CODECS

Methodology Handbook

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D2.3 CODECS methodology handbook

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Authors	Katrine Soma (WR), Gianluca Brunori (UNIPI), Emīls Ķīlis (BSC), Cynthia Giagnocavo (UAL), Rosa Maria Heredia Hortigüela UAL), Constantine Iliopoulos (ELGO-D. AGRERI), Chiara Mannari (CNR), Beatriz Herrera (HOH), Julie Menadi (ACTA), Ninon Violeau (ACTA), Alexia Gobrecht (INRAE), Veronique Bellon-Maurel (INRAE), Alexandra Sintori (ELGO-D.ALGRERI), Daniele Vergamini (UNIPI), Fabio Bartolini (UNIPI), Mario Petkovski (AGFUTURA), Mehdi Hassan Mohammadi (UNIPI), Alessio Ferrari (CNR), María del Mar Delgado-Serrano (UCO), Pierre Labarthe (INRAE), Andrea Knierim (HOH), Livia Ortolani (UNIPI), Femke Meulman (WR), Leanne Townsend (Hutton), Niamh Mahon (Hutton), Tim Pittaway (Hutton), Mauro Florez (INRAE), Thomas Giotis (ELGO-D.AGRERI), Irini Theodorakopoulou (ELGO-D.AGRERI)
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Project Coordinator	University of Pisa

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Colophon

The CODECS Methodological Handbook is one of the exploration outcomes of the project: Maximising the CO-benefits of agricultural Digitalisation through conducive digital ECoSystems (CODECS)

Editors: Katrine Soma[1] and Gianluca Brunori[2]
1. Stichting Wageningen Research; Wageningen Social and Economic Research
2. University of Pisa; Department of Agriculture, Food and Environment

Contributions have been received across all Work Packages and Tasks in CODECS, who have all contributed. The co-authors include: Emīls Ķīlis (BSC), Cynthia Giagnocavo (UAL), Rosa Maria Heredia Hortigüela UAL), Constantine Iliopoulos (ELGO-D. AGRERI), Chiara Mannari (CNR), Beatriz Herrera (HOH), Julie Menadi (ACTA), Ninon Violeau (ACTA), Alexia Gobrecht (INRAE), Veronique Bellon-Maurel (INRAE), Alexandra Sintori (ELGO-D.ALGRERI), Daniele Vergamini (UNIPI), Fabio Bartolini (UNIPI), Mario Petkovski (AGFUTURA), Mehdi Hassan Mohammadi (UNIPI), Alessio Ferrari (CNR), María del Mar Delgado-Serrano (UCO), Pierre Labarthe (INRAE), Andrea Knierim (HOH), Livia Ortolani (UNIPI), Femke Meulman (WR), Leanne Townsend (Hutton), Niamh Mahon (Hutton), Tim Pittaway (Hutton), Mauro Florez (INRAE), Thomas Giotis (ELGO-D.AGRERI), Irini Theodorakopoulou (ELGO-D.AGRERI).

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How to use the CODECS Methodolodical Handbook

The CODECS Methodological Handbook for sustainable digitalisation in the European agri-sector supports planning, assessment, decision-making, business development, and policymaking. It provides analyses suited to different digitalisation levels and highlights the importance of understanding system complexity in the transition toward sustainability. Some research approaches are available as online tools on the CODECS website, while others rely on researchers' expertise to assess social, environmental, and economic impacts. The handbook integrates replication methodologies and tools within the CODECS conceptual framework, linking stakeholder engagement, impact assessments, and socio-ecological systems analysis to support systemic transformation of the European agri-sector. The CODECS Methodological Handbook is structured to guide readers through a systemic approach to sustainable digitalisation in agriculture, examining costs and benefits across multiple levels of analysis, through the following Chapters:

Chapter 1. "Introduction: A system approach to sustainable digitalisation" provides the conceptual foundation of the handbook. It introduces the overall purpose and scope, outlines the CODECS conceptual framework, and presents the role of demonstration farms across 20 living labs. The chapter also discusses how costs and benefits could be viewed from more specific and broader perspectives, introduces the visioning process for sustainable digitalisation, and identifies actors within Agricultural Knowledge and Innovation Systems (AKIS) as key target groups.

Chapter 2. "Business process level" focuses on evaluating digitalisation at the level of farm and organisational processes. It introduces methods for assessing business processes in transition and examines social/human-centred, environmental, and economic costs and benefits. The chapter also presents a Technology Assessment Tool (TAT) to support structured evaluation, which is available online (www.horizoncodecs.eu).

Chapter 3. "Digital ecosystem level" explores the wider digital environment in which agricultural actors operate. It describes a methodological approach to analysing digital ecosystem conduciveness, examines stakeholder perceptions through thematic analysis of focus group discussions, discusses the role of AKIS, and introduces VARI, a bottom-up approach to understanding ecosystem dynamics.

How to use the CODECS Metholodical Handbook

Chapter 4. “Socio-environmental level” expands the analysis to broader societal and environmental systems. It introduces the Socio-Ecological Systems Framework (SESF) and presents a Multicriteria Analysis (MCA) tool for evaluating sustainability impacts.

Chapter 5. “Living Lab identification of costs and benefits” explains how evidence is gathered through Living Labs, including annual workshops, networking activities, virtual demonstration farms, and team discussions with stakeholders.

Chapter 6 examines the policy environment and areas of intervention, while Chapter 7 concludes with a roadmap summarising the key costs and benefits of sustainable digitalisation identified throughout the handbook.

A system approach to sustainable digitalisation

1.1 An overview

The societal benefits and costs of farm digitalisation remain unclear. While digital tools promise higher productivity, efficiency, better working conditions, and reduced environmental pressure, they may also create inequalities, excluding vulnerable farmers, regions, or communities. There is limited collective capacity across Europe to assess trade-offs, anticipate long-term impacts, and ensure digitalisation supports sustainable socio-economic and ecological transitions.

The main aim of this CODECS Methodological Hanbook is to present the mutlitude of methodological approaches applied in CODECS in the period from October 2022 to September 2026. The approaches share that they intend to motivate upscaling of sustainable digitalisation, targeted to researchers and Agricultural Knowledge and Innovation Systems (AKIS) actors. This Methodological Handbook is available in two different versions: as a report and as an online interactive version (playbook).

Approach. CODECS has developed a shared vision of sustainable digitalisation for agriculture, integrating physical, social, and technical transformation. By means of interactions between research and Living Lab operations, CODECS co-created conceptual and methodological frameworks, tools, and evidence through a transdisciplinary, consortium-wide approach. The project has over the years 2022-2026 strengthened knowledge access, peer learning, innovation networks, rural-urban and producer-consumer connections while aiming to reduce bureaucracy. Through 20 diverse Living Labs, CODECS supports co-creation, testing, and validation of approaches. It builds collective capacity to evaluate digitalisation impacts and develop digital ecosystems that maximise net societal benefits. Outcomes include a validated common research approach and policy guidance for European agricultural digital transformation.

This report analyses the costs and benefits of digitalisation in agriculture using a systems approach developed in the CODECS Project. It begins by presenting the conceptual framework and the contextual factors observed across 20 Living Labs. The report then examines digitalisation from multiple perspectives, including economic, environmental, and social costs and benefits. Several analytical levels are explored. At the business process level, the report assesses how digital tools affect farm operations, workflows, and farm management decisions. At the digital ecosystem level, it investigates stakeholder perceptions, collaboration, and innovation dynamics among farmers, advisers, and technology providers. At the socio-environmental level, broader impacts on sustainability, society, and ecosystems are evaluated using tools such as technology assessment and multicriteria analysis. See Figure 1.

Future relevance. The CODECS Project Methodological Handbook provides a structured set of frameworks and tools to assess sustainable digitalisation in agriculture. In the future, it can support researchers, policymakers, and AKIS actors in evaluating digital technologies, fostering innovation networks, and guiding evidence-based policies, thereby facilitating responsible digital transformation and maximising societal, environmental, and economic benefits.

Figure 1. Overview of methodological approaches used in CODECS at different levels.

1.2 CODECS Conceptual Framework

Digital technologies in agriculture are often assessed at the level of individual farms or technologies, while their economic, social, and environmental consequences unfold across broader systems. This creates a mismatch between where digitalisation is implemented and where impacts occur, obscuring trade-offs, distributional effects, and long-term sustainability outcomes.

Main aim. Develop a system-based conceptual framework that captures how agricultural digitalisation generates costs and benefits across interconnected levels and contexts. It explores how digital technologies transform farm processes, how ecosystem conditions shape these transformations, and how societal and ecological outcomes emerge.

Approach. Digital technologies are transforming European agriculture, influencing how farms manage production, resources, and sustainability challenges. However, digitalisation does not occur in isolation at the farm level. Its effects emerge through interactions between farmers, technologies, institutions, and environmental systems. To better understand these dynamics, the CODECS conceptual framework adopts a systems perspective that situates digitalisation within a broader social, technological, economic, and environmental context.

The framework recognises that agricultural digitalisation is shaped by both external and internal drivers. External drivers include technological developments, environmental pressures, market dynamics, and policy frameworks, while internal drivers relate to farmers' capabilities, motivations, and opportunities to adopt digital tools.

Here, tools such as sensors, automation, and digital advisory services influence farm management and generate economic, social, and environmental costs and benefits.

The digital ecosystem level examines the wider network of actors, infrastructures, and data systems that support digital farming. Platforms, advisory services, technology providers, and Agricultural Knowledge and Innovation Systems (AKIS) shape how technologies are accessed, used, and integrated.

The socio-environmental level considers the broader societal and ecological context. At this level, digitalisation interacts with governance structures, environmental systems, and societal goals, influencing issues such as resource management, data governance, inclusion, and long-term sustainability. (See Figure 2)

Introduction

Future relevance. The CODECS conceptual framework highlights that agricultural digitalisation is a systemic transition with cross-scale implications rather than a purely technical innovation. By linking farm processes, ecosystem dynamics, and broader societal and ecological outcomes, the framework captures complexity, feedbacks, and distributional effects often overlooked in single-level analyses. It provides a coherent basis for research, evaluation, and policy design, supporting more responsible, transparent, and sustainable digitalisation pathways in agriculture and helping stakeholders better understand the long-term implications of digital transformation.

Scientific article: Sustainable digitalisation - a system thinking approach; CODECS D2.1 Conceptual Framework (draft); CODECS D2.2 Conceptual Framework (final); CODECS Policy Brief Conceptual Framework , Policy brief Gender Dimension

Katrine Soma (WUR), katrine.soma@wur.nl and Gianluca Brunori (UNIPI), gianluca.brunori.unipi.it.

