoT and UAVs cluster. Differences are also visible, though smaller in absolute terms, at the actor level, where Platforms again show higher rates of added and removed actors. This suggests that platform-based solutions tend to produce broader reconfiguration of the process.

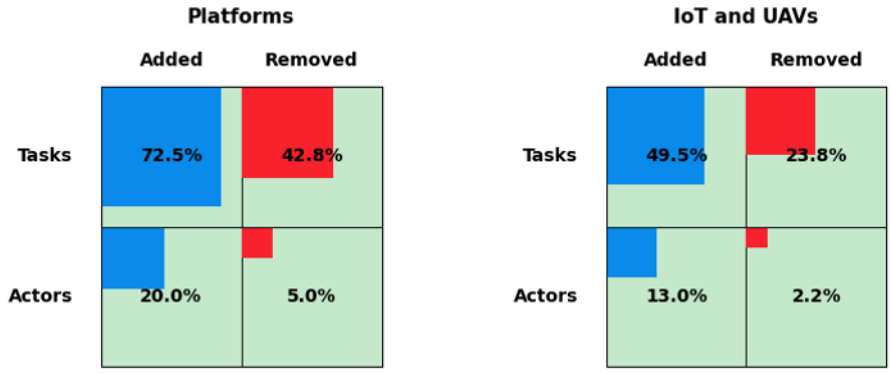

Figure 7. Change impact matrix by technology clusters

Across sector clusters, depicted in Figure 8, the same general pattern remains visible, but with varying intensity. Crop and grassland and marketing show the strongest task additions, whereas livestock appears comparatively more stable, with lower levels of both task addition and actor change. At the same time, the marketing cluster showing the highest actor addition, suggesting that commercial and promotional processes may require the involvement of additional roles or intermediaries when digital tools are introduced.

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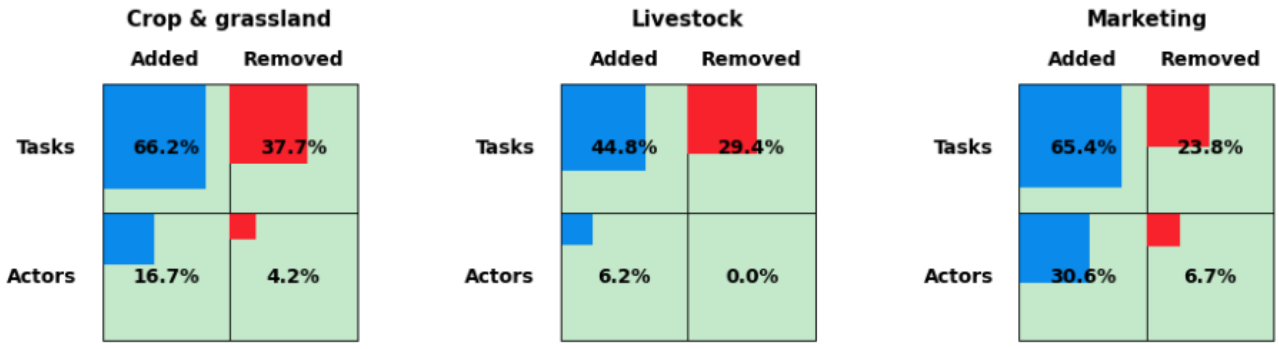

Figure 8. Change impact matrix by sector clusters

Taken together, these findings indicate that the main impact of digitalisation across the CODECS LLs lies in the enrichment and partial reorganisation of process activities, rather than in a radical transformation of who is involved in the process. Overall, the figures show a clear and consistent tendency across both clustering dimensions: digitalisation primarily affects the task level, while changes in the set of involved actors remain comparatively limited. In both technology clusters, the most visible effect is the addition of tasks, which is higher than task removal and clearly higher than actor-level change. This suggests that the introduction of digital technologies more often leads to an expansion or reconfiguration of activities than to a substantial reshaping of the social structure of the process. More specifically, digitalisation tends to increase complexity by introducing new operational tasks, data-processing activities, or coordinational mechanisms, while leaving the core set of actors relatively stable.

4.1.2.2 Change intensity

Figures 9 and 10 present the distribution of the change ratio across the LLs, with Figure 9 highlighting items by technology cluster and Figure 10 by sector cluster. As described in Section 3.1, this ratio provides a comparative value for assessing the intensity of change in each case. Ordered from the most to the least disruptive cases, the figures offer an overall view of how strongly the introduction of the digital solution transformed the farm process.

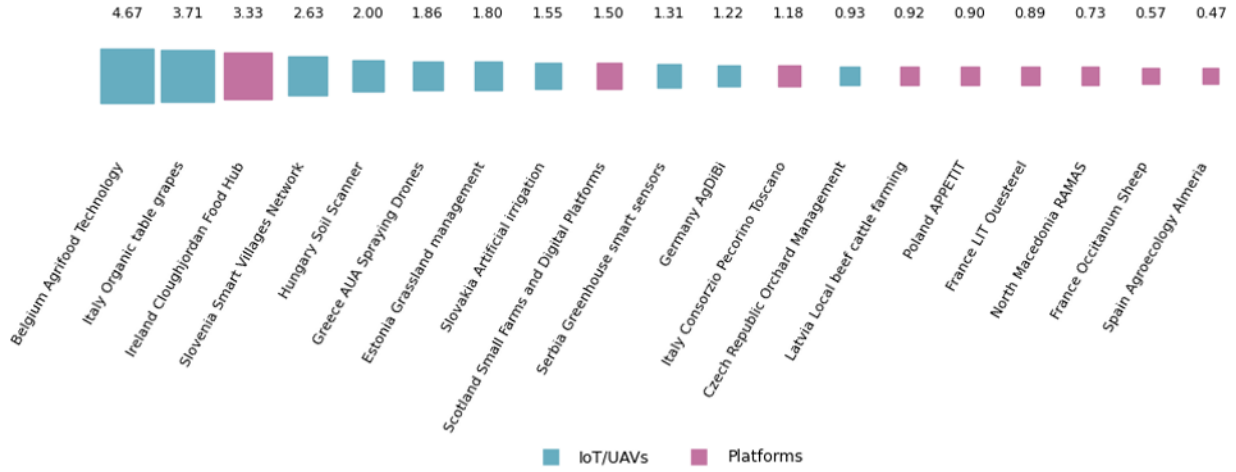

Figure 9. Cases comparison by intensity changes with cases coloured by technology cluster

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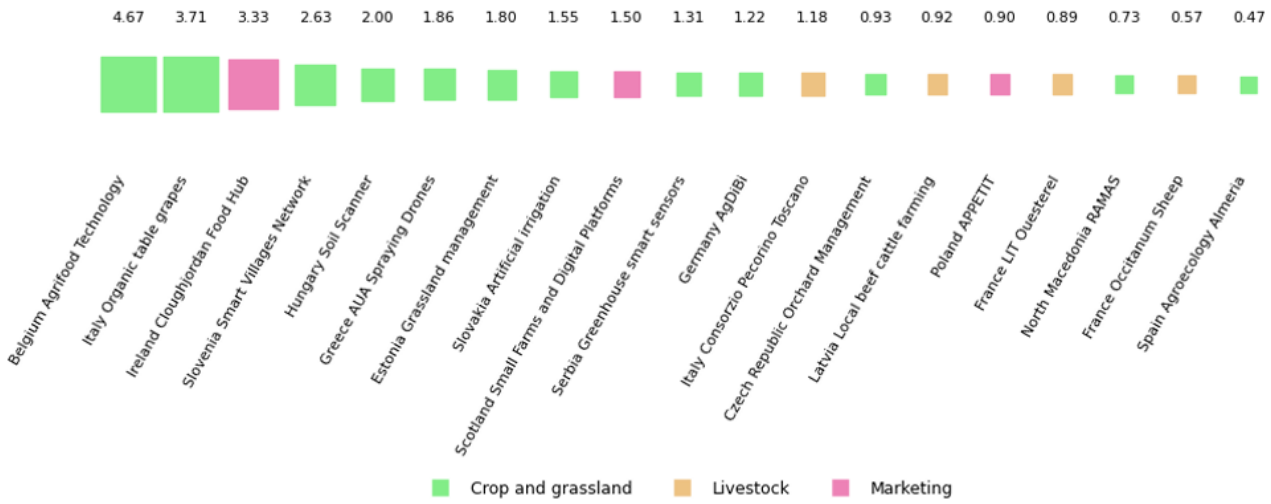

Figure 10. Cases comparison by intensity changes with cases coloured by sector cluster

A first observation is that a limited number of cases show higher values and a larger group is positioned around medium or low values. This suggests that digitalisation does not affect all LLs to the same extent but rather produces different degrees of process transformation depending on the initial configuration of the process and the extent to which existing practices are restructured. Cases with the highest change intensity, such as Belgium, Italy–Apulia, Ireland, and Slovenia, indicate that the introduced digital solution had a more disruptive effect on the process. In these LLs, the technology appears to replace, reorganise, or significantly reconfigure practices that were previously more manual or less integrated. By contrast, cases such as Spain, France–Occitanum, North Macedonia, and France–LIT show comparatively low change ratios. In these LLs, the digital solution seems to operate more as an extension or integration of practices that were already partly supported by technology. In such cases, the transformation is less visible in structural terms, because many tasks and actors remain formally unchanged. Nevertheless, the lower change ratio should not be interpreted as indicating limited relevance of the digital solution. Rather, it may reflect a more incremental form of digitalisation, in which the main effects concern the quality of data, the efficiency of coordination, the interoperability between systems, or the refinement of existing decision-making processes.

When the figures are read through the clustering dimensions, some tendencies also emerge. In technology clustering (Figure 9), the highest values are mostly associated with IoT/UAV cases, although platform-based cases are distributed across medium and low values, with a few exceptions. This suggests that IoT and UAV solutions are often introduced in contexts where they directly reshape operational activities, while platform solutions may range from highly transformative to more incremental depending on whether they primarily replace existing coordination mechanisms or simply integrate them. In the clustering sector (Figure 10), the upper part of the distribution is dominated by crop and grassland cases, while livestock and marketing cases appear more frequently in the medium-to-low range, although with some exceptions. This may indicate that crop and grassland processes are, in several cases, more strongly affected by the introduction of monitoring and automation technologies replacing totally manual workflows, whereas livestock and marketing solutions more often build on already partially digitalised practices.

Overall, the change ratio confirms and complements the cluster-level matrices: digitalisation across the CODECS LLs tends to generate multiple patterns of transformation, ranging from relatively incremental adjustments to substantial process reconfigurations. Metric is therefore useful not only for comparing single cases, but also for highlighting that the impact of digital technologies depends on the extent to which they intervene in pre-existing routines, redistribute activities, and alter the organisation of the process.

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4.1.3 Analysis of transition effort

The thematic analysis of the question on transition across the Process Modelling Reports indicates that the introduction of digital solutions is generally described as a gradual and articulated process. While the specific technologies, farming contexts, and organisational settings differ across LLs, the reports show a consistent pattern in the way transition is approached. In most cases, the transition process can be synthesised into seven subsequent steps:

1. Preparatory activities

In this phase, the initial conditions for adoption are assessed. This includes the analysis of current practices, infrastructural constraints, and user requirements, as well as the identification of possible barriers to adoption. For example, reports refer to "*User requirements analysis*" or "*Assessing the current situation on farms in terms of network coverage, and possibilities to adopt digital solutions*" as early components of the transition process.

2. Technical implementation

A second recurrent element relates to the deployment of the technical infrastructure and the integration of the solution into the existing operational environment. In many reports, transition includes the installation of sensors or devices, the configuration of software, the setup of cloud or server infrastructures, and the management of data exchange between different components. This indicates that the transition often requires a substantial technical preparation phase before regular use can take place. For instance, one report describes the "*Installation/revision of soil moisture sensors, weather stations, and other IoT devices to collect real-time data*" together with the "*Set up of the data servers and storage systems to manage and process the collected data efficiently*." Likewise, another report notes that "*The data was imported into the cloud*" and later refers to a "*Configuration learning process for integration of technologies, design, and learning to use the standard data model for interoperability*."

3. User support

The reports also show that capacity building and user support constitute an important component of the transition process. In several LLs, specific attention is devoted to helping users understand how to operate the system, interpret the generated data, and progressively incorporate the solution into decision-making processes. This indicates that the transition is not limited to the delivery of a technical artefact but also involves the development of practical competences among farmers and advisors. One report explicitly mentions "*Training the farmers on how to use the system and providing them with user guidelines*." Similarly, other states that "*LL members get an educational material and help from the advisor for interpreting the soil scanner data for the local conditions*."

4. Experimentation in real settings

A further recurrent element is the use of testing, piloting, and demonstration activities as intermediate steps between implementation and broader uptake. Rather than describing an immediate transition to stable use, several reports present the process as one in which the solution is first trialled under practical conditions and its value is demonstrated to relevant actors. One LL, for example, refers to "*Demonstrating at experimental farm the added value and open this farm to farmers and companies*." Another report similarly mentions "*Testing of interoperability among different devices*" and "*Testing of the data collection process".*

5. Coordination among actors

Another common element concerns the coordination among stakeholders involved in the transition process. In several reports, adoption is described as requiring interaction among farmers, advisors, developers, technology providers, and other actors in order to align expectations and clarify practical outcome. This suggests that transition is also shaped through discussion, negotiation, and collective adjustment. One report provides a clear example through actions such as "*Reach an agreement with the farmers about the information that will be included on the product labels*" and "*Discuss and agree with the farmers on the best and most appropriate ways to integrate the digital [solution] with other digital marketing solutions they are currently using*." In a similar way, one report refers to "*workshops, focus groups, and informal meetings to discuss the benefits of the technology and address any hesitations or concerns*". This confirms that digital transition often includes an organisational and relational dimension alongside the technical one.

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6. Incorporation into farming practices

The reports further indicate that transition becomes visible in the progressive incorporation of the solution into everyday practices. In this phase, the digital system begins to influence routine decisions and operational behaviours, and its role shifts from experimental or occasional use to situated application within real work processes. This aspect is especially relevant because it reflects the practical embedding of the solution in the daily activities of the farmers. One report, for example, notes that "*The farmer started changing from long to short irrigation shifts during the working time...*" based on the use of the application and its recommendations. Similarly, another report describes the process as "*trial and error and peer to peer learning*". These excerpts show that the transition is also expressed through gradual changes in habits, timing, and decision routines at farm level.

7. Adaptation and maintenance

Finally, several reports present the transition as a continuing process beyond initial implementation through feedback collection, adaptation, and maintenance, with the understanding that the solution may need to be adjusted after exposure to real conditions of use. A report states that "*feedback from farmers as users will be collected. According to the feedback adaptation and updates will be done in the future steps*", another report adopts an even more explicit formulation, describing the transition phase as "*an ongoing and unfinished process*".

Overall, the cross-case analysis shows that the transition process is commonly described as a sequence of interconnected activities that move from contextual preparation to technical deployment, user support, practical experimentation, stakeholder coordination, operational uptake, and iterative refinement. Across the reports, this process is consistently characterised by the interaction between technical, organisational, and human factors. The evidence therefore suggests that successful transition depends not only on the availability of a digital solution, but also on the extent to which it can be progressively embedded within local infrastructures, user capabilities, work practices, and stakeholder relationships.

Comparison of transition effort across clusters

To explore whether transition processes vary across the clusters, the themes were analysed by technology and by sector. The comparison does not suggest completely different transition logics across clusters, since the reports broadly converge on a common process including the aforementioned steps. However, some differences can be observed in the emphasis and sequencing of the transition process.

Regarding the technology clusters, three main differences emerge between the IoT and UAVs cases and the platform cases. First, the IoT and UAVs cluster is more strongly characterised by technical deployment and infrastructural setup. These reports more frequently describe the installation of sensors or devices, software and hardware configuration, data transmission, cloud or server setup, and interoperability among components. Transition in these cases has a more operational and technical focus, linked to making the system reliable under field conditions. By contrast, in the platform cluster, transition is more often associated with communication, coordination, and integration into organisational practices. Second, the two clusters differ in the main purpose of testing and demonstration. In the IoT and UAVs cases, testing is more often aimed at verifying technical performance, data quality, and interoperability in real or semi-controlled conditions. In platform cases, testing tends to focus more on usability, usefulness, stakeholder acceptance, and practical relevance within ongoing workflows. Third, the social dimension of transition is more explicit in the platform cluster, where reports more frequently describe negotiation among actors, agreements on use, and changes in information-sharing practices. In the IoT and UAVs cluster, transition is more often framed around embedding a technical tool into agronomic decision-making and operational routines.

With respect to the cluster sector, the main difference concerns the primary focus of transition. In the cases of crops and grassland, greater emphasis is devoted to integrating the technology into production and monitoring activities such as irrigation, spraying, soil sensing, or orchard management. The reports more often refer to field assessment, device installation, data collection, testing, and gradual adjustments of agronomic routines. In the livestock cluster, by contrast, transition appears more strongly shaped by organisational, social, and contextual factors. While technical implementation is still relevant, the reports more often stress coordination among actors and the influence of broader economic and social conditions. The marketing cluster shows a different profile again, as transition is less concerned with field-level deployment and more with the introduction of digital tools into communication,

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coordination, exchange, and outreach practices. In these cases, the reports place greater emphasis on user engagement, changes in organisational routines, and progressive uptake through use.

4.1.4 Analysis of technological maturity

We present the results based on the three perspectives presented in Section 3.1, namely farm and LL, moving from the most internal to the most external viewpoint.

1. Farm perspective

This perspective reflects the viewpoint of the farm that chose to invest in and experiment directly with technology. The results are drawn from the thematic analysis of the reports produced by the demo farms.