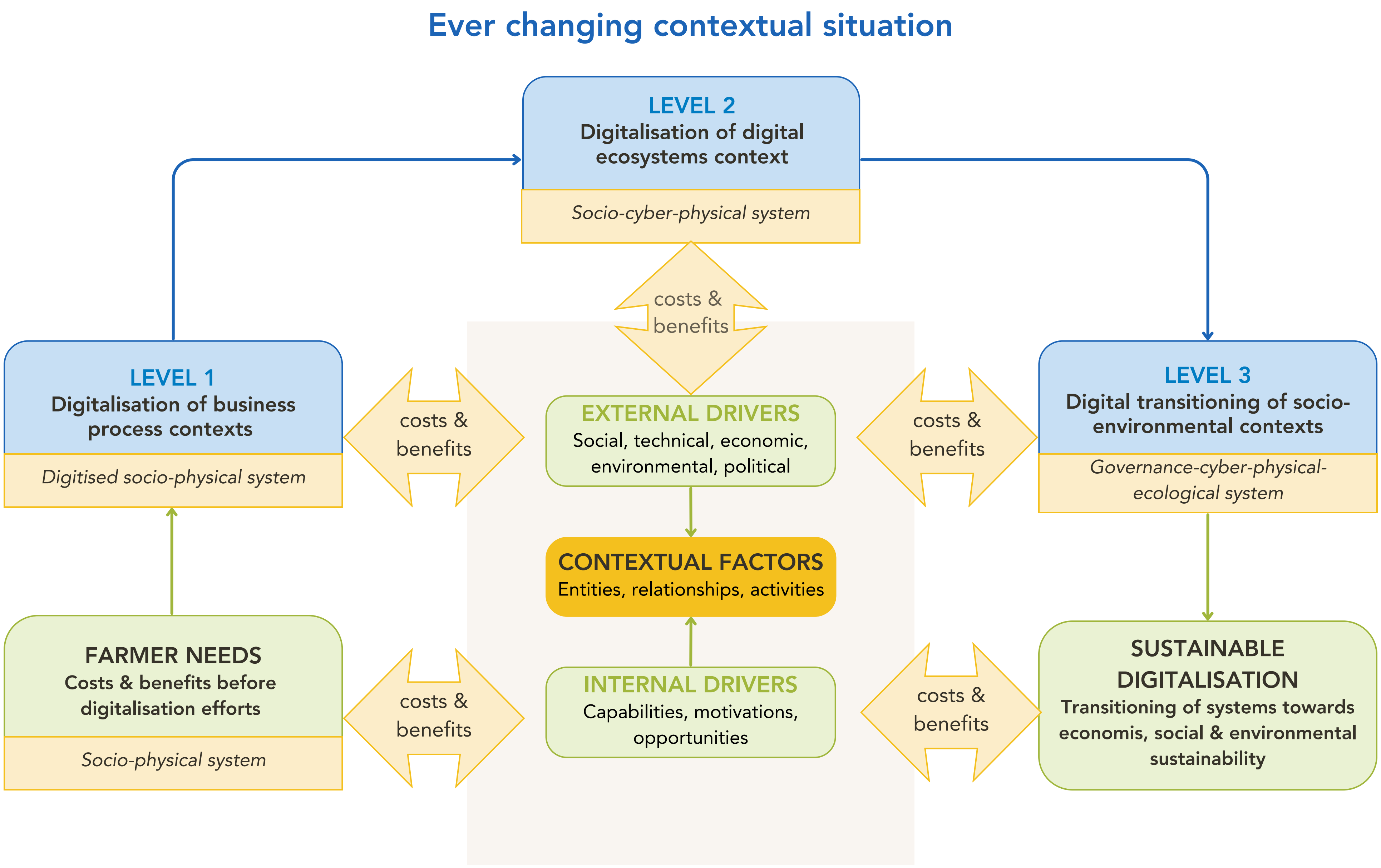


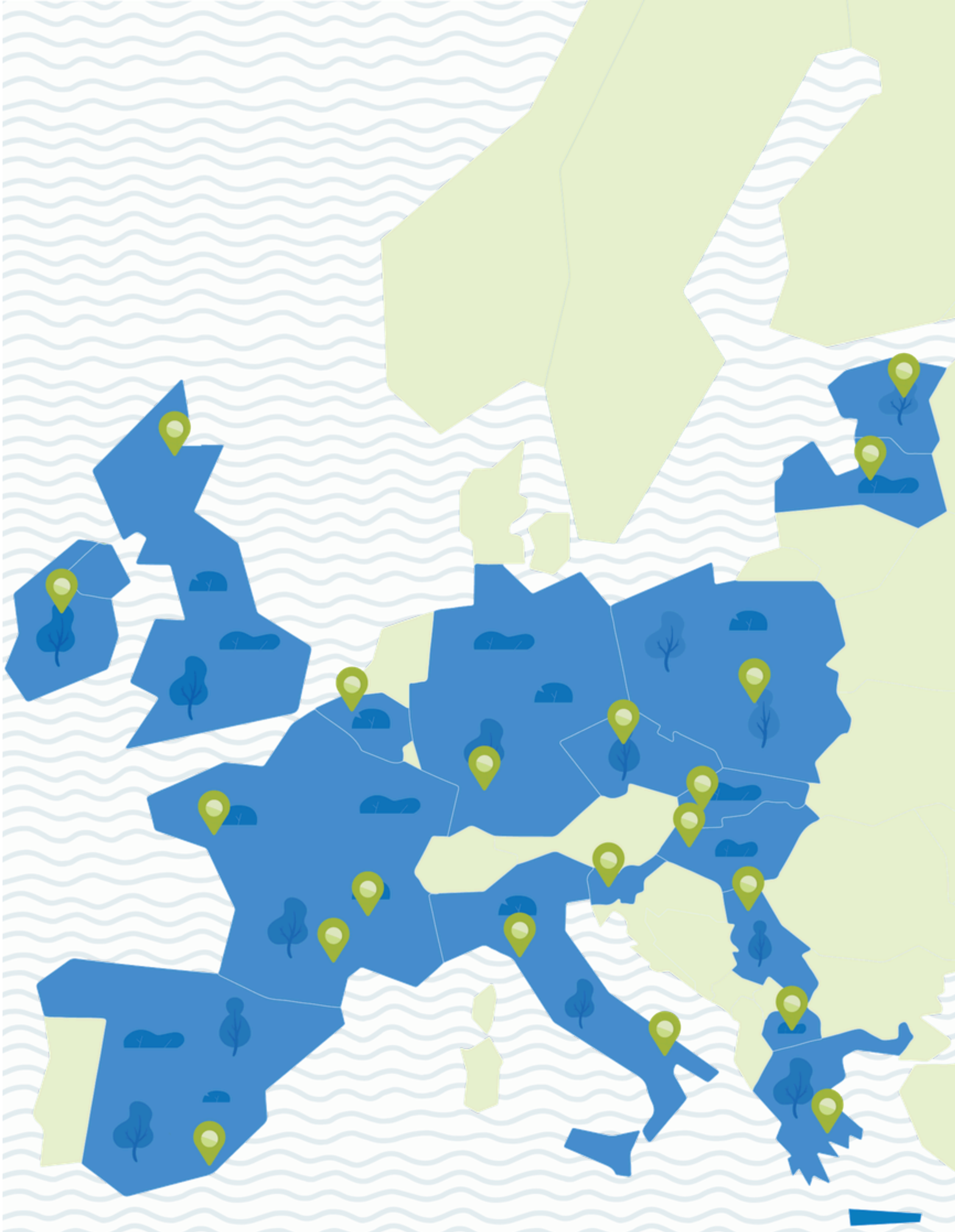
Figure 2. *CODECS Conceptual Framework.*

1.3 Demonstration farms across 20 Living Labs

Farmers often hesitate to adopt digital agricultural technologies because they lack practical evidence of their usefulness, costs, and benefits in real farming conditions. Information is often theoretical or fragmented, limiting trust and understanding. As a result, knowledge exchange between farmers, advisers, researchers, and technology providers remains insufficient for informed adoption decisions.

Main aim. The main aim is to showcase digital agricultural technologies in real farming contexts, facilitate peer-to-peer learning among farmers and innovation actors, and gather stakeholder feedback on the costs and benefits of digitalisation. Demonstrations also support knowledge exchange, technology assessment, and improved understanding of digital ecosystems in agriculture.

Approach. A demonstration farm is a real agricultural setting where innovative technologies, practices, or systems are presented and tested to facilitate learning and knowledge exchange among stakeholders. By observing technologies operating in real farming conditions, farmers can better understand their practical applications, advantages, and limitations. Demonstration events typically encourage peer-to-peer learning, allowing farmers to interact directly with other farmers, advisers, researchers, and technology providers. This approach promotes experiential learning – "seeing is believing" – and supports the dissemination of best practices, practical knowledge, and innovation across the agricultural sector.



Introduction

In the context of the CODECS project, 27 demonstration farms have been established within a network of 20 Living Labs where partners showcase digital technologies used in agriculture. Across these farms, a total of 60 demonstration events have been organised, including 40 physical on-farm demonstrations and 20 virtual events (15 Farminars and 5 Virtual Tours). These activities bring together diverse stakeholders to observe technologies in practice, exchange experiences, and collectively assess their economic, social, and environmental costs and benefits. Feedback collected during these demonstrations contributes to research on farmers' readiness to adopt digital technologies and helps evaluate the broader digital ecosystem in agriculture.

Future relevance. Demonstration farms can play an important role in accelerating the future adoption of digital technologies in agriculture. By strengthening collaboration between farmers, researchers, advisers, and technology providers, they help build trust in innovations and make digital solutions more tangible for end-users. In the long term, this approach supports more informed decision-making, sustainable farming practices, and a more effective digital transformation of the agricultural sector

CODECS Living Labs; CODECS demonstration farms; CODECS demo farm virtual tours; CODECS Farminars; Past and upcoming CODECS demonstration events; CODECS D5.3 Handbook of demonstration of digital technologies., CODECS Living Lab Story Books.

Julie Menadi (ACTA), julie.menadi@acta.asso.fr and Ninon Violeau (ACTA), ninon.violeau@acta.asso.fr

1.4 Costs and benefits - at different levels

Assessments of digitalisation in agriculture often focus mainly on farm-level financial costs and benefits because these are easier to measure. However, this narrow perspective risks overlooking broader system-level impacts, including social, environmental, and institutional effects, as well as differences across regions, actors, and time horizons that shape the real value of digitalisation.

Main aim. The aim of this section is to explain a broader understanding of the costs and benefits associated with digitalisation in agriculture. This perspective considers not only easily quantifiable farm-level effects but also wider system-level implications, including advantages, disadvantages, risks, and trade-offs across economic, social, and environmental dimensions over both short- and long-term timeframes.

Approach. At farm level, digital technologies involve costs such as hardware, software, connectivity, training, and maintenance, but may also bring benefits including improved efficiency, better decision-making, reduced input use, and increased productivity. These factors strongly influence farmers' willingness and capacity to adopt new technologies. CODECS advances beyond the current state-of-the-art approaches to calculating the costs and benefits of farm digitalisation by considering related transactions costs. Transaction costs in farm digitalisation are the coordination and motivation costs involved in negotiating, organising, monitoring, and enforcing exchanges related to digital technologies and data use on the farm. In practice, this includes the costs of searching for suitable tools, comparing providers, agreeing on contracts and data-sharing terms, integrating information across actors, monitoring performance, and ensuring that farmers, workers, advisers, and technology suppliers follow through on commitments.

However, digitalisation also produces wider effects at the level of value chains, rural communities, and the environment. These system-level impacts can operate within and across three digital levels:

1) business process level,
2) digital ecosystem level and
3) socio-environmental level.

System dimensions may include changes in labour demand, knowledge exchange, advisory services, market access, data governance, and relationships among agricultural actors, as well as environmental effects linked to resource management and emissions.

To capture these dynamics, the approach investigated in CODECS analyses digitalisation through three behavioural dimensions, including perceptions and trust, motivations-opportunities–capabilities, and resulting adoption behaviour. Within the CODECS project, research across 20 Living Labs combines focus groups, demonstrations, and stakeholder engagement to analyse these dynamics and assess digitalisation across business processes, digital ecosystems, and socio-environmental systems.

Future relevance. This approach helps policymakers better understand the complex interactions shaping digitalisation in agriculture. By considering behavioural drivers, trust, and systemic impacts, policies can be designed to address barriers, reduce inequalities, and strengthen digital ecosystems. This supports more effective strategies for sustainable agricultural innovation and responsible digital transformation.

1.5 Visioning sustainable digitalisation

Sustainable digitalisation operates as a guiding target which will embrace societal benefits while anticipating and mitigating risks associated with agricultural digital transformation. Sustainable digitalisation is a process of social transformation by which digital technologies are embodied into socio-economic life to promote intra-generational, inter-generational, inter-species wellbeing, reduce inequalities, and improve the health of ecosystems.

Main aim of CODECS is to achieve sustainable digitalisation in the European agri-sector by integrating social, economic, and environmental dimensions. It aims to ensure that digital technologies enhance productivity and efficiency while promoting equitable, long-term sustainability outcomes, rather than reinforcing unsustainable growth or technological inequality.

Approach. In CODECS, sustainable digitalisation is driven through Living Labs, where niche-level experimentation explores innovative practices (Figure 3). Innovation intermediaries encourage stakeholders to adopt responsible digitalisation behaviors, while evaluators monitor sustainability outcomes. The initiative emphasises co-creation, stakeholder engagement, and local adaptation of technologies. It integrates social, environmental, and economic objectives, ensuring that digital tools support broader sustainability transitions rather than purely efficiency gains. CODECS explicitly accounts for system interdependencies, feedback loops, and ethical considerations. By combining experimentation, evaluation, and motivation, CODECS creates pathways for agricultural actors to transition from current practices toward practices that embed sustainability in technological, institutional, and ecological interactions.

Future relevance. The system approach also aligns with a need for a shift in how policymakers think about agricultural digitalisation. Work done in CODECS suggests that the problem is not necessarily a lack of knowledge about what to do, but often a persistent failure to translate that knowledge into sustained, coordinated action. A credible policy vision for sustainable digital transformation must therefore start by treating this as a systematic and multi-level implementation challenge. That means moving away from one-off funding calls and short-term project logic, and instead committing to multi-year roadmaps with adaptive governance mechanisms that can respond to fast-moving technological change and vastly heterogeneous on-the-ground realities.

Critically, such a vision must resist the temptation to treat digitalisation as inherently progressive or beneficial. Policy should instead define what sustainable digitalisation means in agricultural terms: tools and systems that demonstrably reduce environmental burdens, support (rather than monitor and surveil) farmers, and distribute value (including data) fairly across the value chain. The EU's existing frameworks (the Green Deal, the Farm to Fork Strategy, and the CAP) provide useful anchors, but there is no robust baseline against which to measure progress. Establishing credible digital baselines and tying financial support explicitly to sustainability outcomes would give coherence to what is currently a fragmented landscape. Knowledge intermediaries and AKIS actors more generally have a crucial role to play in this.

CODECS D2.1 Conceptual Framework (draft); CODECS D6.2 report on policy environments.

Leanne Townsend (Hutton), leanne.townsend@hutton.ac.uk, Katrine Soma (WUR), katrine.soma@wur.nl, Emīls Ķīlis (BSC), emils.kilis@bscresearch.lv

Figure 3. *Transition pathways through Living Lab experiences and sustainability evaluations in CODECS.*

1.6 The Agricultural Knowledge and Innovation Systems (AKIS) - actors as target group

Agricultural digitalisation depends on effective knowledge exchange among diverse actors, yet the structure and functioning of Agricultural Knowledge and Innovation Systems (AKIS) remains insufficiently understood. Fragmented interactions, unclear roles of intermediaries, and gaps between policy, research, and practice hinder coordinated knowledge flows, limiting the adoption, scaling, and impact of digital innovations in agriculture.

Main aim. The main aim is to analyse actor constellations and governance mechanisms within AKIS surrounding the CODECS Living Labs for agricultural digitalisation. The research seeks to identify key actors influencing innovation processes and to examine which governance mechanisms support or constrain collaboration, knowledge exchange, and the implementation of digital solutions in agriculture.

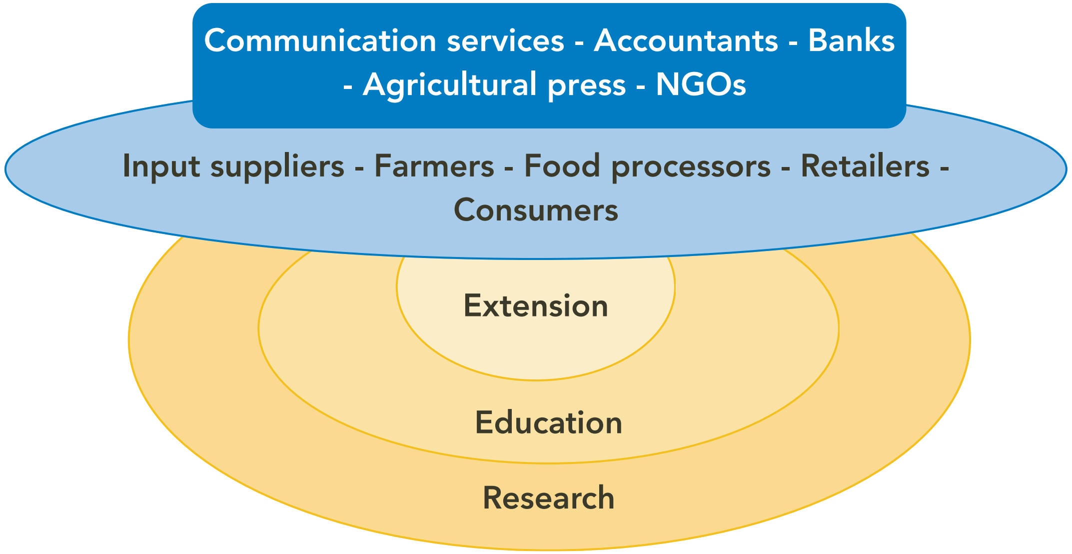


Figure 4. Actors in the Agricultural Knowledge and Innovation System (AKIS) of direct relevance for agricultural innovation in the food chain (Adopted from SCAR AKIS-2012:9).

Approach. The approach analyses AKIS in relation to digitalisation initiatives implemented through CODECS Living Labs (Figure 4). The analysis focuses on actor constellations, interactions, and governance mechanisms that shape knowledge generation, sharing, and application. A socio-ecological systems perspective is used to explore how actors, institutions, and resources interact within specific innovation contexts.

Empirical research was conducted across 19 Living Labs (Figure 5). In each case, stakeholders participated in a structured mapping exercise to identify the actors involved in the focal action situation related to digitalisation. The mapping tool visually represented relationships among actors and enabled participants to reflect on their roles, interactions, and influence within the innovation process. Data were collected through facilitated workshops and discussions with farmers, researchers, advisors, companies, and other stakeholders engaged in the Living Labs.

The analysis followed two cycles of qualitative coding. In the first cycle, relevant actors and governance elements were identified and categorised. In the second cycle, these categories were refined and compared using an AKIS analytical framework to interpret patterns across cases. This approach enabled the identification of key actor types, the role of intermediary organisations, and the governance mechanisms shaping collaboration and knowledge flows. The results provide a comparative overview of how different actors contribute to digital innovation processes within agricultural systems.

Future relevance. Understanding AKIS structures is essential for supporting sustainable digital transformation in agriculture. The analysis highlights the importance of intermediary actors who connect stakeholders, facilitate knowledge exchange, and enable coordination across organisations and governance levels. Strengthening these roles can improve collaboration, enhance learning processes, and accelerate innovation adoption. Future research and policy developments can use AKIS analysis to design more inclusive and effective innovation systems, ensuring that digital technologies contribute to economic viability, environmental sustainability, and resilience in agricultural systems.

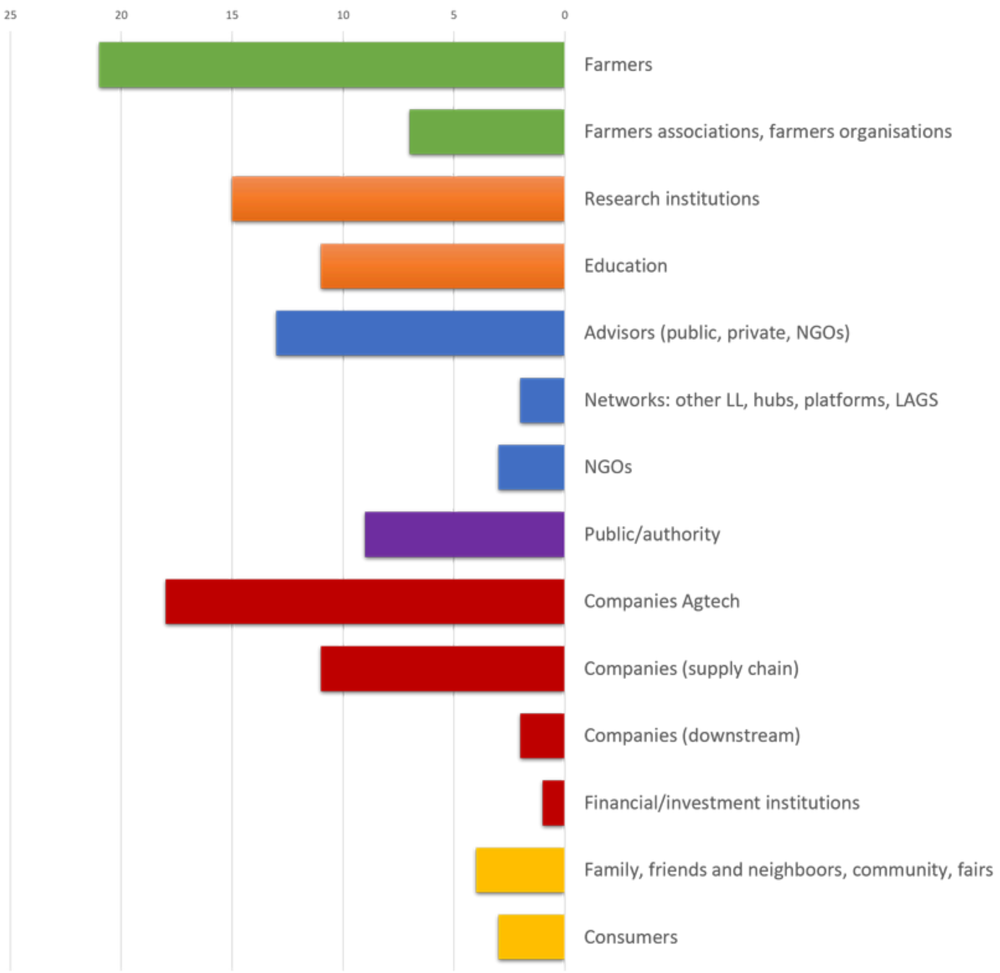


FIgure 5. Frequency of responses in which a type of actor was mentioned during the mapping exercise.