Across the technology clusters, the IoT and UAVs cases show a largely positive maturity profile. These technologies are most often described as already mature, commercially available, and usable in routine farming practices. They are also seen as valuable and increasingly standard in precision agriculture, particularly for sensing, monitoring, and decision support, with some potential for transfer to similar farms or crops. At the same time, the main limitation concerns the gap between the maturity of individual components and that of the overall system: sensors, drones, or platforms may be mature on their own, while integration, interoperability, analytics, and AI-based functions remain less developed. Other recurring issues concern the need for local adaptation, onboarding, and training, as well as the still limited diffusion of some solutions in specific niches. From the farm viewpoint, technological maturity appears closely linked to farm readiness, as the conditions that support adoption also shape how maturity is perceived in practice. Positive aspects mainly concern the presence of innovative or pioneer farms, often combined with a clear perception of technology's usefulness and an openness to experimentation. Readiness is further strengthened by advisory services, producer organisations, and in field demonstrations. At the same time, negative aspects emerged regarding the main barriers concerning costs, especially for small farms, followed by the need for training and technical assistance, limited digital skills, scepticism, and, in some cases, regulatory constraints, particularly for drone-based applications. The Platforms cluster shows a more mixed picture. On the positive side, platforms are often considered sufficiently mature to support coordination, sales, or farm management, and are valued for their potential to connect producers and communities. On the negative side, their maturity is often described as fragile and highly context-dependent, shaped by market conditions, funding, and user uptake. For farm readiness, positive themes include the presence of collective organisation, basic infrastructure, and clear local value, sometimes combined with initial conditions for scaling. Yet the main barriers concern financial and organisational sustainability, digital limitations among users, especially older or less confident participants, and in some cases a weak perceived need in the farm context.

Across the sector clusters, Crop and grassland shows the strongest positive maturity pattern. Technologies are frequently described as technically mature and ready for real farm use, especially in activities such as irrigation, orchard and vineyard monitoring, soil analysis, and other precision agriculture practices. They are also often regarded as scalable to similar agronomic contexts. Still, practical maturity depends heavily on local adaptation, while integration and analytics are often less mature than the individual technological components. Some systems are also described as expensive or still not widely diffused. In terms of farm readiness, the most positive themes concern interest among innovative farms and advisors, the value of demonstrations in encouraging adoption, and the role of existing infrastructure or support networks. The main barriers are costs, the need for training and interpretation support, uneven digital culture, and occasional regulatory obstacles.

In Livestock, some technologies are considered technically mature, proven in other livestock sectors, or potentially transferable. However, the dominant pattern is more cautious: these solutions are often seen as new and not yet normalised in the specific subsector, especially sheep farming, with low adoption, weak support infrastructures, and practical installation or operational difficulties. A similar pattern emerges for farm readiness: while some tools are considered promising or pilot-ready, the most common themes concern low awareness, limited dissemination, the need for training and local adaptation, and the lack of a strong sector-specific ecosystem of suppliers and support actors.

Finally, Marketing presents a distinct profile. The positive maturity themes mainly concern the ability of platforms and related solutions to support distribution, visibility, and producer coordination, as well as their contribution to community-building and alternative food networks. At the same time, maturity is often described as dependent on

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external market and social conditions, making these systems both functional and fragile. For farm readiness, positive themes relate to collective organisation, local initiatives, and the availability of basic infrastructure. However, the main barriers concern financial and organisational sustainability, digital exclusion or reluctance among end users, and a limited or context-dependent motivation among farms to adopt the solution.

2. Living Lab perspective

This perspective reflects the viewpoint of LL as the network coordinating, supporting, and observing the introduction of the technology within its local context. It therefore provides a more intermediate and organisational view than that of the individual demo farm. The results are drawn from the Process Modelling Reports and triangulate the quantitative data on the positioning of the technology on the proposed maturity scale with the thematic analysis of the related open-ended question.

4.1.4.1 Quantitative analysis: LLs positioning in the maturity scale

Figure 11 presents the distribution of the maturity scores assigned by the LLs to the digital solutions introduced in their contexts. The figures are organised in two boxplots: the first shows the distribution by technology cluster and the second by sector cluster. This representation makes it possible to compare not only the central tendency of maturity across clusters, but also the variability and spread of the assigned scores.

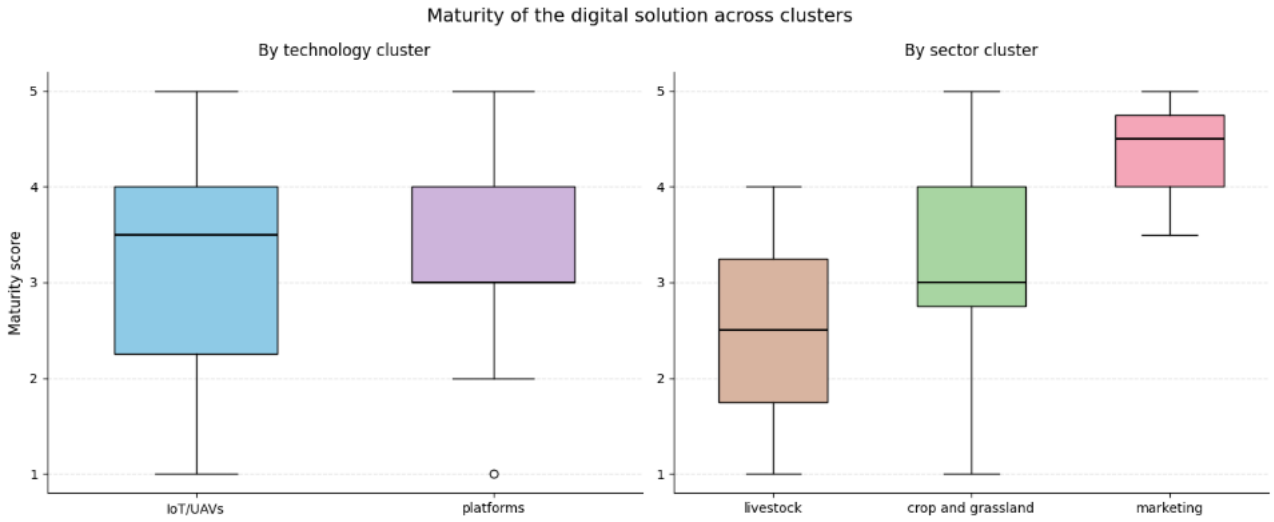

Figure 11. Distribution of maturity scores assigned by the Living Labs to the digital solutions introduced in their contexts, shown by technology cluster and by sector cluster

Looking first at the technology clusters, both IoT/UAVs and platforms show overall medium-to-high maturity values. However, the platforms cluster appears slightly more concentrated in the upper part of the scale, with most cases positioned between scores 3 (pilot) and 4 (novel system) and a median around the mid-to-high range, although one lower outlying case is also visible. By contrast, IoT and UAVs display a wider spread, ranging from very low (proof of concept or prototype) to very high maturity levels (mature system), which suggests greater heterogeneity across cases.

The differences are more visible in the sector clusters. Marketing shows the highest and most compact distribution, with scores concentrated in the upper range of the scale, suggesting that these solutions are generally perceived as more mature and more coherently positioned across cases. Crop and grassland occupy an intermediate position, with a median around the middle of the scale but also considerable variability, spanning from low to high maturity. Livestock, in contrast, shows the lowest overall distribution, with lower median values and a broader spread in the lower-to-middle part of the scale. Overall, the figure suggests that perceived maturity varies more clearly by sector

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than by technology type, with marketing-related solutions appearing more mature on average and livestock-related solutions showing comparatively lower maturity.

4.1.4.2 Qualitative analysis: technological maturity in LLs

The thematic analysis of the descriptions accompanying the maturity levels assigned to the technologies within the LLs shows that technological maturity is rarely understood as a purely technical attribute. Rather, the LLs describe it as a contextual and practice-based condition, shaped not only by the technological solution itself, but also by its integration into local workflows, its actual use by farmers, and its readiness for adoption in real operating conditions.

Across the technology clusters, the IoT/UAVs cases show a recurring theme: maturity is shaped more by context than by the novelty of individual components. Many solutions combine sensors, drones, apps, or communication infrastructures that are already available, yet they are still described as having intermediate or limited maturity because they are being validated in specific farming environments, integrated in new ways, or not yet fully adopted by end users. A second strong theme concerns maturity as constrained by adoption conditions. In several reports, the assigned level depends not only on technical performance, but also on training needs, affordability, limited uptake, and farmers' hesitation. The Platforms cluster is mainly characterised by maturity as iterative deployment and organisational embedding. These solutions are often described as being at pilot or intermediate stage not because the technical architecture is immature, but because the platform is still being tested, adapted, or extended across users, functions, and local contexts. A second recurring theme is that of situated maturity: technologies may already be available on the market, yet they are assigned lower maturity because they are new in that sector, newly integrated, or still being adapted to a specific ecosystem. More generally, this cluster places particular emphasis on interoperability, coordination, data exchange, and multi-actor experimentation as key criteria for judging maturity.

Across the sector clusters, Livestock reports often describe technologies as feasible in technical terms but still limited in maturity because they are not yet fully integrated into livestock routines, accepted by users, or workable in daily herd management. Crop and grassland is the most heterogeneous cluster, but the dominant theme is validation in real agronomic conditions. Here maturity is often linked to field testing, environmental variability, and local adaptation, with strong emphasis on how well the technology performs under specific climatic, ecological, or infrastructural conditions. By contrast, Marketing is mainly characterised by maturity as socio-organisational viability. In this cluster, maturity depends less on technical readiness and more on whether digital platforms are actively used, scaled, and embedded in stable producer-consumer networks.

4.1.4.3 Triangulation of quantitative and qualitative results

The triangulation of the quantitative and qualitative results provides a more nuanced understanding of technological maturity across the LLs. The quantitative analysis provides a comparative overview of how the LLs position their digital solutions on the proposed maturity scale. It shows that maturity scores vary across both technology and sector clusters, making it possible to identify broader patterns of higher, lower, or more heterogeneous maturity. Overall, the results suggest that differences are more visible across sectors than across technology types. At the same time, the qualitative analysis explains the underlying reasons for higher or lower positioning and clarifies how maturity is shaped by specific conditions. Taken together, the results indicate that maturity is not assessed solely in terms of technical advancement, but also in relation to contextual adaptation, integration into existing processes, actual use by end users, and readiness for broader adoption.

4.1.5 Insights from cross-case analysis

The following section provides a synthesis of the insights emerging from the cross-case analysis.

The analysis at the farm-process level has focused on three main dimensions: the impacts of process transformation, the effort associated with digital transition, and the maturity of the technologies selected by the LLs. Analysed across the cluster dimensions, the results highlight both recurring patterns and important variations related to technology type, sector, and local conditions. The key insights are summarised below according to the three analytical dimensions to support the analysis of the CODECS LLs, as well as future adopters and analysts.

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4.1.5.1 Impacts of process transformation

- At the farm-process level, digitalisation mainly affects tasks rather than actors. Across the LLs, the most visible impacts of process transformation after digitalisation concern the reorganisation of farm processes in terms of task addition or removal, while actor-level changes remain comparatively limited. This indicates that digitalisation tends to involve the same actors already engaged in farm processes, while reshaping their activities and the competences required. In turn, this suggests the importance of analysing the costs and benefits associated with the newly introduced tasks, especially in consultation with the actors expected to perform them.
- Digitalisation mainly drives process enrichment and increased complexity. Added tasks are generally more frequent than removed tasks, suggesting that digital technologies often introduce new activities such as monitoring, data handling, coordination, control, and other desk-based operations. This means that the same actors are often required to perform more tasks and to combine operational work with new digital and administrative activities. As a consequence, digitalisation may increase the complexity of everyday farm work and the burden placed on practitioners. This, in turn, points to the need to further investigate, with practitioners themselves, the actual costs and benefits of this process reengineering, adopting a more qualitative perspective on how these changes are experienced in practice.
- The intensity of change may vary considerably across cases and clusters. In some LLs, digitalisation is more disruptive at the process level, resulting in substantial process reengineering, while in others it is more incremental. Higher change intensity is more often found where the technology replaces previously manual practices, whereas lower intensity tends to reflect the integration of solutions into already partly digitalised processes. Across clusters, IoT and UAV cases are often more disruptive at the process level, while platform solutions tend to produce broader workflow reorganisation. Concerning sectors, crop and grassland cases more frequently show stronger structural change, whereas digitalisation in livestock and marketing tends to produce less pronounced process transformation.

4.1.5.2 Transition effort

- Digital transition is generally described as a progressive and socio-technical process. Across the LLs, the introduction of digital solutions is not represented as an immediate shift, but as a sequence of interconnected steps involving preparation, implementation, support, experimentation, coordination, incorporation into practice, and continuous maintenance and adaptation. The reports consistently show that successful transition depends not only on deploying and testing the technology, but also on training users, aligning stakeholders, adapting process, and supporting practical use over time. This suggests that human factors are not secondary to transition but are a core condition for its effective implementation and long-term uptake of digital solutions.
- Different technologies and sector-specific conditions affect how transition is carried out in practice. Transition effort related to IoT and UAV technologies is more strongly characterised by the setup of infrastructure and technical testing, while platform cases place greater emphasis on communication, coordination among stakeholders and embedding in organisational practices. Across sectors, transition is more often centred on integrating technologies into monitoring and production routines in crop and grassland. By contrast, in livestock, it is more strongly shaped by organisational factors; in marketing, it is linked more closely to communication, coordination, and outreach practices.

4.1.5.3 Technological maturity

- Technological maturity in agriculture should be assessed in relation to both the technology itself and the context in which it is applied. A digital solution may consist of a combination of technologies commercially available and already operational in technical terms. However, this solution may still be perceived as only partially mature if the local conditions for use are not in place. The analytical perspectives used to evaluate technological maturity shed light on complementary aspects: farm-level needs; needs at the ecosystem level.
- Technological maturity may vary across contexts and sectors. Across the analytical perspectives, maturity has been rarely treated as a purely technical attribute. Instead, it is assessed in relation to contextual

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adaptation, integration into workflows, actual use, and readiness for adoption in real-world conditions. Differences in maturity are more visible across sectors than across technology types. These findings therefore point to the importance of further investigating ecosystem-level solutions together with farmers to facilitate access to the digital solutions, and to create the conditions for technology scaling.

4.2 AKIS perspective

This section presents the findings from a comparative analysis of AKIS across the CODECS LLs derived from Task 3.2, *Mapping the Socio-Ecological Context*. The analysis focuses first on grouping the LLs according to structural and contextual factors (type of technology, level of innovation readiness, LLs objectives, and the institutional composition of national advisory systems). Second, we compare the influence of those groups in the mobilisation and utilisation of knowledge and innovation support. We further examine the composition, roles, and proximity of key actors, the extent of institutional pluralism, and the nature of coordination mechanisms that govern knowledge flows.

4.2.1 Grouping the LLs according to the characteristics influencing knowledge flows

We grouped the LLs according to the four dimensions presented in the chapter 3.2. As it can be observed in Figure 4, LLs are almost evenly distributed with respect to the type of technology and the types of advisory services. However, we also note that most of the LL are located in TRL 7-9 and have as an objective increased productivity or efficiency or natural resource management. Very few LLs are located in the conceptual development or prototyping of the innovation (TRL 1-4, 5-6) or have as an objective to work with social or human capital (Figure 12).

	Living Lab	Type of technology		TRL Level			Objective of the LL				Type of advisory services (national)		
		IoT and UAV	Platforms	TRL 1-4	TRL 5-6	TRL 7-9	Human/social capital	Natural resources mgt	Productivity and efficiency	Value creation	Firm-led	Pluralistic	Policy-driven
BE	Agrifood Technology (BE)	●				●			●		●		
CZ	Automation of Orchard Management (CZ)	●			●				●		●		
EE	Grassland Management(EE)	●		●				●					●
FR-Pi	LIT Ouesterel Pigs (FR)		●			●				●		●	
FR-Vi	Occitanum Viti (FR)		●			●		●				●	
DE	AgDiBi(DE)	●				●	●					●	
GR	Spraying drones (GR)	●				●		●			●		
HU	Innovative Soil Scanner (HU)	●				●			●			●	
IR	Chloughjordan Food Hub (IR)		●	●						●			●
IT-Pe	Pecorino Toscano DOP (IT)		●		●				●		●		
IT-Gr	Organic Table Grapes (IT)	●				●				●	●		
LT	Local Beef Cattle Farming (LT)		●			●				●			●
MA	RAMAS (MA)		●		●				●				●
PL	Liszki Basket Buyers Club (PL)		●			●				●			●
ST	Scottish Small Farms and Digital Platforms (ST)		●	●			●					●	
SE	Greenhouse Smart Sensor Laboratory (SE)	●				●			●			●	
SK	Artificial Irrigation Management (SK)	●				●		●				●	
SV	Smart Villages Network (SV)	●				●			●				●
ES	Almería Agroecology (ES)		●			●		●			●		

Figure 12. Grouping of LLs according to the selected dimensions

4.2.2 Actors

In this section we explore number and type of actors that are identified by the LLs in the FAS. As indicators of comparison, we analysed number of actors, presence of type of actors in each FAS, representation of type of actor and the innovation support activities that would typically be provided to LLs by such actors. Here, we distinguish grosso modo researchers (generating knowledge), advisors (operationalising and mediating knowledge), IT providers (technology producers) (cf. Table 11).

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4.2.2.1 Number of actors

Actors were classified according to the level of distance as perceived by the participants in the workshops. There were three levels in which actors could be classified: Level 1 (be part of the LL), Level 2 (be close to the LL, potential collaboration with the LL) and Level 3 (Influential, but a cooperation is unlikely). Figure 13 depicts the distribution of the actors according to the LL.