CODECS D3.1 Report on Digital Ecosystems; CODECS D3.2 Report on Digital Ecosystems (final); CODECS D6.1 report on policy environments (draft). Policy brief AKIS.

Beatriz Herrera (HOH), B.Herrera@uni-hohenheim.de and Andrea Knierim (HOH), andrea.knierim@uni-hohenheim.de

2.1 Introduction – costs and benefits at business process level

At business process level, risks of overlooking how digital technologies affect farm operations can lead to low sustainability in digitalisation outcomes. Without analysing changes in tasks, actors, resources, and decision-making, digitalisation may introduce inefficiencies, increase costs, or create organisational challenges, leading to poor adoption outcomes and ineffective policy, advisory, or investment decisions.

The aim of this chapter is to analyse how digitalisation affects agricultural business processes by examining the changes it introduces in actors, tasks, resources, and decision points. This perspective helps identify the specific costs and benefits of digital technologies and improves understanding of how digital tools transform farm-level operations.

The business process methodological approaches. Within the CODECS project, five complementary assessment approaches were developed to analyse digitalisation at the business process level.

- A socio-technical process modelling approach examines how digital technologies reshape farm processes. By combining Business Process Modelling and Requirements Engineering, the method represents actors, resources, goals, and workflows before and after digitalisation, enabling systematic comparison of "as-is" and "to-be" processes.
- A social and human-centred assessment investigates how digitalisation affects farmers, workers, and family members. Using qualitative methods such as workshops and interviews across Living Labs, the approach analyses impact on well-being, skills, quality of work, time management, and social relations within farming systems.
- An environmental assessment applies comparative Life Cycle Assessment to quantify how digital technologies influence resource use, emissions, and environmental impacts of agricultural processes by comparing digitalised and non-digitalised scenarios and identifying environmental hotspots and trade-offs.
- An economic assessment evaluates the financial implications of digitalisation through surveys, budget analysis, and Net Present Value calculations, measuring investment costs, operational changes, productivity gains, and profitability linked to digital technology adoption.
- A Technology Assessment Tool (TAT) supports structured decision-making by comparing digital technologies through a multi-criteria framework across technical, economic, environmental, and usability dimensions, generating ranked results to help farmers and advisors select the most suitable solutions.

Business process level

Future relevance. Assessing digitalisation at the business process level provides valuable insights for improving the design and implementation of digital technologies in agriculture. By analysing operational, social, environmental, and economic impacts, stakeholders can better identify barriers to adoption and opportunities for optimisation. Such integrated assessments support evidence-based policymaking, targeted advisory services, and technology development aligned with farm realities. In the future, these approaches will assist guiding on digitalisation strategies that strengthen productivity, sustainability, and resilience across European farming systems.

In particular, this chapter addresses assessments approaches at business process level focusing on:

1. Process modelling
2. Social/human centered assessment
3. Environmental assessment
4. Economic assesment
5. A Technology Assessment Tool (TAT)

2.2 Procceses modelling

Digital technologies are often introduced into farming without a clear understanding of how they could transform day-to-day business processes. Changes in tasks, roles, decision-making, and coordination remain implicit, making it difficult to assess costs, benefits, and trade-offs or to compare digitalisation effects across contexts.

Main aim. The main aim is to develop and apply a methodology to systematically capture and analyse how digital technologies may transform farm-level business processes. Key research questions address how to represent changes in actors, resources, activities, and information flows after digitalisation, and how to actively involve stakeholders in creating the representations.

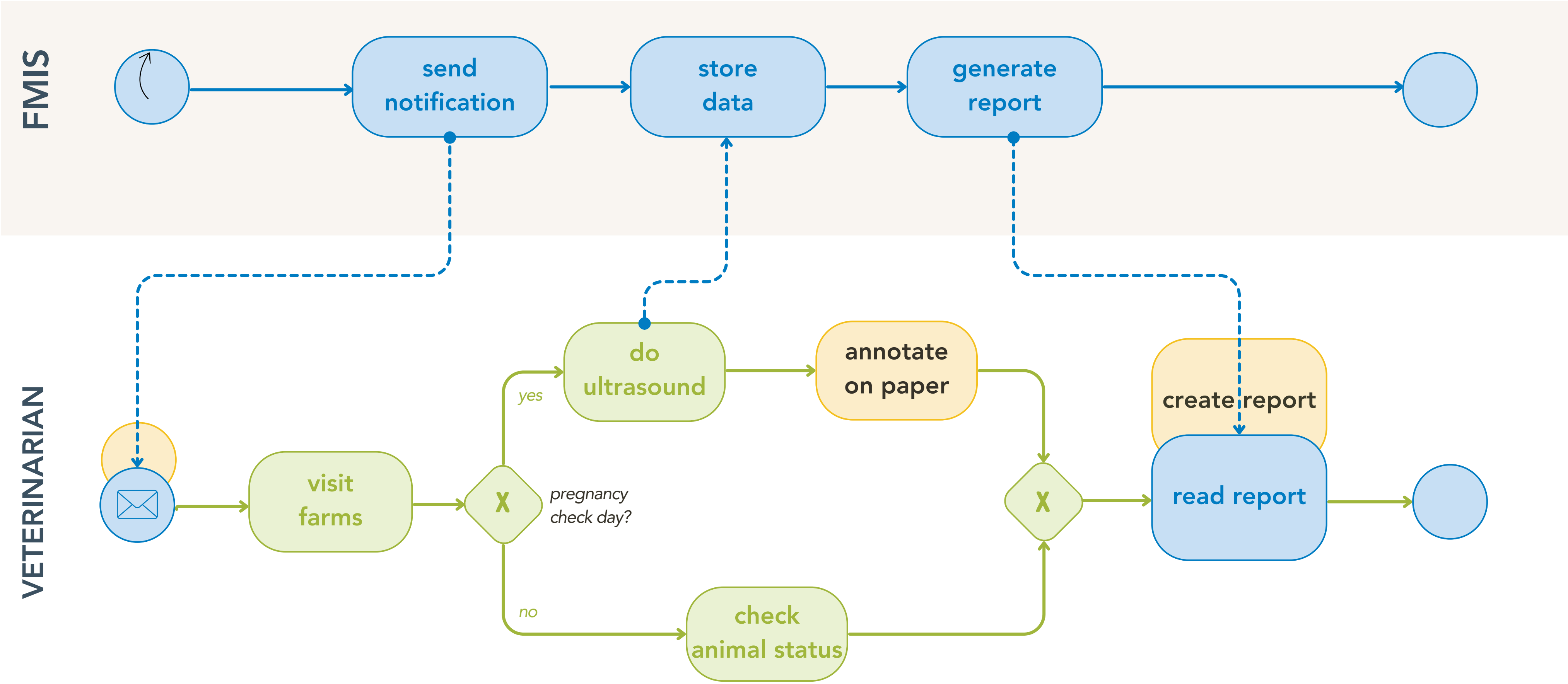


Figure 6. *Example of an activity model or BPMN diagram representing the process transformation through the overlap of before and after.*

Business process level

Approach. The socio-technical process modelling approach combines standard notations from Requirements Engineering (RE) and Business Process Modelling (BPM)—iStar, UML and BPMN—to represent digital transformation through three complementary representations: goal, structure, and activity diagrams. Figure 6 illustrates an example of an activity transformation diagram showing the overlapping views of a veterinarian's farm visit activities before and after the introduction of a Farm Management Information System (FMIS). The diagram highlights the process transformation through a colour-coded system: blue indicates tasks introduced with the digital solution, red indicates tasks removed after digitalisation, and green indicates unchanged tasks. For example, activities such as do ultrasound are unchanged, while new tasks include generate report by the FMIS. Conversely, manual activities such as annotate on paper are removed.

The approach has been applied in CODECS Living Labs following the step-by-step procedure presented in Figure 7. The data needed to derive the representations have been collected at the level of Living Labs, with information structured in pre-designed templates. Process models have been then formalised, representing the process before ("as-is") and after ("to-be") digitalisation. Stakeholders have been involved in validating and refining the models. The main outcomes are the visual representations of process transformation, highlighting added and removed activities, actors, and resources. These outputs enhance the shared understanding among researchers and practitioners, support qualitative cross-case comparison, and provide inputs for cost–benefit analysis.

Future relevance. Socio-technical process modelling captures how digital tools reshape practices, responsibilities, and decision-making on farms. It supports iterative, longitudinal analysis, allowing models to be updated as technologies evolve. Using a shared modelling language enables comparison across farms and technologies while preserving context. The approach links qualitative insights with economic, social, and environmental evaluation, and its visual models facilitate stakeholder dialogue, validation, and learning, making complex process changes accessible and understandable for both researchers and practitioners.

Chiara Mannari (CNR) chiara.mannari@isti.cnr.it and Manlio Bacco (CNR) Manlio.Bacco@isti.cnr.it

CODECS D3.1 Report on Digital Ecosystems; CODECS D3.2 Report on Digital Ecosystems (final); CODECS D6.1 report on policy environments (draft).

Business process level

Figure 7. *Metholodgy to develop process models.*

2.3 Social/human-centred costs and benefits assessment of farm digitalisation

Human and social impacts of farm digitalisation, technologies and policies risk overlooking farmers' real needs and capacities. This may result in technostress, skill mismatches, unequal adoption, and resistance to innovation.

Over time, poorly aligned digital tools could weaken well-being, reduce trust in technology, and undermine the social sustainability of rural communities.

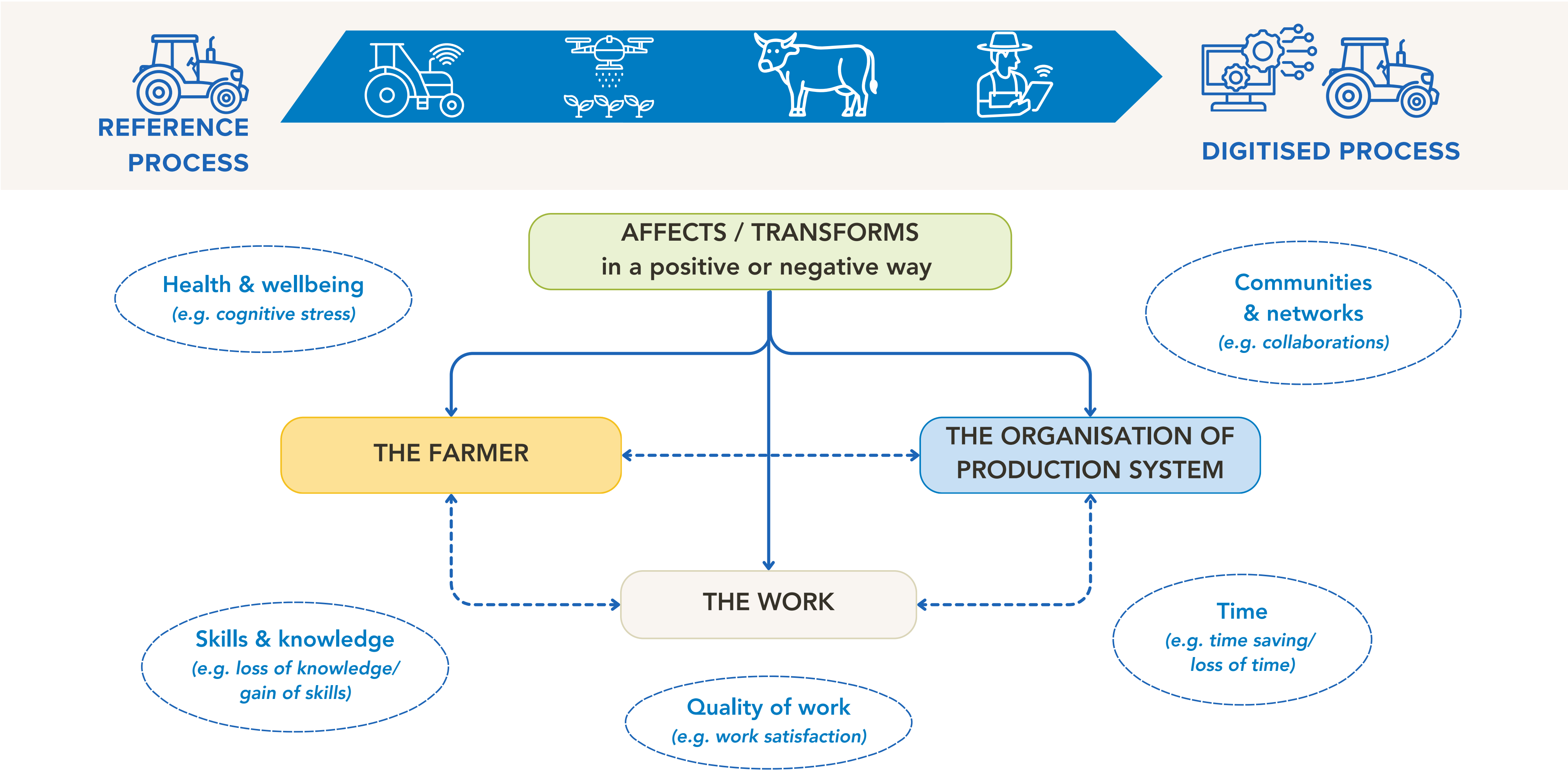


Figure 8. *Human-centered Cost and Benefits digitalisation at the farm level.*

Business process level

Main aim. The main aim is to understand how digital technologies influence farmers' everyday practices, well-being, and social dynamics at the farm level. By focusing on farmers, employees, and family members, the study explores how digitalisation reshapes work organisation, skills, professional identity, and relationships within diverse agricultural systems.

Approach. This assessment adopts a qualitative, human-centred approach to investigate how digitalisation affects individuals within farm businesses. Rather than focusing only on economic efficiency or rates of technological adoption, the approach examines the lived experiences of farmers, employees, and family members. It explores how digital tools influence everyday work routines, decision-making processes, learning needs, and social interactions, as well as how these changes shape well-being and professional identity within agricultural contexts.

Within the CODECS Project, the study followed a structured two-step methodology designed to capture the complexity of human impacts at farm level. The first step involved a multidisciplinary workshop bringing together researchers with expertise in agricultural systems, digital innovation, and social sciences. During this workshop, key dimensions of human impact were identified and structured around three core components: individuals, work, and farm organisation. These components were further translated into five thematic areas used as analytical indicators: Health & Well-being, Skills & Knowledge, Quality of Work, Time, and Communities & Networks. This framework ensured that both tangible and intangible effects of digitalisation could be systematically examined. (Figure 8).

The second step consisted of semi-structured interviews with farmers across 24 farms participating in 14 European Living Labs. The sample included both highly digitalised farms and farms currently undergoing digital transition, covering a variety of crop and livestock systems. Interviews captured both realised experiences and anticipated changes related to the use of digital tools. The collected data were analysed using NVivo and MAXQDA through a hybrid thematic analysis combining deductive coding based on the workshop framework with inductive coding to identify emerging themes. This approach enabled a comprehensive understanding of the benefits and human-centred costs associated with farm digitalisation.

Future relevance. The assessment provides a foundation for integrating human-centred indicators into future digitalisation strategies in agriculture. Building on this framework, future research can combine qualitative insights with quantitative surveys to compare impacts across countries, farm types, and levels of digital adoption. Such evidence can help policymakers, advisors, and technology developers design tools and support measures that reduce technostress, address skill gaps, and strengthen farmers' well-being, autonomy, and social cohesion while promoting inclusive and sustainable digital transformation in agriculture.

CODECS D4.1 Synthesis report on Environmental, Economic and Social C&B of farm digitalisation (draft I); CODECS D4.2 Systhesis report on Environmental, Economic and Social C&B of farm digitalisation draft II); Policy brief Gender dimention.

Alexia Gobrecht (INRAE), alexia.gobrecht@inrae.fr and Mauro Florez (INRAE), mauro.florez@inrae.fr

2.4 Environmental assessment of farm digitalisation

Technologies may be adopted without understanding their full life-cycle consequences. This can lead to hidden trade-offs, such as increased energy use, material demand, or emissions from digital infrastructure. Policymakers and farmers may therefore promote solutions that unintentionally undermine environmental sustainability.

Main aim. The main aim is to evaluate how digital technologies influence the environmental footprint of agricultural processes. By comparing digitalised and non-digitalised farming practices, the assessment identifies changes in energy use, emissions, and resource consumption, and determines which stages of the production system contribute most to environmental impacts.

Approach. This assessment applies the principles of Life Cycle Assessment (LCA) to analyse the environmental implications of digitalisation at the farm process level. LCA is a widely used methodology for evaluating environmental impacts across the entire life cycle of a product or activity, from raw material extraction and production to use and end-of-life. In the context of agriculture, this approach allows researchers to quantify how the introduction of digital technologies modifies resource use, emissions, and environmental pressures within farming operations.

Within the CODECS Project, the methodology follows a comparative design in which each agricultural process is analysed under two scenarios: a reference scenario representing the conventional, non-digitalised process, and a digitalised scenario incorporating the relevant digital technology.

This comparison allows the identification of environmental changes directly attributable to digitalisation (Figure 9).

Data collection combines several sources, including information from Living Labs, farmer interviews, technical documentation, and established environmental databases. These inputs are used to build a Life Cycle Inventory that records all relevant material and energy flows associated with each process

Business process level

FIgure 9. *Principles of comparative LCA in the context of farm digitalisation in CODECS.*

Environmental impacts are then calculated using midpoint indicators such as climate change potential, eutrophication, water consumption, and resource depletion. These results are further aggregated into broader endpoint categories, including Human Health, Ecosystems, and Resources, in order to provide an integrated view of environmental performance.

By applying this cradle-to-grave perspective, the assessment captures impacts from the production, operation, and disposal of both agricultural inputs and digital technologies. Comparative analysis highlights environmental hotspots and reveals where digital tools reduce impacts, such as through improved input efficiency, as well as where trade-offs may occur, for example through increased energy demand and material resources from advanced technologies.

Future relevance. This approach provides a foundation for systematically evaluating the environmental sustainability of digital agriculture. Future research can expand the framework by integrating LCA results with farm-level operational data and qualitative insights from farmers. Including full hardware life cycles, applying multiple functional units, and conducting sensitivity analyses will improve accuracy. Such standardised assessments can support policymakers, advisors, and technology developers in promoting digital solutions that maximise environmental benefits while minimising unintended ecological trade-offs.

CODECS D4.1 Synthesis report on Environmental, Economic, and Social C&B of farm digitalisation (draft I); CODECS D4.2 Synthesis report on Environmental, Economic, and Social C&B of farm digitalisation (draft II).
Co-benefits & costs of digitalisation in agriculture: evidence from Europe (CODECS Knowledge Accelerator Webinar)
Journal article: Environmental assessment of digitalisation in agriculture: A systematic review
CODECS Environmental calculator.

Véronique Bellon-Maurel (INRAE) veronique.bellon-maurel@inrae.fr and Alexia Gobrecht (INRAE) alexia.gobrecht@inrae.fr

2.5 Economic assessment of farm digitalisation

Farmers may invest in technologies without clear evidence of financial viability. This can lead to unexpected costs, poor return on investment, and increased financial risk. Policymakers and advisors may also promote solutions that are economically unsustainable for diverse farm types.

Main aim. The main aim of the economic assessment is to identify and quantify the economic costs and benefits associated with adopting digital technologies in agriculture. By comparing pre- and post-digitalisation scenarios, the assessment evaluates financial performance, investment requirements, and profitability, helping determine whether digital solutions provide sustainable economic value at the farm level.

Approach. This assessment adopts a mixed-methods economic evaluation framework to analyse how digital technologies affect farm-level financial performance (Figure 10). Rather than focusing solely on technological capabilities, the approach examines the economic consequences of adoption, including investment requirements, operational changes, and potential productivity gains. The objective is to capture both direct financial outcomes and broader economic implications associated with digital transformation in agricultural systems.