This distribution of actors by LL can be interpreted as the proximity of actors to the Focal Action Situation. While actors in Level 1 represent those who are actively engaged in the activities of the LL, actors in LL 2 represents actors which are potentially available for collaborations. Actors in the Level 3 are those who are important in a larger system point of view from which the LL has less oportunities to collaborate.

As can be derived from Figure 1, the diversity of distance distribution among the CODECS LL actors is considerable, and no patterns are recognisable at first sight.

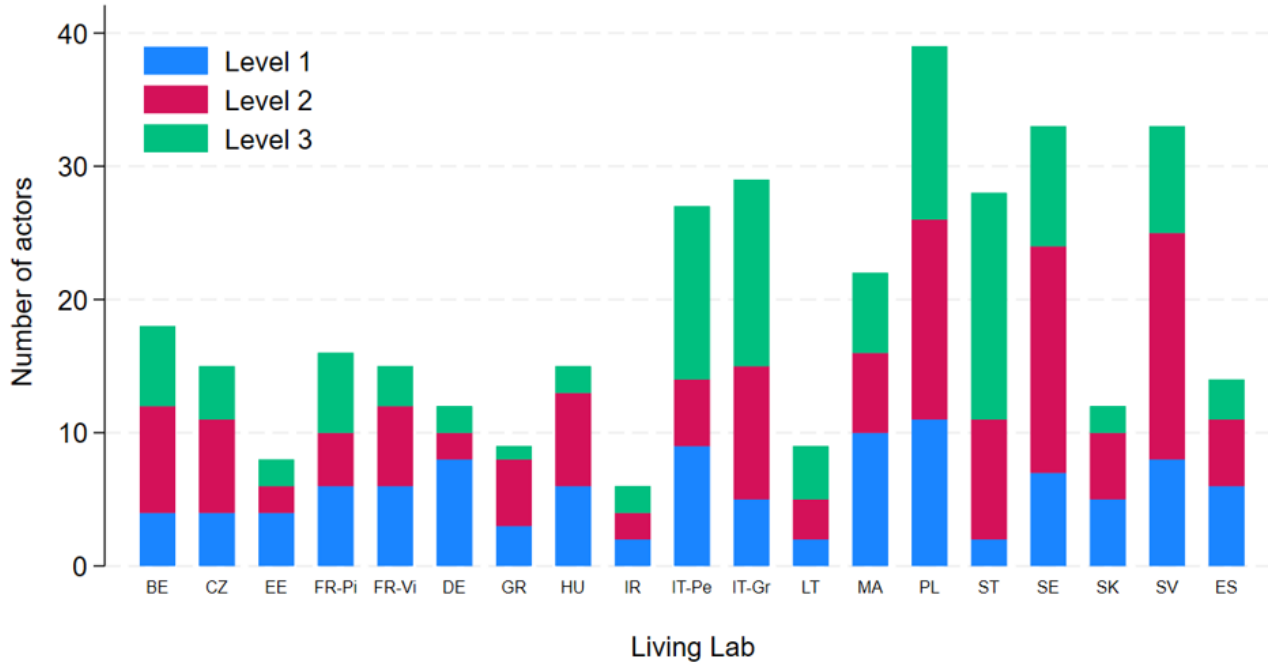

Figure 13. Presence of actors by LL according to the level of proximity to the Focal Action Situation.BE =Agrifood Technology (BE), CZ=Automation of Orchard Management (CZ); EE=Grassland Management(EE); FR-Pi=LIT Ouesterel Pigs (FR); FR-Vi=Occitanum Viti (FR); DE=AgDiBi(DE); GR=Spraying drones (GR); HU=Innovative Soil Scanner (HU);IR=Chloughjordan Food Hub (IR); IT-Pe=Pecorino Toscano DOP (IT); IT-Gr=Organic Table Grapes (IT); LT=Local Beef Cattle Farming (LT);MA=RAMAS (MA); PL=Liszki Basket Buyers Club (PL); ST=Scottish Small Farms and Digital Platforms (ST); SE=Greenhouse Smart Sensor Laboratory (SE); SK=Artificial Irrigation Management (SK); SV=Smart Villages Network (SV); ES=Almería Agroecology (ES)

The pattern observed in the individual LL is different when we look at the differences between the different groups of LLs described in section 4.2.1. Most of the actors actively participating in a LL are participating in i) LL with technologies already developed and tested (TRL 7 to 9), ii) LL with the objectives to increase productivity and/or efficiency and iii) LL located in pluralistic advisory service systems. A similar pattern is observed for those actors identified as potential collaborators, with a light increase in the LL which are working with IoT and UAV technologies (Table 7).

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Table 7. Number of actors by LL according to the level of proximity to the Focal Action Situation, in the different groups of LLs

	Actors in Level 1		Actors in Level 2		Actors in Level 3	
	Total	Average	Total	Average	Total	Average
Type of technology						
IoT and UAV (n=10)	77	7,7	117	11,7	50	5,0
Platforms (n=9)	77	8,6	70	7,8	67	7,4
TRL Level						
TRL 1-4 (n=3)	9	3,0	16	5,3	21	7,0
TRL 5-6 (n=3)	38	12,7	27	9,0	23	7,7
TRL 7-9 (n=13)	107	8,2	144	11,1	73	5,6
Objective of the LL						
Human/social capital (n=2)	12	6,0	15	7,5	19	9,5
Natural resources mgt (n=5)	35	7,0	38	7,6	11	2,2
Productivity/efficiency (n=7)	76	10,9	97	13,9	48	6,9
Value creation (n=5)	31	6,2	37	7,4	39	7,8
Type of national advisory service						
Firm-led (n=6)	49	8,2	61	10,2	41	6,8
Pluralistic (n=7)	54	7,7	71	10,1	41	5,9
Policy-driven (n=6)	51	8,5	55	9,2	35	5,8

4.2.2.2 Type of actors

Beyond the number of actors and their perceived distance to the FAS we aimed to know what type of actors are influencing the FAS. When counting the type of actors overall, we can observe that together with farmers, there is a large number of farmers and private actors in the LL in the three level of proximities. The analysis of the actor types as allocated to influencing levels shows some interesting patterns. Farmers and (private) IT actors are by far the most numerous in level one, which reflects that LLs are strongly marked by their presence. Five other actor types frequently observed at this level are private suppliers, researchers, educators, advisors and public authorities (in this order). Also on level 2, this same group of actor types (except educators) is more present than any other actor type.

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Among the private actors, we can identify agritech/developers, input providers, machinery providers, telecommunication/internet providers, private advisors, certification and audit bodies and finally those related with the general process of production and marketing: retailers and buyers. Those actors have different roles with respect to digitalisation: i) providers of technological innovations, or ii) users of digital technologies, iii) providers of information, data or knowledge generated in the production and commercialisation process. Bridging institutions for formal knowledge exchange were also mentioned frequently. For example, the presence of advisors is widely given, although varying according to the characteristics of the national AKIS structures. Other relevant institutions are networks (spaces for co-production) relevant for the interaction between actors and instrumental in facilitating collaborations (Figure 14).

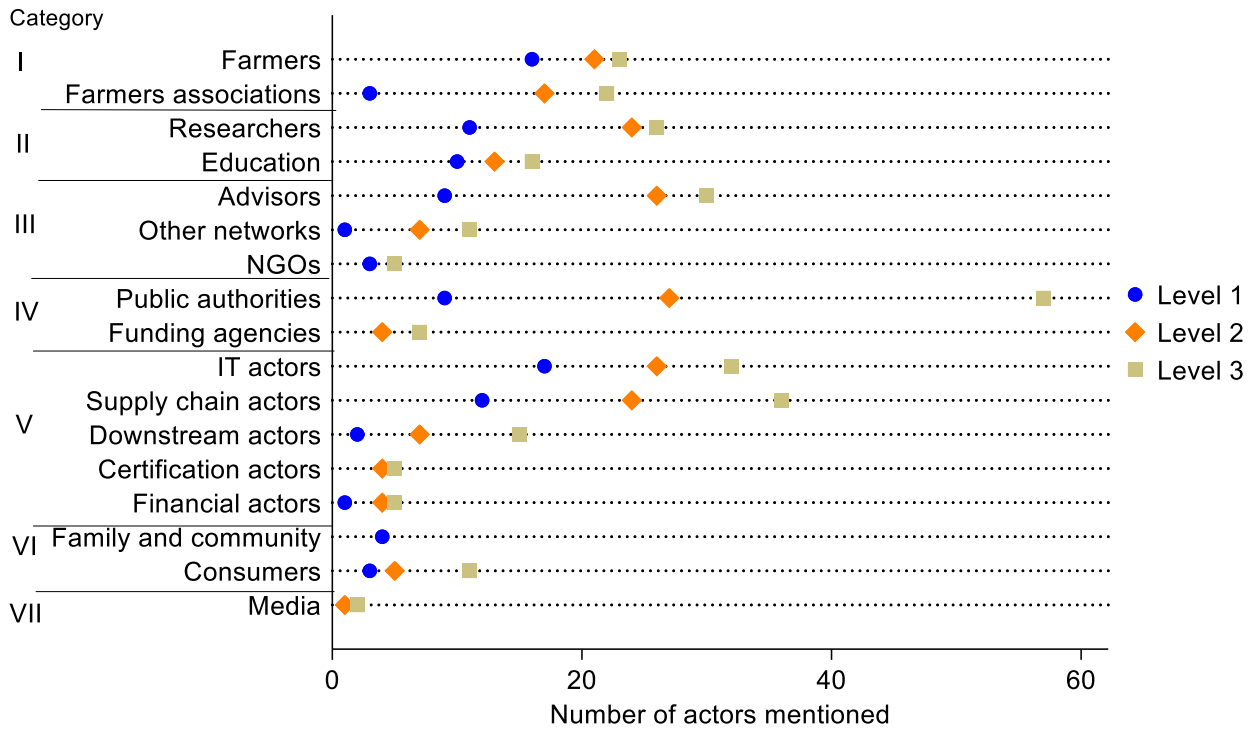

Figure 14. Distribution of actors by category and type according to the level of proximity to the Focal Action Situation

The nature and interaction of actors is highly contextual and difficult to classify due to the heterogeneity of action situations. When we compare the different groups of LLs, we can observe that there are differences in the average presence of actors in the different categories of LL. For example, LL that aim for productivity and efficiency have a higher average of farmers than the other ones. Farmers organisations are more represented on average in LLs developing platforms and in LL with the objective of improving natural resources management. The representation of research actors is higher in human and social oriented LLs while companies, similarly to farmers are more represented on average in productivity/efficiency seeking LLs (Table 8).

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Table 8. Average number of type of actors in the LL by groups of LLs

Actors	Type of technology			TRL Level			Objective of the LL			Type of national advisory system		
	IoT and UAV (n=10)	Platforms (n=9)	TRL 1-4 (n=3)	TRL 5-6 (n=3)	TRL 7-9 (n=13)	Human/social capital (n=2)	Natural resources mgt (n=5)	Productivity and efficiency (n=7)	Value creation (n=5)	Firm-led (n=6)	Pluralistic (n=7)	Policy-driven (n=6)
A.2.1 Farmers	1,8	1,1	0,7	2,0	1,5	1	1,2	2,3	0,8	1,2	1,3	2,0
A.2.2 Farmers associations, organisations	0	0,8	0,0	0,7	0,4	0	0,8	0,3	0,2	0,3	0,6	0,2
A.2.3 Research	0,9	0,7	0,3	1,0	0,8	1,5	0,6	0,9	0,6	0,7	1,0	0,7
A.2.4 Education	1	0,1	0,3	0,3	0,7	2	0,8	0,4	0	0,3	1,1	0,2
A.2.5 Advisors	0,7	0,7	0,0	1,0	0,8	0	0,6	1,1	0,4	0,7	0,9	0,5
A.2.6 Other LL, hubs, platforms, fairs, LAGS	0,1	0,1	0,0	0,0	0,2	0	0	0,1	0,2	0,0	0,1	0,2
A.2.7 NGOs	0	0,3	0,0	0,0	0,2	0	0	0,0	0,6	0,0	0,0	0,5
A.2.8 Public/authority	0,5	0,4	0,0	1,0	0,5	1	0,2	0,6	0,4	0,2	0,6	0,7
A.2.9 Funding institution	0	0,0	0,0	0,0	0,0	0	0	0,0	0	0,0	0,0	0,0
A.2.11 Companies IT	0,9	1,0	0,3	1,0	1,1	0	1	1,3	0,8	1,0	0,9	1,0
A.2.12 Companies (supply chain)	0,3	1,0	0,3	2,3	0,3	0	0,4	1,1	0,4	1,3	0,1	0,5
A.2.13 Companies (downstream)	0,2	0,0	0,0	0,0	0,2	0	0,2	0,0	0,2	0,2	0,1	0,0
A.2.14 Certification/audit bodies	0	0,0	0,0	0,0	0,0	0	0	0,0	0	0,0	0,0	0,0

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Actors	Type of technology			TRL Level			Objective of the LL			Type of national advisory system		
	IoT and UAV (n=10)	Platforms (n=9)	TRL 1-4 (n=3)	TRL 5-6 (n=3)	TRL 7-9 (n=13)	Human/social capital (n=2)	Natural resources mgt (n=5)	Productivity and efficiency (n=7)	Value creation (n=5)	Firm-led (n=6)	Pluralistic (n=7)	Policy-driven (n=6)
A.2.15 Financial/investment institutions	0	0,1	0,0	0,0	0,1	0	0	0,0	0,2	0,0	0,0	0,2
A.2.16 Family, friends and neighbours	0,2	0,2	0,7	0,0	0,2	1	0	0,3	0	0,0	0,3	0,3
A.2.17 Consumers	0,2	0,1	0,0	0,0	0,2	0	0	0,1	0,4	0,2	0,0	0,3
A.2.18 Media	0	0,0	0,0	0,0	0,0	0	0	0,0	0	0,0	0,0	0,0

The configuration of actors is different according to the groups of LLs. To answer the question on which extent the objective, the type of technology, the technological readiness of the technology and the AKIS system influences the composition of actors and the support they receive, we compare the configuration of actors in the different groups of LLs, at Level 1 (actors in the LL).

4.2.2.3 Pluralism and innovation support functions

Pluralism is understood as the organisational variety that originates from the taking place between the various organisations and interests' groups within a democratic society (Knierim et al 2017). To have a measure that indicate pluralism we use two indicators: i) number of type of actors in the LL; ii) relative shares of AKIS related actors: farmers as end users, research, advisory services and IT enterprises (Table 9).

Table 9. Pluralism indicators of actors according to groups of LLs (average per group)

	Number of type of actors	% of farmers on the total amount of actors (user involvement in the LL)	% research actors in the LL	% of advisory services in LL	% IT enterprises in LL	% other actors
Type of technology						
IoT and UAV (n=10)	4,60	24,6	13,9	9,3	14,6	37,5
Platforms (n=9)	4,56	13,6	7,3	7,3	12,9	58,9

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	Number of type of actors	% of farmers on the total amount of actors (user involvement in the LL)	% research actors in the LL	% of advisory services in LL	% IT enterprises in LL	% other actors
TRL Level						
TRL 1-4 (n=3)	2,33	23,3	6,7	0,0	6,7	63,3
TRL 5-6 (n=3)	5,67	17,0	5,9	6,3	5,9	64,8
TRL 7-9 (n=13)	4,85	17,1	10,1	8,7	12,3	51,7
Objective of the LL						
Human/social capital (n=2)	2,5	10,0	15,0	0,0	0,0	75,0
Natural resources mgt (n=5)	4,8	19,3	9,8	7,8	13,8	49,2
Productivity and efficiency (n=7)	5,1	20,9	7,8	9,8	11,7	49,8
Value creation (n=5)	4,4	16,2	7,1	4,9	9,3	62,5
Type of national advisory service						
Firm-led (n=6)	4,83	13,9	9,0	6,3	12,4	58,4
Pluralistic (n=7)	4,29	16,2	10,5	10,2	9,6	53,5
Policy-driven (n=6)	4,67	24,5	6,9	3,9	9,4	55,3

The average number of type of actors varies between 2.33 corresponding to LL working with human and social capital and 5.67 which are LL with a TRL level from 5-6. The relative presence of farmers is higher in LL working with IoT and UAV technologies, LL in lowest TRL, LL working towards increase productivity and LL located in a country with policy-driven advisory services. An important observation is that in all types of LLs, the highest share of actors consists of those that are not part of the traditional “knowledge transfer” researcher-advisory-farmer axis.

This constellation can be further specified by type of grouping. For example, LL working with platforms, presents a diversified number of actors given the larger presence of supply chain actors and farmers associations (Figure 15).

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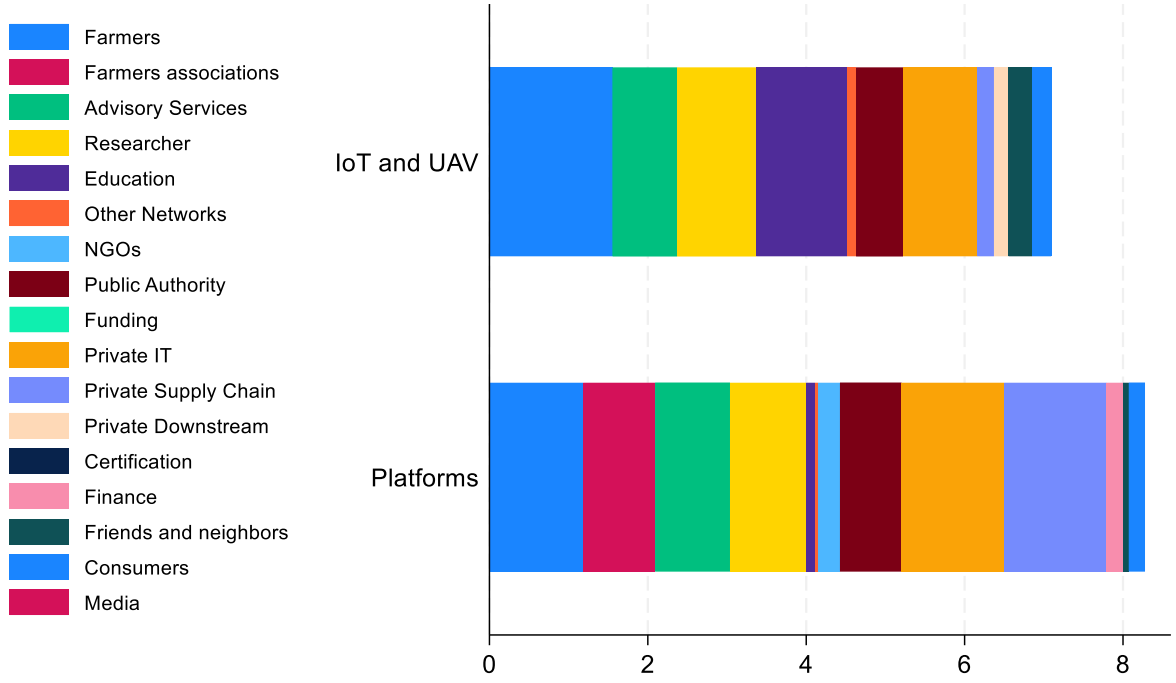

Figure 15. Average composition of actors belonging to each group of LL by type of technology

Productivity aiming LL has a larger total number of actors and a lager diversification of functions. Human and social capital has the fewer presence of farmers and IT companies with a strong presence of researchers, educational actors and community and friends. In LL aiming for natural resource management, farmers association have a larger influence. Value creation-oriented LLs have a higher presence of NGOs, compared to the rest of groups (Figure 16).

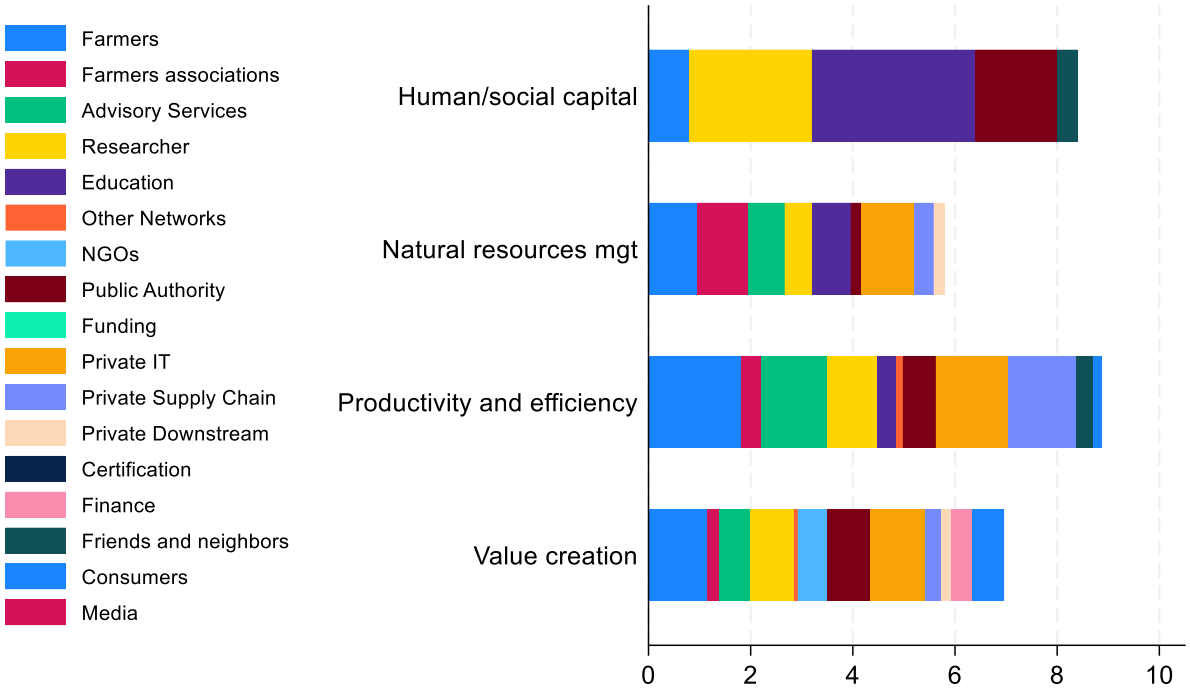

Figure 16. Average composition of actors belonging to each group of LL by objective of the LL

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Despite most of the LL are working with technologies classified from 7 to 9, which implies digital technologies that are ready to be disseminated, LLs working with technologies in pilot or prototype stage have on average a larger variety of actors expressed in the number of farmers, supply chain actors, public authorities and researchers. LLs working on a conceptual phase before proof of concept have on average a limited participation of actors mostly farmers, their neighbours and researchers (Figure 17).

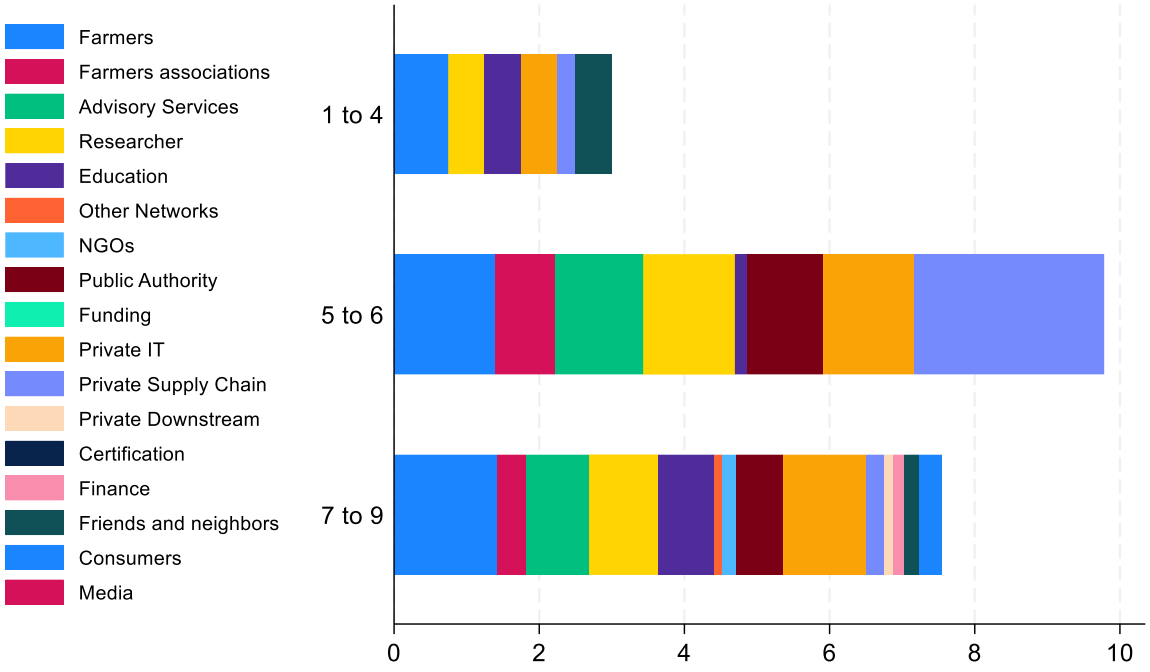

Figure 17. Average composition of actors belonging to each group of LL by technology readiness level

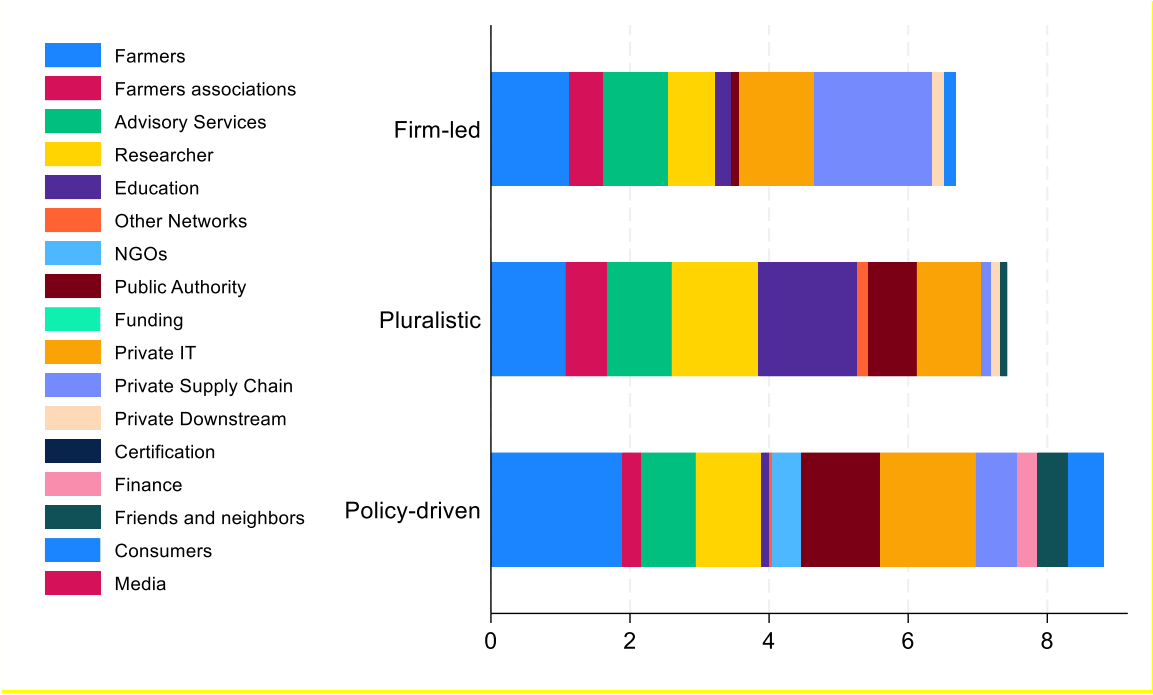

Figure 18. Average composition of actors belonging to each group of LLs by type of advisory service system where they are located

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With respect to the national advisory service system, LLs located in firm-led national advisory services present on average a higher presence of supply chain actors and IT companies with very limited presence of public authorities. LLs located in countries with pluralistic advisory services presents a more balanced presence of different type of actors with a relatively higher presence of educational actors and a low presence of supply chain actors. LLs located in countries with predominant policy-driven advisory services are characterized by a large number of farmers, public authorities, less researchers compared to the other groups and the presence of consumers (Figure 18 above).

4.2.3 Governance

In this section we explore the AKIS related coordination mechanisms mentioned by the LLs. We present the results in two sections considering the classification levels of those governance mechanisms presented in the methodology part. The first sections include governance mechanisms of knowledge flow determined outside the region or local community. The second section includes those coordination mechanisms affecting knowledge flow at the local level. As indicators we use the salience of mechanisms mentioned by the LLs.

4.2.3.1 Governance mechanisms (national and market)

We structured governance mechanisms in view of the knowledge flows that are affected by them, as we are interested to know how those mechanisms affect or are affected by the exchange of data, information or knowledge. We identified that for most of the LLs, national policies and regulations and market derived guidelines are the most frequent governance mechanisms mentioned. On a second place, European level policies and regulations were frequently mentioned. For specific LLs other type of guidelines, for example education related ones, are more relevant. Finally, there was group of LLs which mentioned the general global macro-trend as important factor which influences the work they are doing in the Living Lab (Table 10).

Table 10. Categories, subcategories and description of codes in Governance Subsystem

	Global macro-trends	EU level public policies and regulations	Public policies and regulations	Private companies and market rules	Education related guidelines
Type of technology					
IoT and UAV (n=10)	0,2	1,5	3,3	1,2	0,5
Platforms (n=9)	0,3	0,8	2,2	1,8	0
TRL Level					
TRL 1-4 (n=3)	0	0,3	1,7	1,3	0
TRL 5-6 (n=3)	1	1,7	4,3	1,7	0
TRL 7-9 (n=13)	0,2	1,2	2,7	1,5	0,4
Objective of the LL					
Human/social capital (n=2)	0	1	3	1,5	1,5
Natural resources mgt (n=5)	0	1,2	1,2	1,6	0
Productivity and efficiency (n=7)	0,7	1,6	4,7	1	0,3

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	Global macro-trends	EU level public policies and regulations	Public policies and regulations	Private companies and market rules	Education related guidelines
Value creation (n=5)	0	0,6	1,6	2	0
Type of national advisory service					
Firm-led (n=6)	0,2	1,8	2,7	2,3	0
Pluralistic (n=7)	0,1	0,7	2,9	0,9	0,7
Policy-driven (n=6)	0,5	1	2,8	1,3	0

The comparison between groups of LLs shows differences in those general numbers. National public regulations are the most mentioned coordination mechanisms influencing the FAS for all the groups. With respect to national public regulations, a larger number of regulations are influencing those LLs working with technologies that aim to increase productivity and efficiency. The number of regulations it is also higher in LLs working with IoT and UAV technologies, and in technologies that are on prototype development phase. Apparently, there are not many differences in the number of regulations according to the type of predominant advisory services.

Market based guidelines and requirements are also prominent and shows a different pattern, with higher presence in those LLs working with platforms and those LL aiming to create value to primary agricultural production. Market requirements were also more mentioned in the LLs located in countries where advisory services are firm-led.

Other coordination mechanisms (global macrotrends or education guidelines) mentioned were dependant on the specific objective of the LL.

4.2.3.2 Governance mechanisms (local and regional level)

Local or regional coordination mechanisms were mentioned by the LLs to a less numerous extents. Most of the LLs, on average mentioned those rules less than one time. LLs working with platforms, value creation or those staring to conceptualise their idea in which they are working, mentioned this type of coordination more frequently (Table 11).

Table 11. Categories, subcategories and description of codes in Governance Subsystem

	Networks rules	Local associations norms	Social rules or norms	Farming objectives incentives expectations
Type of technology				
IoT and UAV (n=10)	0,3	0,6	0,2	0,4
Platforms (n=9)	0,9	0,8	0,0	0,0
TRL Level				
TRL 1-4 (n=3)	1,3	1,0	0,3	0,0

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	Networks rules	Local associations norms	Social rules or norms	Farming objectives incentives expectations
TRL 5-6 (n=3)	0,0	1,0	0,0	0,3
TRL 7-9 (n=13)	0,5	0,5	0,1	0,2
Objective of the LL				
Human/social capital (n=2)	0,0	0,5	0,0	0,0
Natural resources mgt (n=5)	0,4	0,4	0,2	0,4
Productivity and efficiency (n=7)	0,1	0,7	0,1	0,3
Value creation (n=5)	1,6	1,0	0,0	0,0
Type of national advisory service				
Firm-led (n=6)	0,0	0,5	0,0	0,5
Pluralistic (n=7)	0,6	0,9	0,1	0,1
Policy-driven (n=6)	1,2	0,7	0,2	0,0

National public policies and regulations emerge as the most frequently cited governance mechanisms across LLs, particularly those focused on productivity and efficiency, IoT and UAV technologies, and prototype-stage innovations (TRL 1–6). This suggests that regulatory environments act as strong drivers or barriers to innovation, especially in technology-intensive and early-stage projects. The higher frequency of regulations in LLs working with platforms and value creation indicates that market-oriented objectives are closely tied to compliance with formal rules.

Market-based guidelines and private company rules are also prominent, especially in LLs aiming at value creation and those located in countries with firm-led advisory services. This reflects a strong market pull in shaping innovation trajectories, where knowledge flows are increasingly directed toward commercialization and supply chain integration. The alignment between advisory service models (e.g., firm-led) and market-driven governance suggests a system where private sector interests heavily influence knowledge exchange and innovation priorities.

The findings show that knowledge flows in AKIS are determined by the presence of actors and technologies, and strongly by the alignment between governance mechanisms and innovation objectives. While national and market-level policies provide structure and direction, local governance mechanisms enable trust and co-creation, particularly in early-stage or socially oriented LLs.

4.3 Comparison of farm digital readiness, scaling readiness and digital ecosystem conduciveness

This section presents the results of the comparative assessment described in Section 3.3, which derives from the results of Task 3.2, *Mapping the Socio-Ecological Context*. The analysis is organised according to the three assessment domains: farm digital readiness, scaling readiness and digital ecosystem conduciveness. For each domain, the results are first examined descriptively at indicator dimension level and subsequently compared across clusters of LLs sharing relevant characteristics.

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4.3.1 Scaling readiness

Scaling readiness was assessed through seven indicators organised into four indicator dimensions: technology usefulness, technology ease of use, technological maturity and adoption feasibility.