Within the CODECS project, the methodology follows a structured multi-step process combining qualitative and quantitative analyses. The first step involves a basic economic assessment based on online surveys and qualitative questionnaires completed by farmers participating in Living Labs.

Figure 10. *Mixed method approach for economic evaluations.*

Business process level

These data help identify key categories of costs and benefits associated with digital technologies, including investment costs, installation, maintenance, training requirements, transaction costs, and potential gains such as reduced input use, improved productivity, and increased revenues.

The second step consists of a budget analysis comparing pre- and post-digitalisation scenarios. This analysis examines changes in input costs, operational expenditures, and revenue streams to evaluate how digital technologies influence farm profitability at the business process level. Where sufficient quantitative data are available, a Net Present Value (NPV) analysis is conducted to calculate discounted cash flows over time, allowing long-term economic impacts to be assessed.

To account for uncertainties typical in agricultural systems, sensitivity and stochastic analyses are applied. Mixed method approach for economic evaluations variables such as market prices, yields, or technology performance may affect financial outcomes. The framework is adapted to each Living Lab depending on farm characteristics, technology type, and data availability, ensuring context-specific and realistic economic assessments.

Future relevance. This framework offers a basis for more comprehensive economic evaluations of digital agriculture. Future research can integrate longitudinal data across farms, regions, and technology types to better capture variability in economic outcomes. Combining economic analysis with environmental and social assessments will support holistic sustainability evaluations. The methodology can also feed into digital decision-support tools, helping farmers estimate investment risks and expected returns while enabling policymakers to design targeted incentives that support economically viable digitalisation pathways.

CODECS D4.1 Synthesis report on Environmental, Economic, and Social C&B of farm digitalization (draft I); CODECS D4.2 Synthesis report on Environmental, Economic, and Social C&B of farm digitalization (draft II); CODECS Economic cost calculator.

Alexandra Sintori (ELGO-DIMITRA, AGRERI), sintori@elgo.gr Constantine Iliopoulos (ELGO-DIMITRA, AGRERI), iliopoulosd@elgo.gr and Thomas Giotis (ELGO-DIMITRA, AGRERI) thomgiotis@elgo.gr

2.6 A technology assesment tool (TAT)

Farmers and advisors may struggle to identify digital solutions that truly match their needs. This can lead to inefficient investments, underused technologies, interoperability problems, and limited benefits from digitalisation. As a result, technology adoption may remain fragmented, costly, and less effective in improving farm performance.

Main aim. The main aim of the Technology Assessment Tool (TAT) is to support transparent and structured decision-making when selecting digital agricultural technologies. By systematically comparing alternative solutions across multiple criteria, the tool helps farmers, advisors, and organisations identify technologies that best match their priorities, operational needs, and farming contexts.

Approach. The TAT applies a structured multi-criteria evaluation framework to support the comparison and selection of digital technologies used in agriculture. The approach recognises that technology adoption decisions depend on multiple dimensions, including technical functionality, usability, economic viability, environmental performance, and data management capabilities. By evaluating technologies across these dimensions, the tool enables a comprehensive and transparent comparison of alternative solutions.

Within the CODECS Project, the TAT was developed to evaluate digital tools tested or implemented in Living Labs and to support informed decision-making at the farm level. The tool is structured around two core components: evaluation criteria and technology alternatives.

Nearly 60 criteria are included in the assessment, covering key thematic dimensions such as user experience and accessibility, enabling infrastructure, interoperability, data governance and security, economic impacts, knowledge exchange potential, and environmental sustainability. Each criterion is evaluated using a Likert-scale scoring system, ensuring consistency and comparability across different technologies.

To analyse these data, weights of criteria are calculated using the Entropy Weight Method, which objectively determines the importance of each criterion by the users of the online tool based on variability across technologies. The final ranking is then generated using the TOPSIS method. This approach identifies technologies that are closest to the ideal performance across all criteria and farthest from the least desirable performance. (Figure 11).

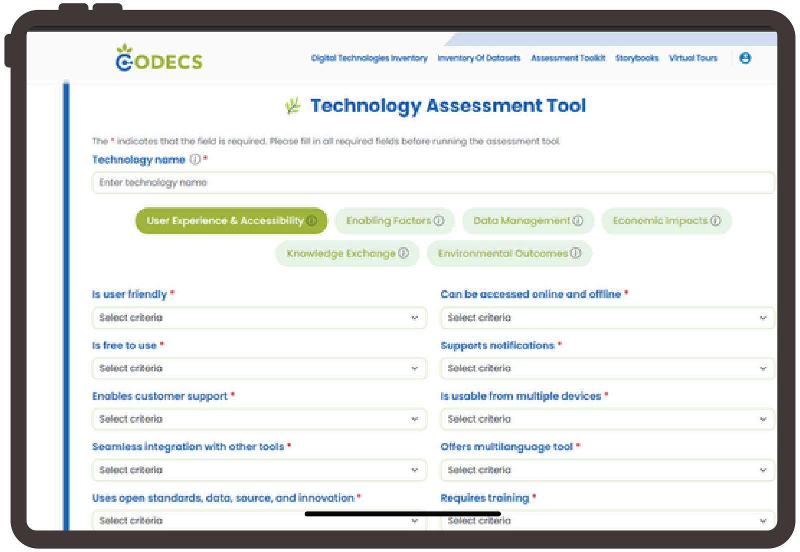


Figure 11. *CODECS Technology Assessment Tool (TAT)*

The tool can be used in two complementary ways. Experts or technology providers can evaluate specific digital solutions based on their technical characteristics, while farmers and advisors can define their preferred technology profile by assigning priorities to the evaluation criteria. The tool then compares these preferences with available technologies and produces a ranked list of the most suitable options.

Future relevance. The TAT provides a scalable framework for guiding the digital transformation of agriculture. As new digital solutions emerge, the tool can be expanded with additional technologies and criteria, ensuring continued relevance for evolving farming systems. By enabling structured comparisons across technical, economic, and sustainability dimensions, the tool can support advisory services, policy design, and farm-level decision-making, helping stakeholders identify technologies that improve productivity, sustainability, and long-term resilience in European agriculture.

CODECS Technology Assessment Tool (TAT); Digital technology inventory.

Mario Petkovski (AGFUTURA) (mario.petkovski@agfutura.com), and Mehdi Hassan Mohammadi (UNIPI) (mehdi.mohammadi@agr.unipi.it)

3.1 Introduction - Costs and benefits at a digital ecosystem level

Ignoring costs and benefits at the digital ecosystem level risks overlooking how infrastructure, institutions, and networks shape digitalisation outcomes. Without this perspective, policies may fail to address barriers such as poor connectivity, weak data governance, or lack of collaboration, limiting innovation, reducing adoption, and reinforcing inequalities across regions and actors.

The aim of this chapter is to introduce approaches addressing costs and benefits of digitalisation from a digital ecosystem perspective. It focuses on the broader set of actors, infrastructures, institutions, and knowledge networks that support or constrain digital transformation in agriculture and influence the adoption and effective use of digital technologies.

Approach. Within CODECS, a Digital Ecosystem is understood as the broader environment in which agricultural digitalisation takes place. It goes beyond technologies alone and includes the dynamic interaction between digital tools, socio-economic conditions, organisational structures, knowledge flows, governance arrangements and physical infrastructures. A Digital Ecosystem 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. Digitalisation in agriculture therefore does not occur in isolation, it is shaped by the actors involved, the institutions governing them, the resources available, and the systems through which information and innovation circulate.

Within this framework, digital ecosystem conduciveness refers to the extent to which this 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. A conducive digital ecosystem is one that creates favourable conditions for the adoption and use of digital solutions, supports collaboration between relevant actors, and helps turn digital opportunities into practical benefits. In agriculture, this includes factors such as access to infrastructure, funding, knowledge, advisory support, governance arrangements, and connections between farmers, technology providers, researchers and other stakeholders.

Farmer readiness, by contrast, focuses on the ability of farmers or farming organisations themselves to engage with digitalisation. It refers to their capacity to adapt to, use and benefit from digital tools in ways that support their own objectives. Digital readiness of farmers is understood as the individual or organisation's ability to adapt and effectively utilise digital technologies and tools in order to achieve their goals and objectives. This includes not only technical skills, but also confidence, knowledge, motivation, access to support, and the ability to integrate digital solutions into everyday decision-making and farm management.

Future relevance. Assessing costs and benefits at the digital ecosystem level is essential for designing policies and strategies that support inclusive and sustainable digital transformation in agriculture. By analysing the broader networks, infrastructures, and institutional conditions that shape digitalisation, stakeholders can identify structural barriers and opportunities for improvement. This perspective helps guide investments in connectivity, knowledge exchange, governance frameworks, and collaboration among actors. In the future, such assessments will be crucial for strengthening resilient digital ecosystems that enable innovation, equitable participation, and long-term agricultural sustainability.

In this chapter, the following assessment approaches are presented:

1. Digital ecosystem conduciveness method
2. Stakeholder perception analysis
3. A sustainability bottom-up approach (VARI)

3.2 Digital ecosystem conduciveness methodological approach

Agricultural digitalisation often fails to deliver expected benefits because technologies are introduced without fully understanding the socio-ecological context in which farms operate. Differences in actors, governance, resources, knowledge flows, and infrastructure across regions create barriers to adoption, making it difficult to identify which conditions enable or hinder successful digital transformation.