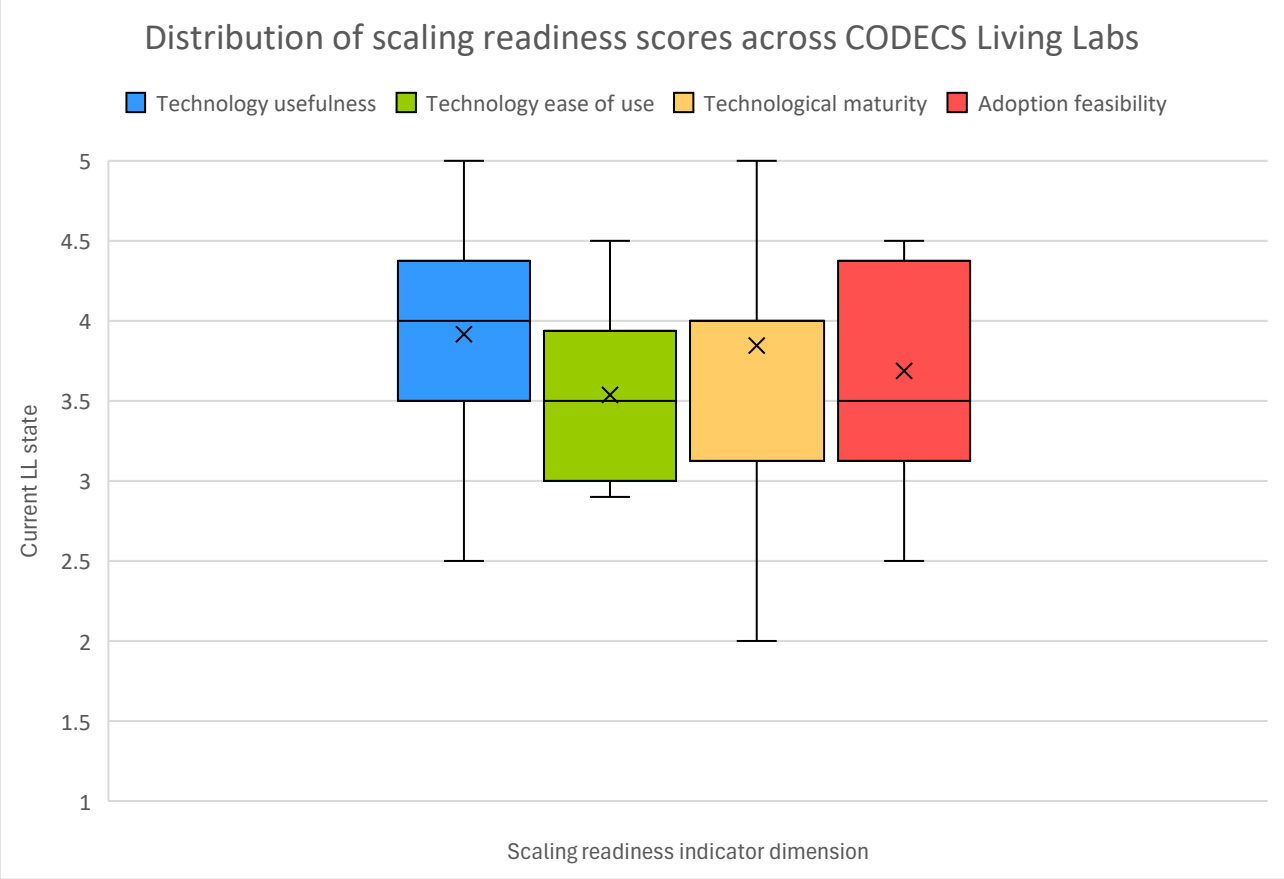

Figure 19. Distribution of scaling readiness dimensions across CODECS LLs. The boxplots represent the scores per indicator dimension calculated as the arithmetic mean of the applicable indicators for each LL. The horizontal line within each box indicates the median, while the cross (x) represents the mean. Each box contains the 50% of the observations and the whiskers (extended lines) show the range of non-outlying values Scores range from 1 (very poor) to 5 (very good)

Figure 19 illustrates the distribution of the scores across the analysed LLs for the four scaling readiness dimensions. Overall, the results indicate a general favourable assessment as the mean scores of all four indicator dimensions exceed 3.50, placing them between acceptable and good. No observations are clearly separated from the whiskers and, therefore, no pronounced outliers are observed. This means that the differences between cases appear to be part of the general variability of the sample and are not caused by exceptionally extreme cases. Overall, it is to be highlighted that:

1. Technology usefulness received the highest average score (mean = 3.92; median = 4.00), indicating that it constitutes the main strength among the indicator dimensions analysed. Half of the LL scores fall approximately between 3.50 and 4.40, while the whiskers extend from 2.50 to 5.00. The proximity of the mean and median suggests a balanced distribution, without significant influence from extreme values. In general terms, participants consider that digital solutions add value and can contribute to improve production or management processes.
2. Technology ease of use received the lowest average score among the four indicator dimensions (mean = 3.54; median = 3.50). Scores are concentrated within a narrow interval, predominantly between 3.00 and

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4.00. The range is relatively narrow, which is consistent with its lower standard deviation and the similarity between the mean and median reflects a balanced distribution. This suggests that ease of use is generally assessed as acceptable to good across the LLs but remains an area with room for improvement. Usability may become a relevant constraint when digital solutions require specialised training, technical support or substantial changes to existing work routines.

3. Technological maturity also obtained a positive score (mean = 3.84; median = 4.00) but displayed the greatest variation across LLs. The whiskers cover the full observed interval from 2.00 to 5.00. This suggests that the current LL state attributed to considerations related to maturity differs substantially depending on the technological solutions and contexts represented in the project. The broad distribution makes it advisable to examine this indicator dimension in greater detail across technology and sector clusters.
4. Adoption feasibility obtained an intermediate average score (mean = 3.69; median = 3.50) and also showed a relatively broad distribution across cases. Half of the scores fall approximately between 3.10 and 4.40, while the whiskers extend from 2.50 to 4.50. The mean is slightly higher than the median which indicates that some high scores slightly raise the average. Adoption is therefore assessed as feasible, but not uniformly across the analysed LLs. The results suggest that the usefulness and maturity of a digital technology do not automatically guarantee its wider uptake. Practical constraints may remain in relation to costs, access to financing, infrastructure, interoperability with existing systems or the skills required to use the technologies.

Taken together, the results indicate that the scaling readiness of the technologies assessed within the CODECS LLs is generally positive. Technology usefulness emerges as the main strength, while technology ease of use presents the biggest room for improvement. The variation observed in technological maturity and adoption feasibility highlights the importance of examining how scaling conditions differ across technology and sector clusters.

4.3.1.1 Scaling readiness by technology cluster

Technology usefulness obtained high scores in both clusters. Platforms reached a slightly higher average score (mean = 4.00) than IoT and UAVs (mean = 3.85), although both clusters have the same median score of 4.00. This suggests that the digital solutions represented in both groups are generally assessed as useful and capable of contributing to the optimisation of agricultural activities or management and operational processes (see Figure 20).

The difference in technology ease of use is also limited. IoT and UAVs obtained a mean score of 3.58, compared with 3.49 for Platforms. Both scores remain between acceptable and good, indicating that usability conditions are assessed positively in both clusters. Nevertheless, the slightly lower score and higher dispersion observed in Platforms suggest that platform solutions may still face some usability challenges, potentially related to interfaces, data management or integration into existing work routines.

The most pronounced difference concerns technological maturity. IoT and UAVs obtained a substantially higher mean score (mean = 4.35) than Platforms (mean = 3.21). This indicates that the IoT and UAV solutions included in the analysed LLs are generally assessed as being at a more advanced stage of development, validation or implementation. By contrast, the platforms represented in the project may require further consolidation, adaptation or integration before scaling can be achieved.

Adoption feasibility shows very similar scores in both clusters, with Platforms obtaining a slightly higher average score (mean = 3.73) than IoT and UAVs (mean = 3.65). This is a relevant finding, as it suggests that a higher level of technological maturity does not automatically translate into better conditions for adoption. Even where technologies are assessed as mature, wider factors such as affordability, adaptability, infrastructure, user skills and organisational conditions may still influence their scaling potential.

Results indicate that the main difference between the two technology clusters lies in technological maturity, where IoT and UAVs display a clearly more favourable profile. In contrast, technology usefulness, ease of use and adoption feasibility are similar between clusters. Platforms show slightly higher scores in usefulness and adoption feasibility, while IoT and UAVs perform slightly better in ease of use and substantially better in maturity. These descriptive patterns suggest that scaling strategies should not focus only on the technical maturity of digital solutions, but also on the external conditions that support their practical adoption.

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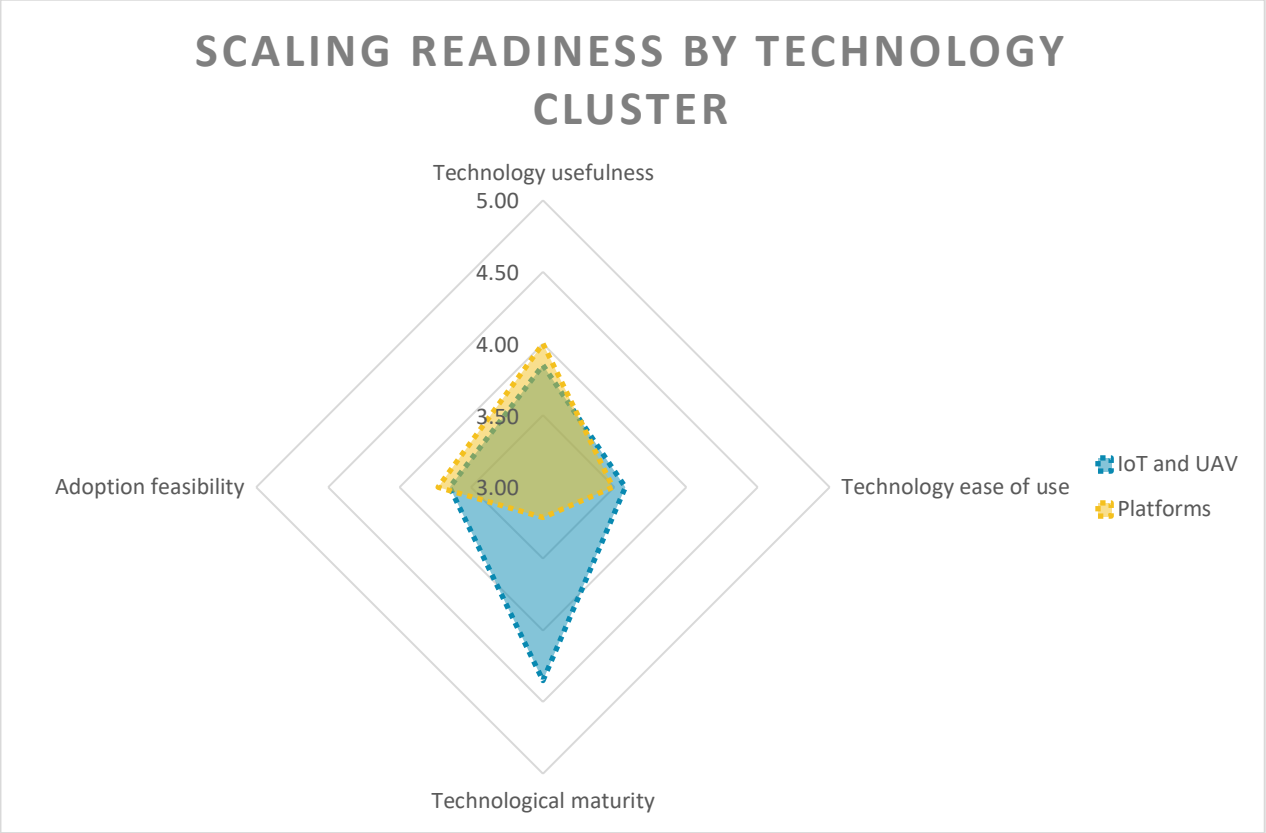

Figure 20. Scaling readiness profiles by technology cluster. The radar chart compares the mean scores obtained by the IoT and UAVs and Platforms clusters across the four scaling readiness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). For visual clarity, the radial axis is displayed from 3.00 to 5.00 in order to make differences between clusters easier to observe. The results should be interpreted cautiously, as the clusters contain different numbers of valid LLs

4.3.1.2 Scaling readiness by sector cluster

The Livestock cluster presents the most positive profile in three of the four indicator dimensions (see Figure 21). It obtained the highest average score for technology usefulness (mean = 4.50), indicating that the digital solutions represented in these LLs are perceived as particularly valuable for addressing sector-specific needs and improving production or management processes. Livestock also achieved the highest scores for technology ease of use (mean = 4.17) and adoption feasibility (mean = 4.00). These results suggest that the technologies assessed within the livestock related LLs are not only considered useful but are also viewed as accessible and feasible to adopt.

Within the Crop and Grassland cluster the most prominent strength is technological maturity (mean = 4.10), for which it obtained the highest score among the three clusters. The remaining indicator dimensions also received largely positive assessments: technology usefulness reached a mean score of 3.79, adoption feasibility 3.65 and technology ease of use 3.51. This suggests that the digital solutions included in this cluster are generally perceived as relatively mature and suitable for implementation, although usability and adoption-related conditions may still require attention in some contexts.

The Marketing cluster presents a more uneven profile. Its score for technology usefulness is promising (mean = 3.83). However, lower scores are observed for technology ease of use (mean = 3.00) and technological maturity (mean = 3.00), both of which remain at an acceptable level. Adoption feasibility received an intermediate score (mean = 3.50). This suggests that marketing-oriented digital solutions may be perceived as useful while still requiring further consolidation, improved usability or adaptation to the practical needs of end users.

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The sectoral comparison indicates that scaling readiness does not follow a single pattern across agricultural contexts. The Livestock cluster shows a comparatively advantageous profile in usefulness, ease of use and adoption feasibility, whereas Crop and Grassland cluster stands out for technological maturity. Solutions related to Marketing appear useful but show more potential for improvement in maturity and usability. These patterns reinforce the importance of considering sector-specific conditions when designing strategies for the broader uptake of digital technologies.

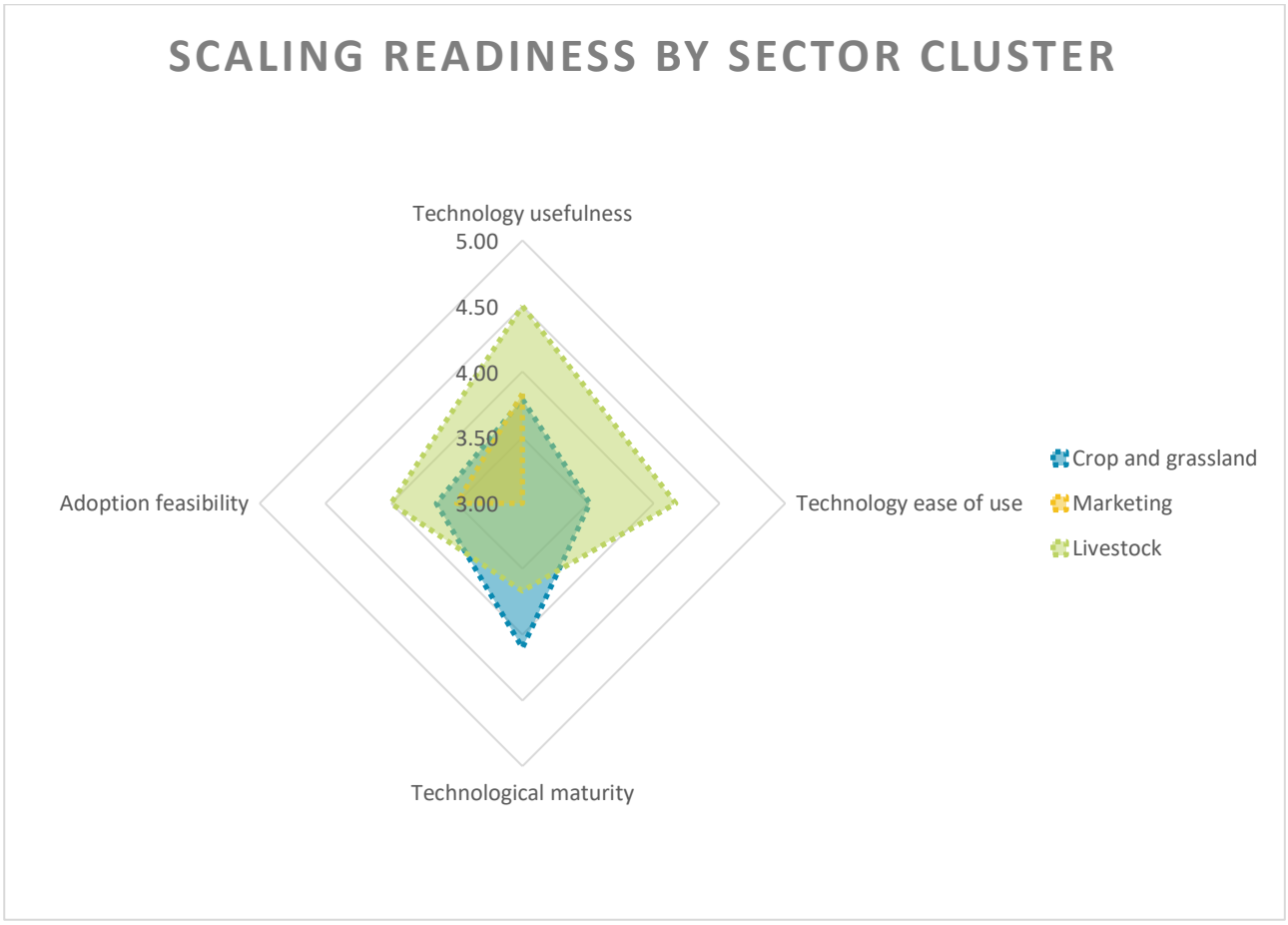

Figure 21. Scaling readiness profiles by sector cluster. The radar chart compares the mean scores obtained by the Crop and Grassland, Marketing and Livestock clusters across the four scaling readiness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). For visual clarity, the radial axis is displayed from 3.00 to 5.00 in order to make differences between clusters easier to observe. The results should be interpreted cautiously, as the clusters contain different numbers of valid LLs

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4.3.2 Farm digital readiness

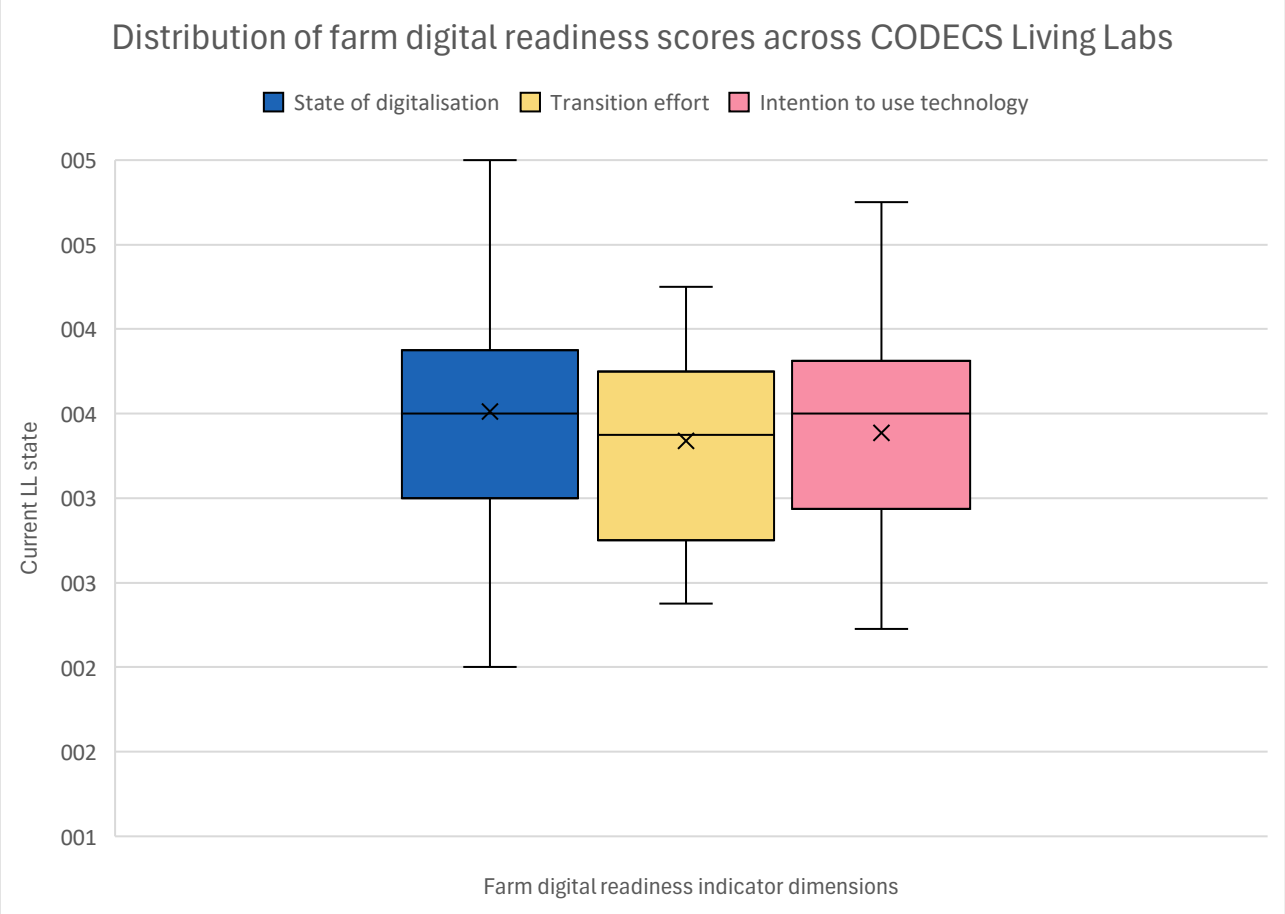

Figure 22. Distribution of farm digital readiness indicator dimensions across CODECS LLs. The boxplots represent the dimension scores calculated as the arithmetic mean of the applicable indicators for each LL. The horizontal line within each box indicates the median, while the cross (x) represents the mean. Each box contains the 50% of the observations and the whiskers (extended lines) show the range of non-outlying values. Scores range from 1 (very poor) to 5 (very good)

Figure 22 illustrates the distribution of the scores obtained across the analysed LLs for the three farm digital readiness indicator dimensions: state of digitalisation, transition effort and intention to use technology. On the whole, the three dimensions received average scores between acceptable and good. Their distributions overlap considerably, indicating that no single indicator dimension presents a different general pattern across the LLs. No outliers are observed. Overall, it is to be highlighted that:

- State of digitalisation obtained the highest average score (mean = 3.51; median = 3.50). Half of the LL scores fall approximately between 3.00 and 3.90, while the whiskers extend from 2.00 to 5.00. This broad range indicates that the integration of digital technologies into everyday farming practices and the availability of farmers' digital skills vary across the LLs.
- Transition effort received the lowest average score (mean = 3.34; median = 3.38), although it also displayed the narrowest distribution. Half of the scores fall approximately between 2.75 and 3.75, while the whiskers extend from 2.38 to 4.25. This suggests that the conditions required to move from the current situation towards a more digitalised state are generally assessed as acceptable, but still present room for improvement across a considerable number of LLs. These conditions include the time available to test and

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implement digital tools, the effort required to complete the transition and farmers' awareness of available technological options.

- Intention to use technology obtained an intermediate average score (mean = 3.39; median = 3.50) and showed a relatively wide distribution across cases. Half of the scores fall approximately between 2.90 and 3.80, while the whiskers extend from 2.23 to 4.75. The slightly lower mean than median suggests that some low scores reduce the overall average. This indicates that willingness to adopt or continue using digital technologies is acceptable to good but is not uniform across the analysed LLs. Differences may be related to farmers' engagement, willingness to innovate and ability to analyse, interpret and integrate digital knowledge.

In conclusion, the results suggest that farm digital readiness is assessed as moderate to favourable across the CODECS LLs. The state of digitalisation constitutes the strongest indicator dimension, although its extended range highlights heterogeneity between contexts. In contrast, the variation and lowest score in transition effort and intention to use technology indicate that farmers' engagement and capabilities remain important considerations in digital adoption.

4.3.2.1 Farm digital readiness by technological cluster

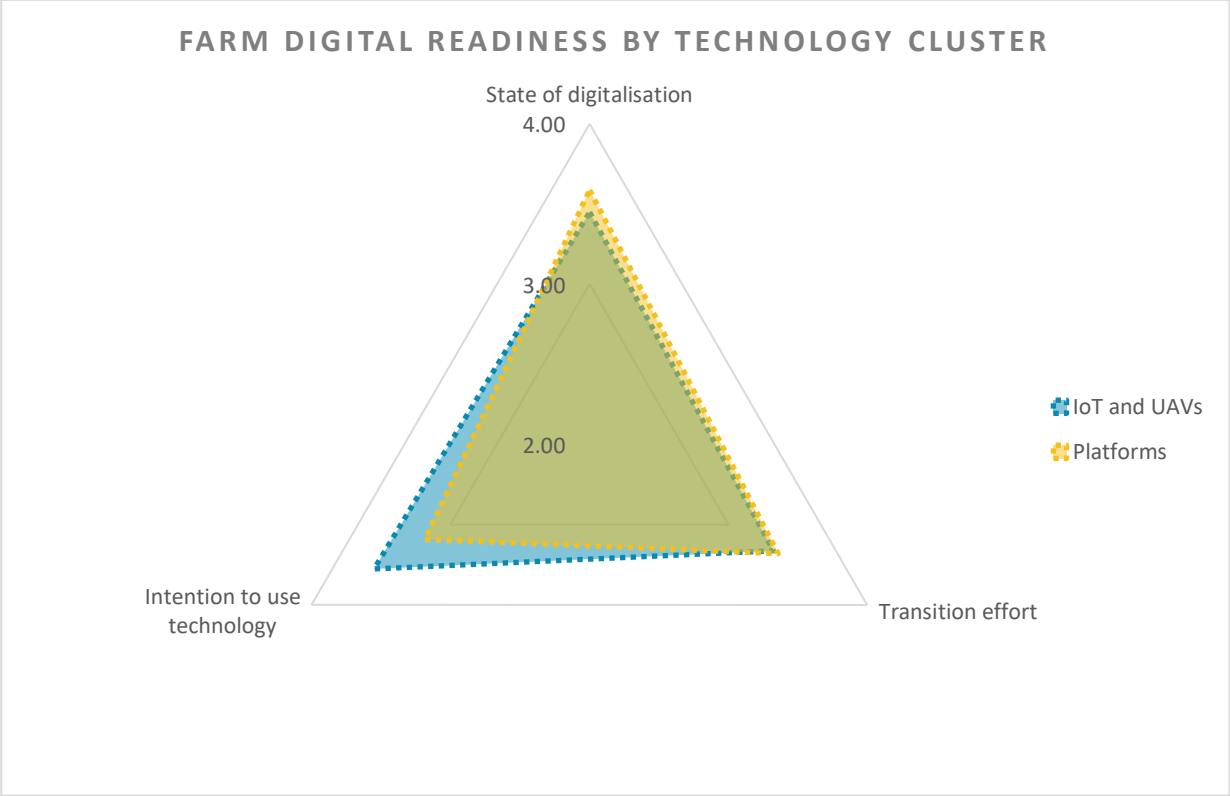

Figure 23. Farm digital readiness profiles by technology cluster. The radar chart compares the mean scores obtained by the IoT and UAVs and Platforms clusters across the three farm digital readiness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). For visual clarity, the radial axis is displayed from 2.00 to 4.00 in order to make differences between clusters easier to observe. The results should be interpreted cautiously, as the clusters contain different numbers of valid LLs

For state of digitalisation, Platforms obtained a slightly higher average score (mean = 3.59) than IoT and UAVs (mean = 3.45) (see Figure 23). This indicates that the integration of digital technologies into everyday farming practices and the availability of farmers' digital skills are assessed somewhat more favourably in the LLs categorised under platforms. However, the difference is limited, and both clusters remain close to the same overall level.

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The smallest difference is observed in transition effort. Platforms reached a mean score of 3.36, while IoT and UAVs obtained 3.33. These almost identical values suggest that the conditions required to move towards a more digitalised state are assessed similarly in both clusters. In both cases, the scores remain close to acceptable, indicating that factors such as the time available to learn, test and implement digital solutions, the resources required for the transition and farmers' awareness of technological options may continue to influence the digitalisation process and transition aspects still require attention regardless of the type of technology considered.

The clearest difference appears in intention to use technology. IoT and UAVs obtained a higher average score (mean = 3.55) than Platforms (mean = 3.18). This suggests that farmers' willingness, engagement and capacity to adopt or continue using digital technologies may be more favourable in the IoT and UAVs cluster. Platform solutions may face additional challenges related to user engagement, perceived practical value, data interpretation or the integration of digital information into everyday decision-making.

The two technology clusters show comparable levels of farm digital readiness. Platforms show slightly higher scores in the current state of digitalisation and transition effort, whereas IoT and UAVs present a more promising profile in intention to use technology. The main difference is therefore not related to the current integration of digital tools, but rather to the willingness and capacity to adopt or continue using them. These results suggest that strategies to support farm digital readiness should pay particular attention to user engagement and practical adoption conditions.

4.3.2.2 Farm digital readiness by sector cluster

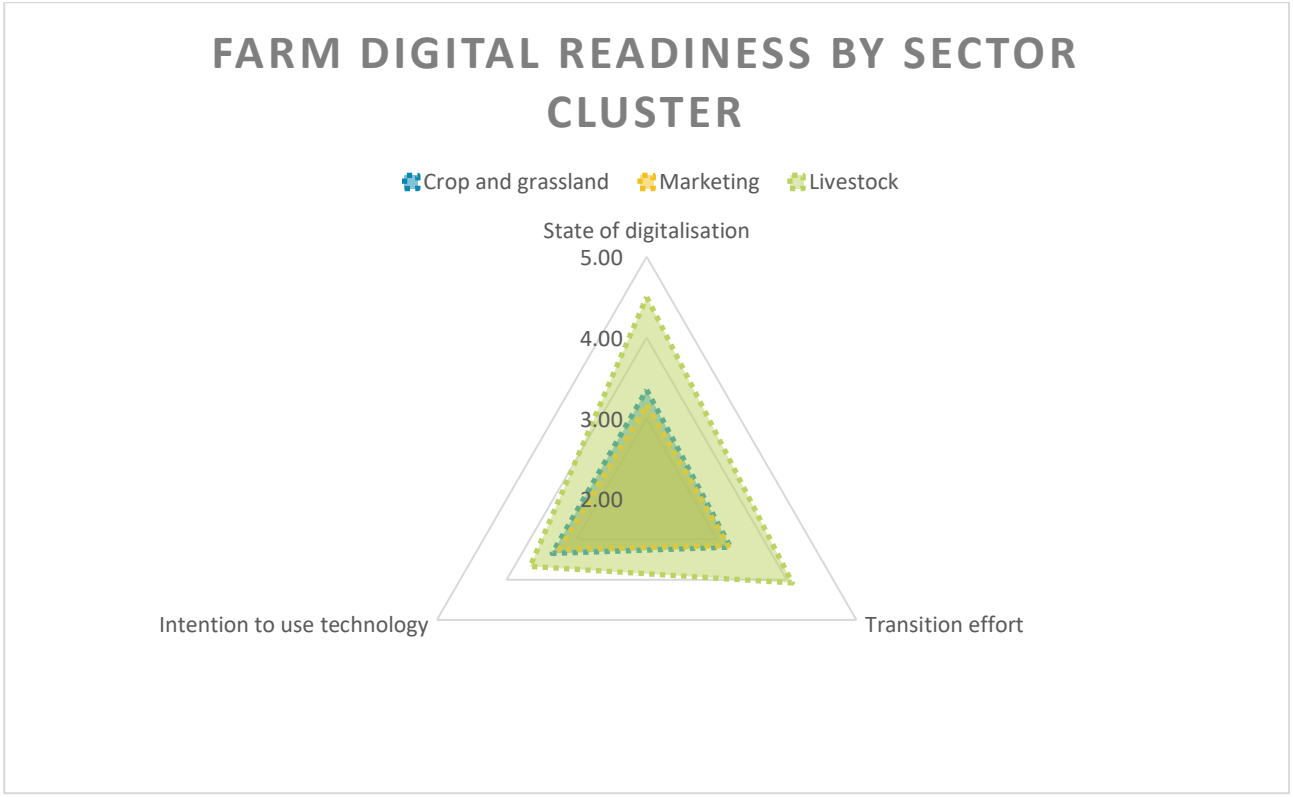

Figure 24. Farm digital readiness profiles by sector cluster. The radar chart compares the mean scores obtained by the Crop and Grassland, Marketing and Livestock clusters across the three farm digital readiness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). For visual clarity, the radial axis is displayed from 2.00 to 5.00 in order to make differences between clusters easier to observe. The results should be interpreted cautiously, as the clusters contain different numbers of valid LLs

The Livestock cluster presents the most favourable profile across the three indicator dimensions. It obtained a particularly high average score for state of digitalisation (mean = 4.50), indicating that the integration of digital technologies into everyday farming practices and the availability of farmers' digital skills are assessed positively

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within the Livestock LLs (see Figure 24). The cluster also received a positive score for transition effort (mean = 4.08), suggesting advantageous conditions for progressing towards further digitalisation. Its score for intention to use technology is also positive, although slightly lower (mean = 3.67).

The Crop and Grassland cluster presents a balanced profile, with average scores situated between acceptable and good. State of digitalisation and intention to use technology received almost identical scores (mean = 3.35 in both cases), while transition effort obtained a slightly lower score (mean = 3.20). This suggests that the cluster has reached an intermediate level of farm digital readiness, but that the conditions required to support the transition towards greater digitalisation may still require attention in some contexts.

The Marketing cluster also displays a relatively balanced profile, although its scores are lower overall. State of digitalisation and transition effort both obtained an average score of 3.17, while intention to use technology reached 3.25. These values remain close to the acceptable level. The results suggest that Marketing LLs may face challenges in consolidating the integration of digital solutions into everyday practices and in strengthening the conditions that support further digitalisation.

The sectoral comparison indicates that LLs under the Livestock cluster display a good profile, particularly in relation to their current state of digitalisation and transition conditions. Crop and Grassland and Marketing show more moderate scores, with transition effort emerging as an area that may merit further attention.