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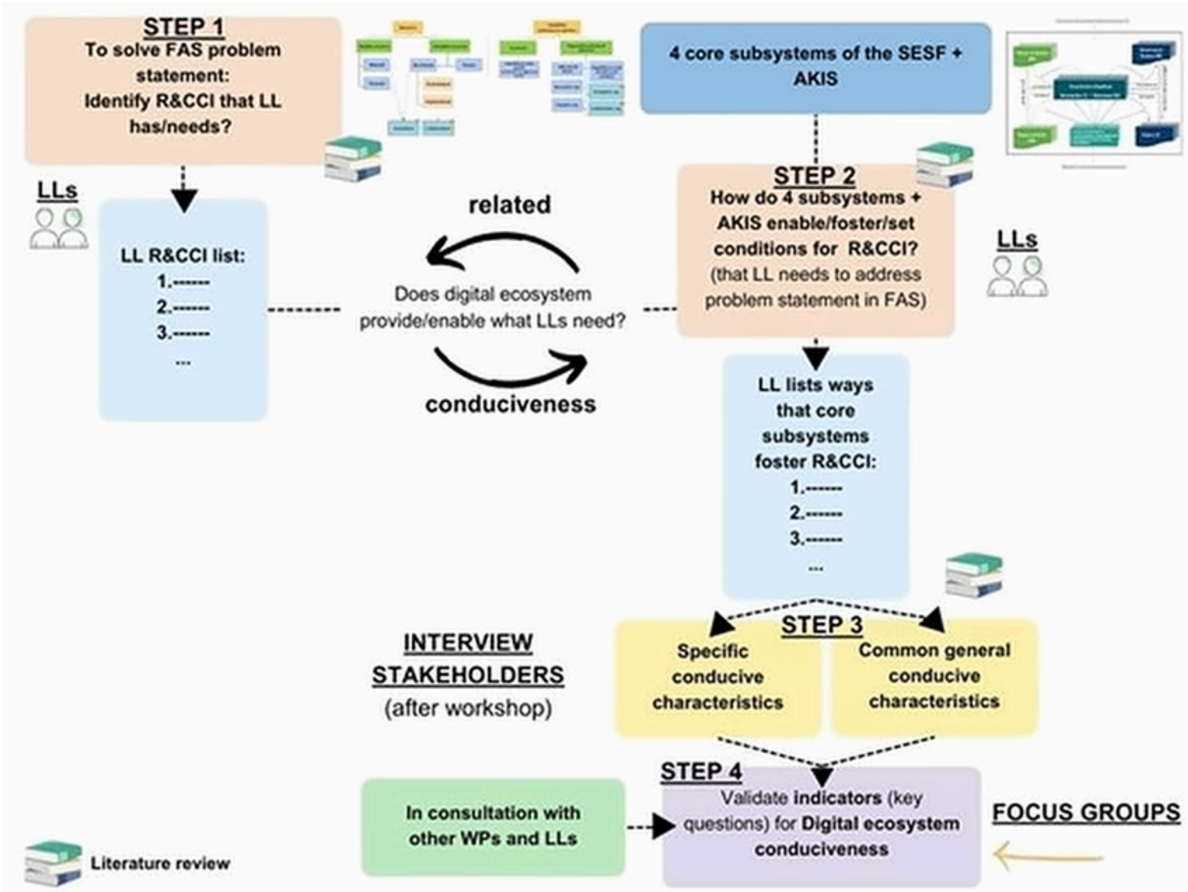

Figure 12. *Resources, Capabilities, Collaborations, and Innovations (RCCIs).*

Digital ecosystem level

Main aim. The aim of the Digital Ecosystem Conduciveness methodological approach is to analyse how socio-ecological conditions influence agricultural digitalisation. It seeks to understand how actors, governance structures, resources, and knowledge flows shape the availability and mobilisation of Resources, Capabilities, Collaborations, and Innovations (RCCIs) within Digital Ecosystems.

Approach. The Digital Ecosystem Conduciveness methodological approach provides a framework to analyse how socio-ecological conditions influence the adoption of digital technologies in agriculture. It combines a systems perspective with a participatory mapping process, drawing on Ostrom's Socio-Ecological Systems Framework (SESF) and the concept of Resources, Capabilities, Collaborations, and Innovations (RCCIs) (Figure 12).

The approach examines how four SESF subsystems, actors, resource units, resource systems, and governance systems, shape the functioning of agricultural Digital Ecosystems. The methodology follows a four-step participatory process applied within CODECS Living Labs. First, stakeholders define their Focal Action Situation (FAS): the key challenge related to digitalisation in their context. In Step 1, participants identify the RCCIs they currently possess and those they require to address the problem. In Step 2, the SESF subsystems are analysed to determine how they influence the availability and mobilisation of these RCCIs. Steps 3 and 4 focus on identifying and validating system-level characteristics and indicators.

Data are collected through workshops involving Living Lab stakeholders and analysed qualitatively using coding software. This process allows researchers to map relationships between actors, resources, governance mechanisms, and knowledge flows. The resulting analysis provides a detailed characterisation of each ecosystem, identifying missing resources, capability gaps, infrastructural constraints, and collaboration opportunities that influence digitalisation pathways.

Future relevance. In the future, the Digital Ecosystem Conduciveness approach can support more targeted and context-sensitive digitalisation strategies in agriculture. By identifying gaps in resources, capabilities, governance, and knowledge flows, it helps policymakers, advisors, and technology developers design interventions that match local needs. The framework can also support longitudinal monitoring of digital ecosystems, enabling researchers to track how changes in infrastructure, skills, and institutional arrangements influence adoption over time and strengthen resilience and adaptive capacity within agricultural systems.

CODECS D3.1 Report on Digital Ecosystems; CODECS D3.2 Report on Digital Ecosystems (final); Policy brief Digital Ecosystem.

Rosa Maria Heredia Hortigüela (UAL), rhh410@ual.es and Cynthia Giagnocavo (UAL), cgiagnocavo@ual.es

3.3 Stakeholder perceptions - a thematic analysis of focus group discussions

Farm digitalisation promises efficiency, productivity, and sustainability gains, but adoption also poses challenges. Costs, risks, and benefits vary across regions, farm sizes, and stakeholder familiarity with digital technologies. Misalignment between available tools and user needs, as well as trust, access, and knowledge gaps, can hinder effective integration of digital innovations.

Main aim. This study aimed to examine how farmers, advisors, and policymakers perceive the economic, social, and environmental costs and benefits of farm digitalisation. It also sought to identify current and future challenges as digital tools become increasingly prevalent in agriculture, to inform evidence-based policies and support sustainable technology adoption.

Approach. The research adopted a qualitative approach based on focus group discussions conducted across several European countries between October 2023 and January 2024. The study was led by AGRERI (ELGO-DIMITRA) and aimed to capture diverse stakeholder perspectives on the implications of farm digitalisation. Each focus group consisted of six to ten participants and was moderated by an experienced facilitator. The optimal session length ranged from 45 to 90 minutes, allowing sufficient time for participants to exchange views and reflect on the topic.

The focus groups followed a semi-structured discussion guide consisting of an engagement question, eight exploration questions, and an exit question (Table 1).

Focus Group semi-structured questions	
Engagement question	• 1. What comes to mind when you hear the term “farm digitalisation”?
Exploration questions	• Bearing in mind the proposed tool/service, do you think it might work? Why? Under what conditions? • How do you think the innovation would change farming activities (operations, organisation, relations in the supply chain, relations with advisers, relations with suppliers)? • How would the innovation contribute to environmental sustainability? Under what conditions? • How would it contribute to farmers' incomes and welfare, quality of work, and gender equality? Under what conditions? • What do you think are the economic, social, and environmental costs associated with the introduction of the proposed digitalisation innovation and who will incur each type of cost? • Would you be willing to pay the associated costs? Up to which level would you be willing to pay? • What kind of problems do you expect to face as more and more farms will become digitalised in the future? • What kind of benefits (economic, social, and environmental) do you expect from digitalisation? Please provide some examples.
Exit question	• Is there anything else you would like to share with us regarding farm digitalisation that you have not shared so far?

Table 1. *Focus group centred around an engagement question, eight exploration questions, and an exit question.*

Participants were asked about their perceptions of digital technologies, their potential impacts on farm management, sustainability, income, and work organisation, as well as the economic, social, and environmental costs associated with adoption. Discussions also explored expected future challenges and benefits as digitalisation becomes more widespread in agriculture. The collected data were analysed thematically to identify recurring concerns, opportunities, and stakeholder priorities regarding farm digitalisation.

Future relevance. Understanding diverse stakeholder perceptions is critical for designing policies that support effective farm digitalisation. Insights from this research help policymakers anticipate challenges, balance costs and benefits, and develop strategies for adoption and education. Future agricultural policy must consider stakeholder capacities, willingness to adopt technologies, and evolving digital demands. Systematic planning and foresight can ensure that digital tools enhance sustainability, efficiency, and resilience, while mitigating risks, fostering equitable access, and aligning technological innovation with broader social, economic, and environmental goals.

CODECS D4.1 Synthesis report on Environmental, Economic, and Social C&B of farm digitalization (draft I); CODECS D4.2 Synthesis report on Environmental, Economic, and Social C&B of farm digitalization (draft II); Journal article: perceptions of the Costs and Benefits of Farm Digitalisation in Europe; Policy brief Farmers motivation.

Constantine Iliopoulos (ELGO-DIMITRA, AGRERI), iliopoulos@elgo.gr, Irini Theodorakopoulou (ELGO-DIMITRA, AGRERI), itheodorakopoulou@elgo.gr, Thomas Giotis (ELGO-DIMITRA, AGRERI), thomgiotis@elgo.gr

3.4 Sustainability outcomes – a context dependent bottom-up approach

Digitalisation in agriculture generates diverse economic, social, and environmental impacts, but these effects vary greatly across regions and farming systems. Current assessments often overlook local conditions and stakeholder perspectives. Without structured, participatory methods to capture contextual priorities within digital ecosystems, policies and innovations risk misaligning with local sustainability needs.

Main aim. The aim is to identify and prioritise sustainability outcomes of agricultural digitalisation within different regional digital ecosystems. The study explores which economic, social, and environmental outcomes stakeholders consider most relevant and how their relative importance varies across Living Labs, supporting context-sensitive and inclusive strategies for sustainable digital transformation in agriculture.

Approach. The study applied a bottom-up, participatory methodology combining Value-Tree Analysis with the Value-Analysis of Relative Importance (VARI) across 14 CODECS Living Labs in Europe. The approach explores sustainability priorities at the level of local digital ecosystems, considering the interactions between farmers, technology providers, advisors, researchers, and policymakers.

The process began with the development of a preliminary value tree based on literature on sustainability and digital agriculture (Figure 13). This initial structure organised potential outcomes hierarchically into economic, social, and environmental dimensions. In the next step, the value trees were discussed and refined through stakeholder workshops within each Living Lab.

Farmers, advisors, researchers, and policy actors collaboratively adapted the outcomes to reflect local realities, priorities, and contextual factors influencing digitalisation in their regional digital ecosystems.

Following this co-creation process, the refined value trees were integrated into a VARI survey. Participants performed pairwise comparisons between outcomes, indicating which outcomes they considered more important and to what degree. These comparisons generated quantitative weightings for each outcome, with the total summing to 100%. The results provided both Living Lab-specific and cross-regional insights, revealing how sustainability priorities differ depending on contextual conditions, governance structures, and levels of digital development within agricultural ecosystems (Figure 14).