4.3.3 Digital ecosystem conduciveness

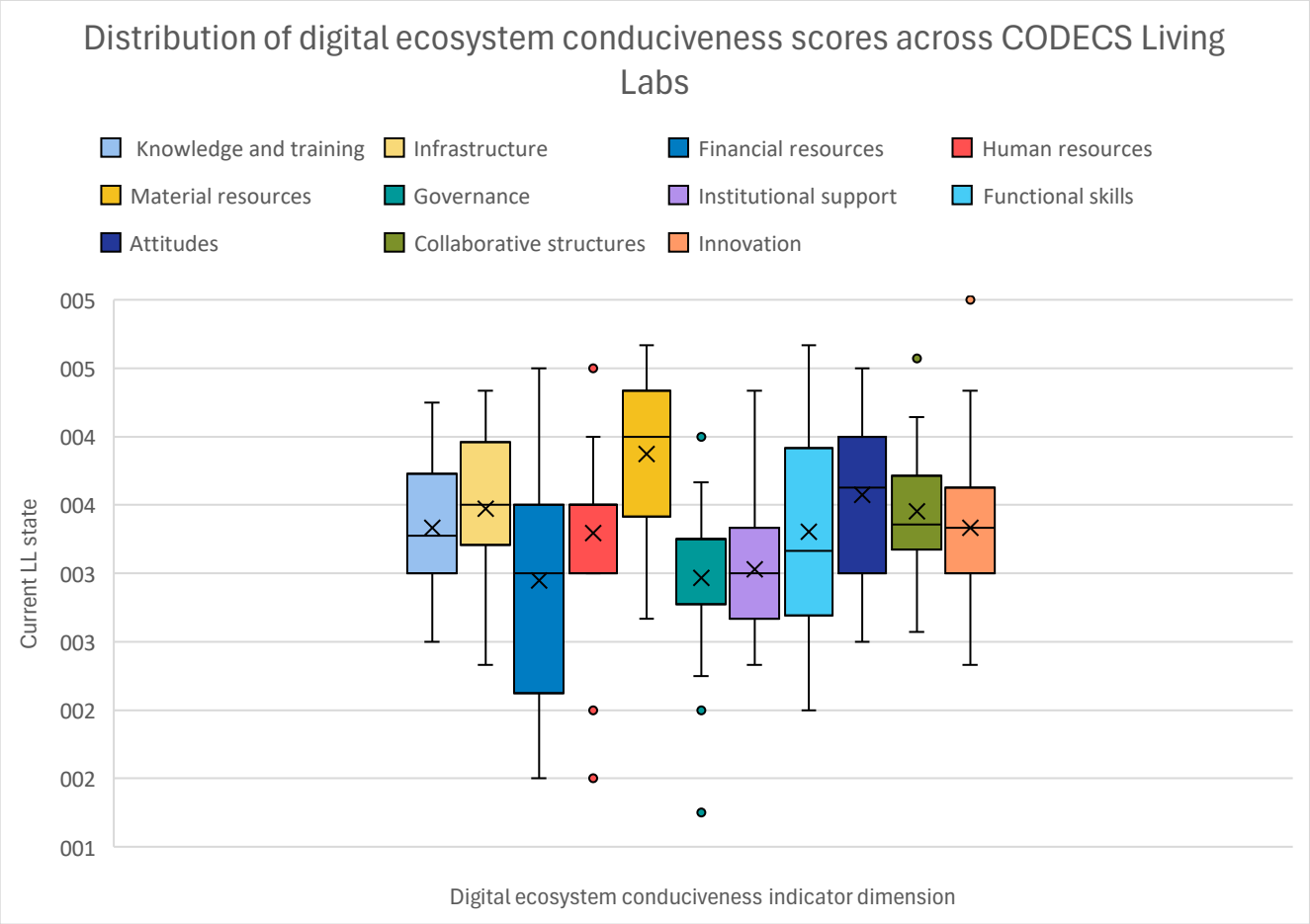

Figure 25. Distribution of Digital ecosystem conduciveness indicator dimension across CODECS LLs. The boxplots represent the dimension scores calculated as the arithmetic mean of the indicators for each LL. The horizontal line within each box indicates the median, while the cross (x) represents the mean. Each box contains the 50% of the observations

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and the whiskers (extended line) show the range of non-outlying values. Individual points located beyond the whiskers represent outlying observations. Scores range from 1 (very poor) to 5 (very good)

Figure 25 illustrates the distribution of the scores obtained across the analysed LLs for the 11 digital ecosystem conduciveness indicator dimensions. In general, the results show a heterogeneous assessment of the conditions supporting sustainable agricultural digitalisation. Most mean scores are situated between 3.00 (acceptable) and 4.00 (good), although differences can be observed both between indicator dimensions and across individual LLs.

Material resources received the highest average score (mean = 3.87; median = 4.00), indicating that the availability of digital devices, equipment and testing facilities constitutes one of the main strengths of the analysed ecosystems. The distribution is relatively broad, but the central values remain close to the good level. Attitudes also obtained an advantageous assessment (mean = 3.57; median = 3.63), suggesting that trust, empathy and positive attitudes towards digital technologies are generally present across the LLs. Similarly, infrastructure (mean = 3.48; median = 3.50) and collaborative structures and networks (mean = 3.46; median = 3.36) show moderately favourable results, although their distributions indicate that the conditions are not uniform across all contexts.

Several indicator dimensions obtained intermediate scores close to the acceptable level. These include innovation (mean = 3.34; median = 3.33), knowledge and training (mean = 3.33; median = 3.28), functional skills (mean = 3.30; median = 3.17) and human resources (mean = 3.29; median = 3.50). These results suggest that the physical availability of technologies is not always accompanied by equally strong knowledge systems, specialised personnel or practical capacities. Functional skills display one of the widest distributions across LLs, highlighting substantial differences in the capacity of actors to access resources, engage stakeholders and support digitalisation processes.

The lowest average scores correspond to financial resources (mean = 2.95; median = 3.00) and governance (mean = 2.97; median = 3.25). Financial resources also display the highest dispersion among the indicator dimensions analysed, indicating considerable variation in access to public and private funding across LLs. Conditions related to governance, including regulatory frameworks, integrated policy support or regulatory gaps, also appear to constitute a relevant area for improvement. Institutional support received a slightly higher but still moderate score (mean = 3.03; median = 3.00), suggesting that advisory services or administrative conditions may not yet provide a consistently enabling environment across all contexts.

Unlike the previous assessment domains, several individual observations are located beyond the whiskers. These outlying values appear particularly in human resources, governance, institutional support, collaborative structures and networks and innovation. They indicate that some LLs face especially favourable or unfavourable conditions in specific indicator dimensions. Rather than representing errors, these cases highlight the contextual diversity of the digital ecosystems included in CODECS and suggest that certain enabling conditions are highly dependent on local institutional, organisational and socio-economic circumstances.

The results indicate that digital ecosystem conduciveness depends on the interaction of multiple factors, such as material resources, attitudes, infrastructure and collaborative structures which emerge as enabler indicator dimensions. However, financial resources, governance and institutional support still constitute areas for improvement. The differences observed across LLs also suggest that the availability of technologies alone is insufficient to create a conducive digital ecosystem, digitalisation requires adequate funding, coherent governance arrangements, institutional support and the development of dynamic and functional capabilities.

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4.3.3.1 Digital ecosystem conduciveness by technological cluster

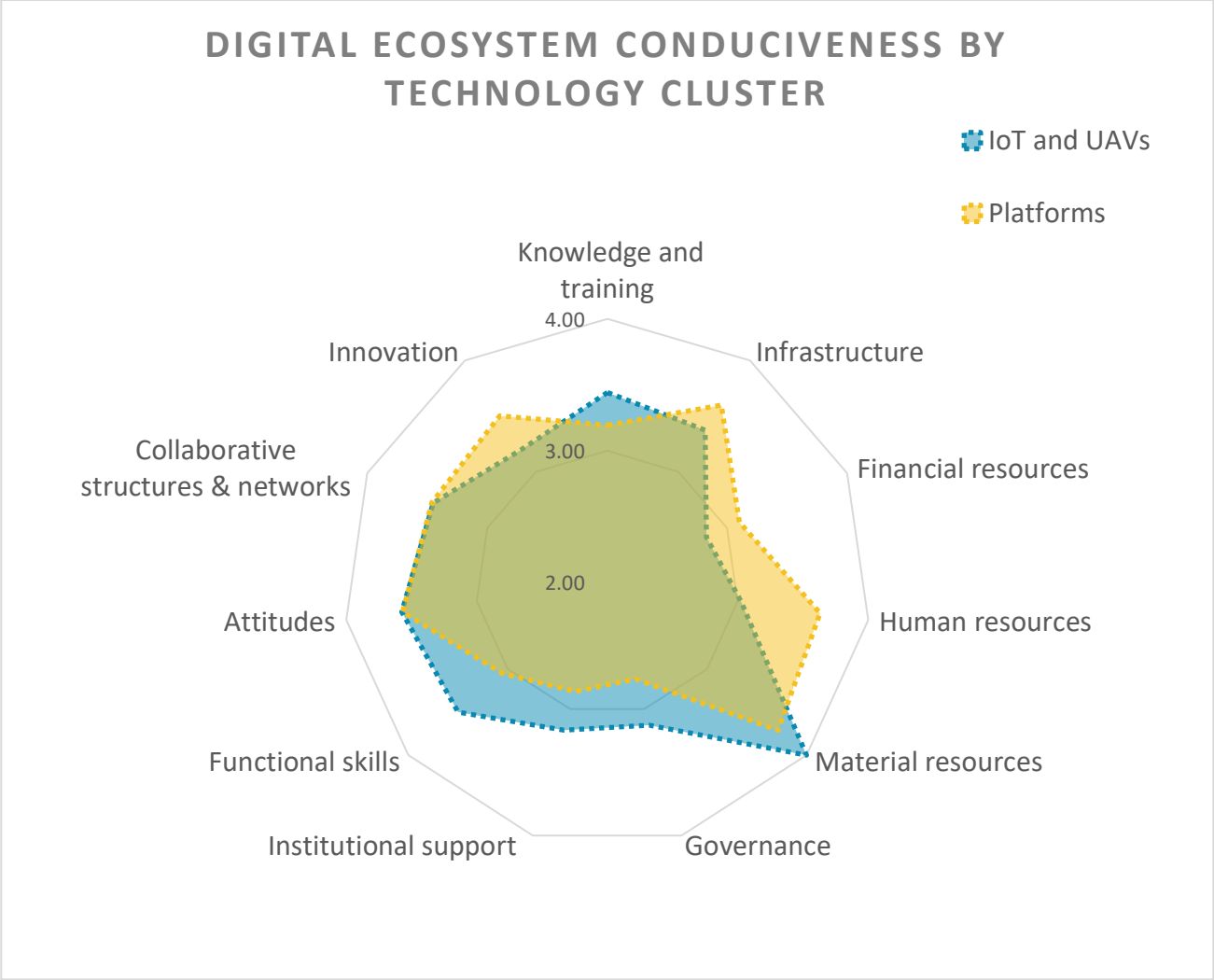

Figure 26. Digital ecosystem conduciveness profiles by technology cluster. The radar chart compares the mean scores obtained by the IoT and UAVs and Platforms clusters across the 11 digital ecosystem conduciveness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). For visual clarity, the radial axis is displayed from 2.00 to 4.00 in order to make differences between clusters easier to observe. The comparison is descriptive and should be interpreted in light of the different number of LLs included in each cluster

The IoT and UAVs cluster obtained higher average scores in several indicator dimensions (see Figure 26). The clearest differences between technologies are observed in functional skills (mean = 3.50, compared with 3.05 for Platforms), governance (mean = 3.13, compared with 2.76), institutional support (mean = 3.17, compared with 2.86), knowledge and training (mean = 3.44, compared with 3.19) and material resources (mean = 4.00, compared with 3.71). These results suggest that the ecosystems supporting IoT and UAV solutions may benefit from a combination of resources and practical skills, and they reflect the relevance of specialised devices, testing environments and technical expertise for the deployment and operation of technologies.

In relation to the Platforms cluster, the most notable difference concerns human resources, where Platforms reached a mean score of 3.63 compared with 3.03 for IoT and UAVs. Platforms also scored higher in infrastructure (mean = 3.60, compared with 3.38), financial resources (mean = 3.10, compared with 2.83) and innovation (mean = 3.50, compared with 3.20). The positive assessment of human resources may indicate that platform solutions depend particularly on the availability of actors capable of managing information, supporting users and facilitating the integration and development of digital tools into existing practices.

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Some indicator dimensions show very similar scores in both clusters. Attitudes obtained almost identical values, with 3.58 for IoT and UAVs and 3.57 for Platforms. Collaborative structures and networks also displayed equivalent scores, with 3.45 for IoT and UAVs and 3.46 for Platforms. This indicates that collaborative arrangements and behavioural conditions are present across the analysed ecosystems and are not strongly differentiated by technology cluster in the analysed LLs.

The comparative analysis indicates that the two technology clusters present complementary ecosystem profiles. IoT and UAVs show stronger scores in material resources, functional skills, knowledge and training, governance and institutional support. Platforms show stronger scores in infrastructure, human resources, financial resources and innovation. These descriptive patterns suggest that support strategies for digital ecosystem development should be adapted to the specific requirements and weaknesses of each type of digital solution.

4.3.3.2 Digital ecosystem conduciveness by sector cluster

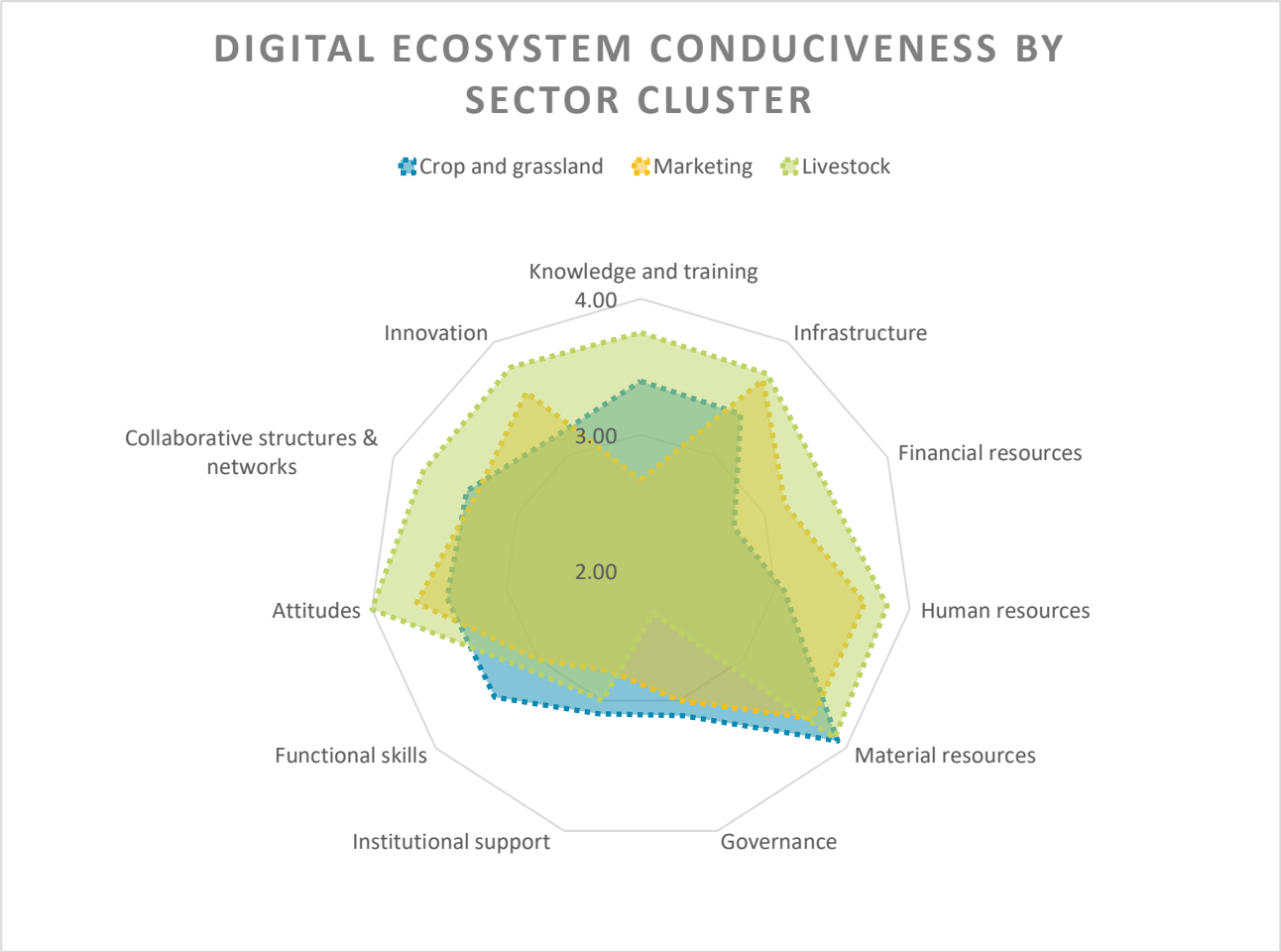

Figure 27. Digital ecosystem conduciveness profiles by sector cluster. The radar chart compares the mean scores obtained by the Crop and Grassland, Marketing and Livestock clusters across the 11 digital ecosystem conduciveness indicator dimensions. Scores range from 1 (very poor) to 5 (very good). The results should be interpreted cautiously, as the clusters contain different numbers of valid LLs

The Livestock cluster displays the most favourable profile across several indicator dimensions (see Figure 27). It obtained the highest average scores for attitudes (mean = 4.00), human resources (mean = 3.83), innovation (mean = 3.78), collaborative structures and networks (mean = 3.76), knowledge and training (mean = 3.75), infrastructure (mean = 3.72) and financial resources (mean = 3.50). These results suggest that the LLs under the livestock cluster benefit from human, relational and innovation enabler conditions. Material resources also received a positive

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assessment (mean = 3.89). However, governance stands out as a notable weakness (mean = 2.33), indicating that regulatory frameworks, policy coherence or other governance conditions may still constrain the development of conducive digital ecosystems in these contexts.

The Crop and Grassland cluster presents a balanced profile. Its strongest indicator dimension is material resources (mean = 3.92), suggesting that the availability of digital devices, equipment and testing facilities constitutes a significant asset. Functional skills (mean = 3.42), attitudes (mean = 3.44), collaborative structures (mean = 3.41), knowledge and training (mean = 3.39) and infrastructure (mean = 3.37) all obtained moderate scores. By contrast, financial resources received the lowest score within this cluster (mean = 2.75), pointing to potential limitations in access public or private funding for digitalisation.

The Marketing cluster displays a more uneven profile. Its strongest indicator dimensions are infrastructure (mean = 3.67), human resources (mean = 3.67), material resources (mean = 3.67) and attitudes (mean = 3.67). Innovation also received a relatively advantageous score (mean = 3.56). However, knowledge and training obtained the lowest average score among all the indicator dimensions assessed within this cluster (mean = 2.67), while institutional support also remained below the acceptable level (mean = 2.78). This suggests that digital ecosystems related to marketing may have access to relevant technological and human assets, but may still require stronger knowledge systems, training opportunities and institutional support.

The sectoral comparison indicates that digital ecosystem conduciveness varies substantially across contexts. Nonetheless, several common challenges can also be identified across clusters. Governance and institutional support remain close to or below the acceptable level in all three groups, as well as functional skills and financial resources. LLs within livestock cluster show promising scores in several indicator dimensions, but governance remains a clear constraint. Crop and Grassland benefits particularly from material resources but faces limitations related to funding. Marketing LLs show strengths in infrastructure, human resources and innovation, while knowledge and training still should be upgrade. These patterns suggest that the development of conducive digital ecosystems depends on the availability of technologies and infrastructure, but also on coherent policy frameworks, enabling institutions and support mechanisms, reinforcing the need to tailor ecosystem support strategies to the specific characteristics of each sector.

5 Conclusions

The comparative assessment of farm digital readiness, scaling readiness and digital ecosystem conduciveness provides a complementary perspective on the current state of the CODECS LLs. The goal of the analysis is to identify common patterns, differentiated profiles and potential bottlenecks across three interconnected indicator domains and indicator dimensions. The results should be interpreted as a descriptive comparison of the LLs included in the project, based on the scores reported by LL coordinators.

5.1 Scaling readiness

Farm-process modelling perspective

A first conclusion is that analysing the farm-process level helps reveal the practical implications of digitalisation for everyday work. Across the LLs, the introduction of digital technologies mainly affects tasks, leading to the addition, removal, or reorganisation of activities. This suggests that scaling readiness of technology cannot be understood only in terms of technical performance, but also in terms of whether the new or reconfigured activities required by the technology can be realistically incorporated into routine farm practices.

The farm-process perspective helps clarify the relationship between technological maturity, farm digital readiness, and digital ecosystem conduciveness. The findings suggest that a solution may be technically mature and positively accepted by users, while still facing important barriers to wider uptake because farms lack the necessary resources, skills or support conditions. This means that scaling readiness depends not only on the intrinsic qualities of the technology, but also on whether the farm context and the surrounding ecosystem are sufficiently prepared to support its use.

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Agricultural knowledge and innovation systems

In order to scale out digital technologies that are beneficial for farmers, knowledge structures must be capable of navigate the tension between dealing with systemic challenges at a local level (essential for relevance and adaptation) and standardisation (required for interoperability). The observed governance asymmetry calls for deliberate efforts to strengthen local governance capacity and foster bottom-up legitimacy in innovation processes.

Digital ecosystem analysis and resources, capabilities, collaborations and innovations perspective

In the general analysis of scaling readiness, all four indicator dimensions obtained average scores above the midpoint of the scale, suggesting that the digital solutions assessed within the CODECS LLs present relevant conditions for scaling.

Technology usefulness emerged as the strongest indicator dimension. This indicates that the digital solutions represented in the LLs are generally assessed as capable of addressing relevant challenges and contributing to the optimisation of agricultural activities or operational processes. Technology ease of use obtained the lowest average score, suggesting that usability remains an area with room for improvement, particularly when digital tools require specialised training, technical support or changes to established work routines.

Technological maturity also received a promising overall assessment but showed the biggest variation across LLs. This indicates that some technologies are perceived as ready for implementation or scaling, while others may still require further development or adaptation to specific contexts. Adoption feasibility showed an intermediate but relatively dispersed profile, suggesting that usefulness and maturity do not automatically translate into easy or straightforward adoption.

The analysis based on clusters further nuances these results.

- By technology cluster, IoT and UAVs showed a clearly more favourable profile in technological maturity, whereas Platforms obtained slightly higher scores in technology usefulness and adoption feasibility.
- By sector cluster, Livestock displayed the most advantageous profile in usefulness, ease of use and adoption feasibility, while Crop and Grassland stood out for technological maturity. Marketing solutions appeared useful but showed greater improvement potential in the rest of the indicator dimensions.

5.2 Farm digital readiness

Farm-process modelling perspective

The transition effort is itself a key component of farm digital readiness. The LLs consistently described the introduction of technology as a gradual socio-technical transition involving preparation, technical setup, user support, testing, coordination, and subsequent refinement. From this perspective, the practical manageability of the transition pathway is particularly relevant to the assessment of farm readiness, as it reflects whether farms can integrate and sustain the technology in everyday operations, while also providing a more granular view of the ecosystem-level support required to facilitate this transition.

Digital ecosystem analysis and resources, capabilities, collaborations and innovations perspective

The three indicator dimensions evaluated under Farm digital readiness obtained scores situated between acceptable and good, with relatively similar average values. This suggests that readiness at the farm level is present across the LLs but remains less clearly consolidated than some aspects of scaling readiness.

State of digitalisation obtained the highest average score, indicating that the integration of digital technologies into farming practices and the availability of farmers' digital skills are, overall, assessed positively. However, the broad range of scores shows that the level of digitalisation varies substantially across contexts. Transition effort received the lowest average score, suggesting that the conditions required to move towards a more digitalised state still require attention. Intention to use technology obtained an intermediate score, but with relevant variation across LLs. This indicates that farmers' willingness, engagement and ability to adopt or continue using digital technologies are not uniform. The results suggest that farm digital readiness depends not only on the availability of digital

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technologies, but also on farmers' capacities, motivation and ability to integrate digital information into everyday decision-making.

The analysis based on clusters promote the differentiation of these results:

- The technology cluster comparison shows similar profiles between IoT and UAVs and Platforms. Platforms scored slightly higher in state of digitalisation and transition effort, while IoT and UAVs obtained a higher score in intention to use technology. This suggests that the main difference is not necessarily the current integration of digital tools, but rather the willingness and capacity to adopt or continue using them.
- By sector cluster, Livestock showed the most advantageous profile across the three indicator dimensions, while Crop and Grassland and Marketing displayed more moderate scores. In both of these latter clusters, transition effort appears as the area with the lowest score, meaning that the time available to learn and the effort required to complete the digital transition and farmers' awareness of available technological options may require more support and development.

5.3 Digital ecosystem conduciveness

Agricultural knowledge and innovation systems

Viewing AKIS as a network of knowledge flows involving different actors, the effectiveness of innovation processes is linked to the presence of diverse actors, and to the processes of exchange and coordination between them. The aim of the comparison was to describe patterns observed in the focal action situations under investigation.

The results show, first of all, that the constellations of actors, as well as the objectives in the LLs and their FAS are highly heterogeneous. Overall, the variety of presence of stakeholders among the CODECS LLs is considerable with 17 identified categories and three different levels of involvement. Comparing the LLs against four characteristics (objective, TRL, type of innovation and predominant advisory services) reveals that most stakeholders actively participating in an LL are involved in: i) an LL with technologies that have already been developed and tested (TRL 7 to 9); ii) LLs that aim to increase productivity and/or efficiency; and iii) LLs that operate within pluralistic advisory systems.

Differences can be seen in the average presence of actor types across the different categories of LL, with pluralism and diversification of actors differing according to the compared groups. For example, LLs aimed at productivity and efficiency have a higher average proportion of farmers than those with other objectives. Agricultural associations are, on average, more strongly represented in LLs that develop platforms, as well as in LLs aimed at improving the management of natural resources. The representation of research and education stakeholders is higher in human and socially oriented LLs, whilst that of farmers and IT entrepreneurs is relatively lower; meanwhile, companies and farmers are, on average, more strongly represented in LLs aimed at productivity and efficiency. A general observation applicable to all types of LLs is that they are characterised by a wide diversity of actors, and that the largest proportion in each case consists of actors who are not part of the traditional 'knowledge triangle' comprising research, advisors and farmers. Diversification of actors and professional interest (profit or common good) where appropriate, can be used as an indicator for future participation processes

For most of the LLs, national policies and market derived guidelines are the most frequent governance mechanisms mentioned. On a second place, European level policies and market regulations were frequently mentioned, while local-level coordination mechanisms were considerably less present. This could potentially be aligned with the fact that most of the technologies used are at the dissemination stage, meaning that coordination actions are more influenced by external actors (such as the government, markets and IT companies) than by local-level decisions. The presence of multiple coordination mechanisms confirms that the governance of knowledge flows is located in several centres.

We conclude that, in the analysed cases, the characteristics of the technology, the objectives of the FAS and the type of knowledge infrastructures present in the territories influence how actors implement collective actions in the development and implementation of digital technologies. Our findings indicate that the coordination of knowledge flows in the implementation of digital technologies is influenced more by external actors than by local coordination mechanisms. This suggests a technology-driven rather than demand-driven uptake of innovations.

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The findings are based on specific LL cases and cannot be generalised to other contexts or digitalisation processes. They reflect the particular configurations and conditions of these cases. However, the comparison of analysis of actors and comparison between LLs characteristics provides a first bases for hypotheses on conducive actor constellations that can be tested more systematically.

Digital ecosystem analysis and resources, capabilities, collaborations and innovations perspective

Digital ecosystem conduciveness presents the most multidimensional and heterogeneous profile. The results show that the conditions supporting sustainable digitalisation are unevenly distributed across indicator dimensions and LLs.

Material resources emerged as one of the strongest indicator dimensions, indicating that the availability of digital devices, equipment, demo farms and testing facilities constitutes a relevant asset in many LL contexts. Attitudes, infrastructure and collaborative structures also received favourable assessments, suggesting that several ecosystems benefit from positive stakeholder attitudes, basic infrastructural conditions and existing collaboration channels.

However, financial resources, governance and institutional support appear as the main areas for improvement. Financial resources received one of the lowest scores and showed high variability across LLs, indicating that access to public and private funding remains uneven. Conditions related to governance, including regulatory frameworks, policy coherence and regulatory gaps, also represent a recurrent constraint. Institutional support obtained only moderate scores, suggesting that advisory services, administrative conditions and AKIS support are not yet consistently enabling across all contexts.

The analysis based on clusters explore even more these results:

- The technology cluster comparison points to complementary ecosystem profiles. IoT and UAVs obtained higher scores in material resources, functional skills, knowledge and training, governance and institutional support. Platforms scored higher in infrastructure, financial resources, human resources and innovation. Attitudes and collaborative structures were very similar across both technology clusters. These patterns suggest that different types of digital solutions rely on different enabling conditions: IoT and UAVs appear more closely associated with material assets and practical capabilities, while Platforms depend strongly on human resources, infrastructure and innovation conditions.
- The sector cluster comparison also reveals differentiated patterns. Livestock showed comparatively positive scores in several indicator dimensions, particularly attitudes, human resources, innovation, collaborative structures and knowledge and training, but governance emerged as a clear weakness. Crop and Grassland displayed a balanced profile, with material resources as its strongest indicator dimension and financial resources as its main limitation. Marketing LLs showed strengths in infrastructure, human resources, material resources, attitudes and innovation, but weaker scores in knowledge and training and institutional support. These findings underline the importance of adapting digital ecosystem strategies to sector-specific characteristics.

5.4 Cross-cutting conclusions

The cross-case analysis brings together evidence from the three indicator domains (scaling readiness, farm digital readiness and digital ecosystem conduciveness) across multiple perspectives of analysis: farm-process, AKIS and digital ecosystem. Taken together, the three perspectives show that digitalisation in the CODECS LLs is not constrained by a single factor but rather involves a layered challenge.

A key implication is that technological usefulness alone is not sufficient to ensure scaling or adoption. Even when digital solutions are assessed positively, their wider uptake may be limited by usability issues, transition effort, lack of financial resources, insufficient institutional support or uneven governance conditions. Similarly, the presence of digital devices and infrastructure does not automatically guarantee farm-level readiness unless farmers have the skills, time, support and motivation required to use them properly.

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The cluster analyses further show that digitalisation pathways differ across technology types and sectoral contexts. IoT and UAVs, Platforms, Crop and Grassland, Marketing and Livestock each display specific strengths and weaknesses. This suggests that support measures should not be designed as one to fit all the needs. Instead, strategies for sustainable agricultural digitalisation should be adapted to the technological profile, sectoral context and ecosystem conditions.

Overall, the comparative assessment indicates that the CODECS LLs provide a diverse set of digitalisation contexts, with favourable but uneven conditions for readiness, scaling and ecosystem conduciveness. The main opportunities lie in building on existing strengths, such as technology usefulness, material resources, positive attitudes and collaborative structures, while addressing persistent bottlenecks related to ease of use, transition effort, financial resources, governance and institutional support.

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7 Annex

Glossary

(A) Actors Subsystem: The actors (individual and collective) involved inhabit particular contexts within the FAS, with their own interests, ambitions, capabilities, access to resources, knowledge levels, and beliefs.

(AKIS) Agricultural Knowledge and Innovation Systems: Knowledge flows between persons, organisations and institutions who use and produce knowledge for agriculture and interrelated fields (*Article 102a Modernization, COM 2018/392*). Conceptual construct used to identify, examine, and evaluate the actors, relations and subsystems engaged in generating, sharing, and applying knowledge and innovation related to agriculture and related fields, and how their interactions shape these dynamic.

(AI) Artificial Intelligence: A field of computer science focused on developing systems capable of learning from data and performing predictive or decision-support tasks, such as pattern recognition, classification, forecasting.

(BPMN) Business Process Model and Notation: A standardised graphical notation for modelling business processes, providing a set of symbols to represent activities, events, gateways, and flows in order to describe and analyse organisational workflows.

(BPM) Business Process Modelling: A specific type of system modelling that represents the sequence of activities, decisions, and resources involved in accomplishing a business objective. Business process models provide a visual representation of how work is performed within an organisation, highlighting dependencies, inputs, outputs, and control flows.

Capabilities: Individual/collective know-how/abilities to undertake specific activities, which implies a combination of resources and individual actions or organisational routines.

Digital ecosystem conduciveness: the extent to which the environment supports the growth, success, and adoption of digital activities, such as the development of new technologies, the creation of new businesses, and the adoption of digital solutions.

(DEs) Digital Ecosystems: A DE is defined as a dynamic system where digital, socio-economic, organisational, knowledge, and physical components converge to support the production, storage, communication, and utilisation of digital technologies and data.

Digital readiness of farmers: the individual or organisation's ability to adapt and effectively utilise digital technologies and tools in order to achieve their goals and objectives.

Dynamic capabilities: Understood as the ability to mobilise/reorganize the assets and competences that a company/LL possesses not only to be able to respond to changing environments but also to increase its capacity for adaptation, survival, and competitiveness.

(FMIS) Farm Management Information System: An information system designed to support farm operations by collecting, managing, and analysing agricultural data related to crops, livestock, resources, and farm activities to improve decision-making and efficiency.

(FAS) Focal Action situation: LL situation where subsystems of a socio-ecological system interact to provide an outcome. (Outcome =solution for the LL problem statement)

(GS) Governance Subsystem: This subsystem looks into the processes through which decisions are made, implemented, reformed and reinforced. That is, “who decides what, and how?” It comprises formal and informal interactions, rules and self-governance mechanisms, focusing on decision-making processes and their implementation, reform, and reinforcement.

(ICT) Information and Communication Technologies: Digital technologies used to collect, store, process, and transmit information, including computers, software, networks, telecommunications systems, and internet-based services.

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(IoT) Internet of Things: A network of interconnected physical devices embedded with sensors, software, and communication technologies that enable them to collect, exchange, and act upon data over the internet.

(KAOS) Knowledge Acquisition in automated Specification: A goal-oriented requirements analysis method that enables the analysts to capture requirements through the realization of the business goals.

(LLs) Living Labs: A LL is understood as a network of farmers, knowledge intermediaries, stakeholders, policymakers, technology providers, and other concerned actors, constituted around an emerging problem within a given application scenario, and willing to develop solutions through collaboration.

(REST API) Representational State Transfer Application Programming Interface: a web-based interface that enables communication between software systems using standard methods, following an architectural style which promotes stateless interactions and resource-oriented design.

(RE) Requirements Engineering: A discipline within software and systems engineering concerned with the elicitation, analysis, specification, validation, and management of stakeholders' requirements.

(RS) Resource Subsystem: Resource systems describe the conditions in which resource units are managed and organised. It outlines the management and organisational conditions of these resource units, including social, economic, technological, knowledge/information, and environmental aspects.

(RU) Resource units: represent the assets accessible to actors within the agricultural ecosystem, beyond just the LL.

(RCCIs) Resources, Capabilities, Collaborations and Innovations: "mediating" layer utilised so that LLs can identify and explore the influence of the SESF on their Focal Action situation.

Resources: tangible and intangible assets owned, controlled or accessed by an entity (e.g., farm enterprise, LL, organisation, etc.), which may be utilised in order to create value, achieve an objective, or solve a problem.

(SESF) Socio-Ecological System Framework/Socio-Ecological Systems (SES): It conceptualises the ecosystem into four main subsystems; resource systems, resource units, governance systems, and actors.

Sustainable digitalisation: Sustainability implies that digitalisation should help maintain or, better, increase, the capacity of socio-ecological systems to respond to external threats (e.g. climate change), and support the livelihood, wellbeing and resilience of individuals, groups and rural communities situated in various contexts across the EU. The incorporation of socio-ecological considerations ensures that digital solutions are not only technically effective but also socially acceptable and environmentally sustainable.

System modelling: A methodology used to represent and analyses complex systems. It involves creating abstractions of real-world systems, allowing stakeholders to gain insights into their structure, behaviour, and interactions. By using graphical or textual notations, system models capture the essential elements and relationships within a system, facilitating a holistic understanding of its dynamics.

(UML) Unified Modelling Language: A general-purpose modelling language that provides a set of standardised diagrams (e.g., class, sequence, use case) to specify, visualise, and document the structure and behaviour of software and systems.

(UAV) Unmanned Aerial Vehicle: an aircraft operated without a human pilot onboard, typically controlled remotely or autonomously, and used in agriculture for tasks such as field monitoring, crop assessment, mapping, and data collection through onboard sensors and cameras.

(VRA) Variable Rate Application: an agricultural practice that uses digital technologies and sensor data to apply inputs (e.g., fertilizers, pesticides, seeds, or water) at variable rates across different areas of a field, optimising resource use according to spatial variability in soil and crop conditions.

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