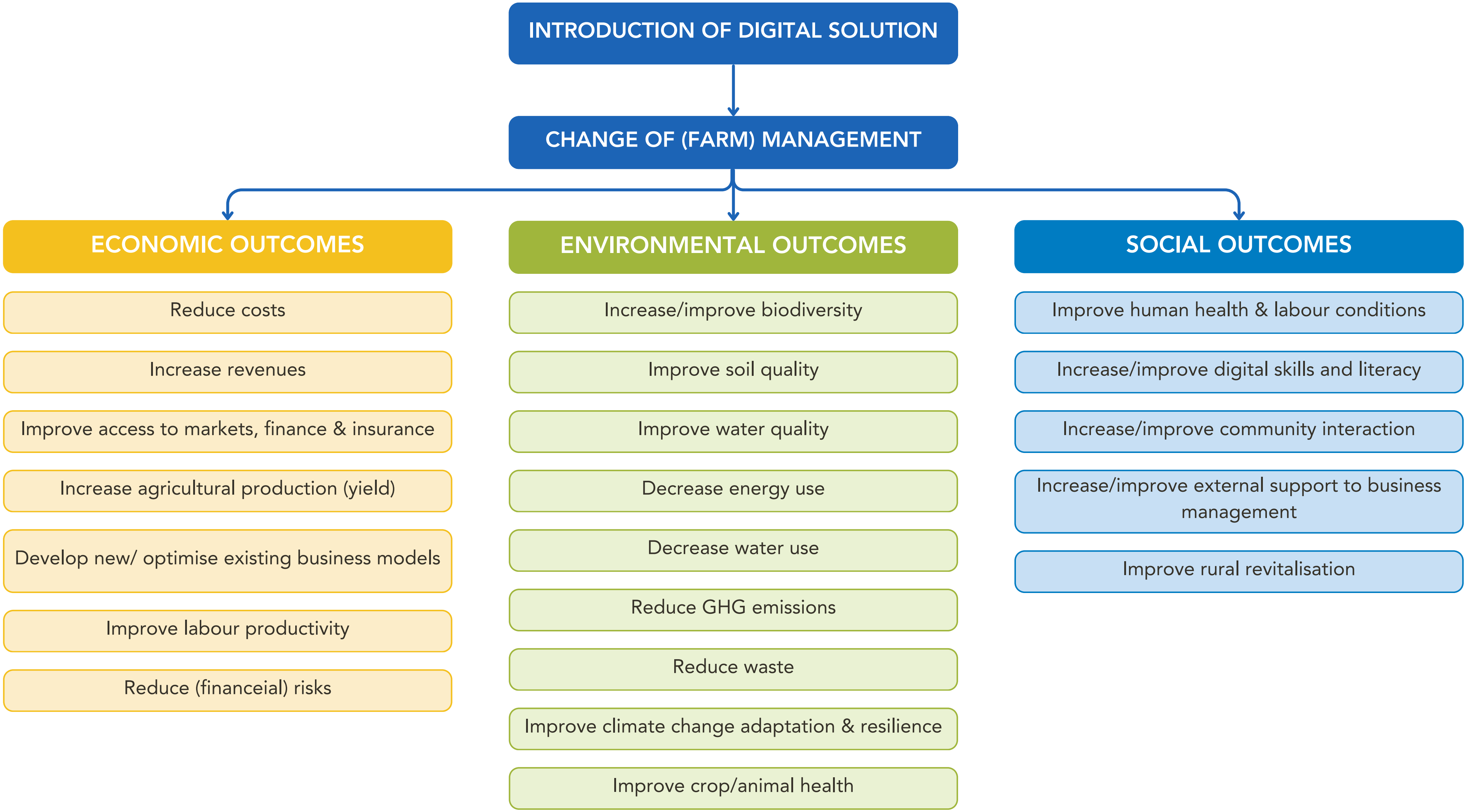

Figure 13. *A value-tree with explanatory factors leading to outcomes of digitalisation at farm process level based on literature review.*

Future relevance. The VARI-based value-tree approach provides a transparent, bottom-up framework for identifying sustainability priorities within agricultural digital ecosystems. By capturing contextual factors and stakeholder perspectives, it supports the design of policies, innovations, and investment strategies that align with local needs.

In future research, the method can be used to monitor evolving priorities, assess the impacts of digital technologies, and compare digital ecosystem dynamics across regions. Integrating VARI with other participatory foresight and evaluation tools can further support adaptive governance and sustainable digital transformation in agriculture.

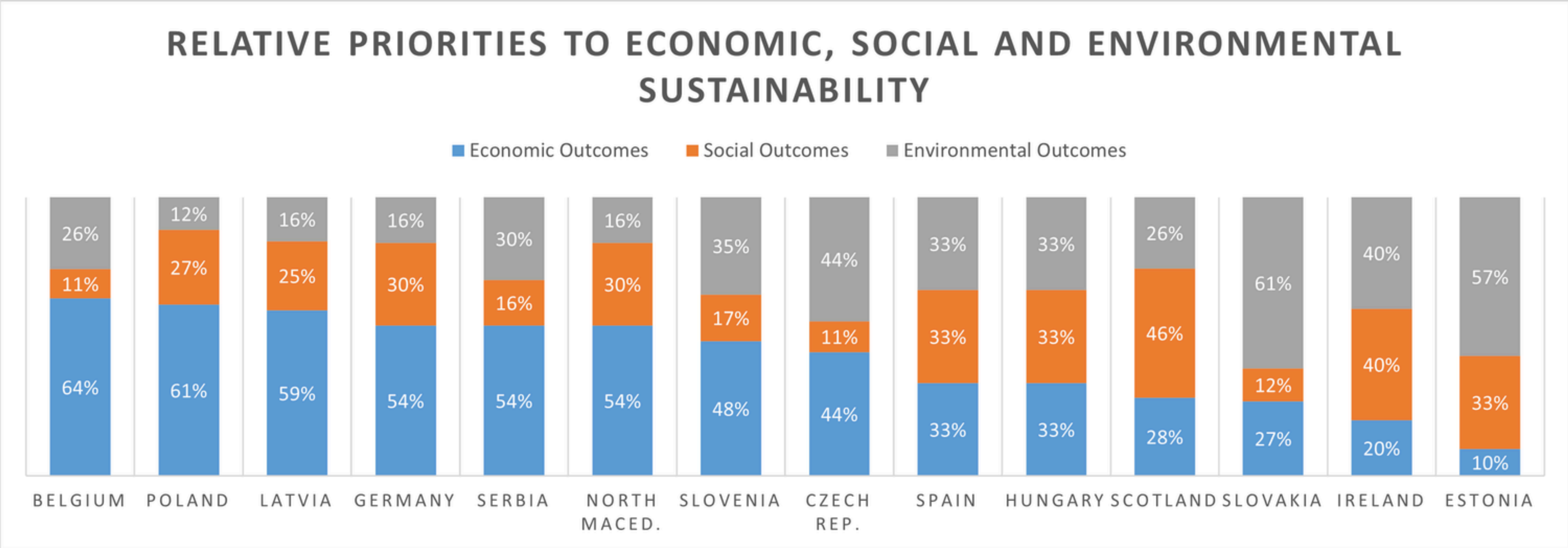

Figure 14. *The relative priority scores of economic, social and environmental sustainability outcomes – comparison across CODECS Living Labs*

CODECS D2.2. Conceptual framework

Femke Meulman (WR) (femke.meulman@wur.nl) and Katrine soma (WR) katrine.soma@wur.nl

4.1 Costs- and benefits at a socio- environmental level

Digitalisation in agriculture is advancing rapidly, yet its broader socio-environmental implications are often poorly understood. Technological change can interact with governance, social relations, and natural resources in complex ways. Without systemic analytical tools, digital transitions risk creating fragmented policies, unintended environmental impacts, and uneven benefits across agricultural communities and regions.

The aim of this section is to introduce analytical approaches that support system-level assessment of agricultural digitalisation. Specifically, the Socio-Ecological Systems Framework (SESF) and Multi-Criteria Assessment (MCA) are presented as complementary tools to analyse interactions within digital ecosystems and evaluate sustainability outcomes across economic, environmental, and social dimensions.

Approach. Two complementary approaches are applied in CODECS to analyse digitalisation at the socio-environmental system level: the Socio-Ecological Systems Framework (SESF) and Multi-Criteria Assessment (MCA). Both provide structured, interdisciplinary tools to understand how digital transformation interacts with agricultural systems and sustainability outcomes.

The SESF offers a conceptual framework for analysing the complex interactions between actors, governance systems, technologies, and natural resources. Originally developed by Elinor Ostrom, the framework conceptualises agricultural systems as interconnected subsystems, including resource systems, resource units, governance arrangements, and actors.

Socio-environmental level

Within CODECS Living Labs, these elements interact through focal action situations where stakeholders experiment with digital solutions and make decisions about technology adoption. Digital ecosystems are analysed as embedded within these broader socio-ecological systems, incorporating digital infrastructures, data resources, governance arrangements, and networks of actors. To further explore these dynamics, the framework is complemented by the Resources, Capabilities, Collaborations, and Innovations (RCCI) perspective, which helps identify how actors mobilise assets, develop capacities, and create innovations within local contexts.

The MCA complements this systemic perspective by providing a participatory evaluation tool. Using scenario-based analysis, stakeholders assess different levels of digitalisation against economic, environmental, and social criteria. Through structured judgement and discussion, the approach highlights potential trade-offs, synergies, and uncertainties associated with alternative digitalisation pathways.

Future relevance. Together, SESF and MCA provide powerful tools for analysing and guiding responsible digital transformation in agriculture. By combining systemic understanding with participatory evaluation, these approaches help identify sustainable digitalisation pathways that balance economic performance, environmental stewardship, and social inclusion. In future research and policy design, they can support comparative learning across regions, improve stakeholder engagement, and inform adaptive governance strategies. As digital technologies evolve, these frameworks will remain valuable for anticipating impacts, managing trade-offs, and strengthening resilient agricultural digital ecosystems.

Hence, in this chapter, the two analytical approaches including the socio-ecological systems framework and the multi-criteria assessment are introduced.

1. Socio-Ecological System Framework (SESF)
2. Multicriteria Analyses Tool (MCA)

4.2 Socio - ecological systems framework (SESF)

Digital transitions in agriculture risk overlooking the complex interactions between actors, governance structures, technologies, and natural resources. This may lead to fragmented understanding, poorly designed policies, and unintended socio-environmental consequences, including increased inequalities, weak governance arrangements, and unsustainable use of natural resources.

Main aim. The aim of applying the socio-ecological systems framework (SESF) in CODECS is to provide a structured and interdisciplinary approach for analysing how digitalisation interacts with social, institutional, and environmental systems. It enables comparison across Living Labs and supports a shared analytical language for understanding digital transformation within agricultural systems.

Approach. The SESF approach. The SESF provides a comprehensive analytical structure for understanding how digitalisation interacts with broader societal and environmental systems. In CODECS, the framework is used to analyse how digital technologies initiate transitions and influence actions within complex agricultural contexts. At its core, the SESF conceptualises systems through several interrelated subsystems: resource systems, resource units, governance systems, and actors. These subsystems interact through processes and decision-making contexts known as focal action situations (FAS). Within CODECS Living Labs, the FAS represents the specific context in which stakeholders interact, experiment with digital solutions, and make decisions about technology adoption and management practices.

The approach. The SESF approach. The SESF provides a comprehensive analytical structure for understanding how digitalisation interacts with broader societal and environmental systems. In CODECS, the framework is used to analyse how digital technologies initiate transitions and influence actions within complex agricultural contexts (Figure 15).

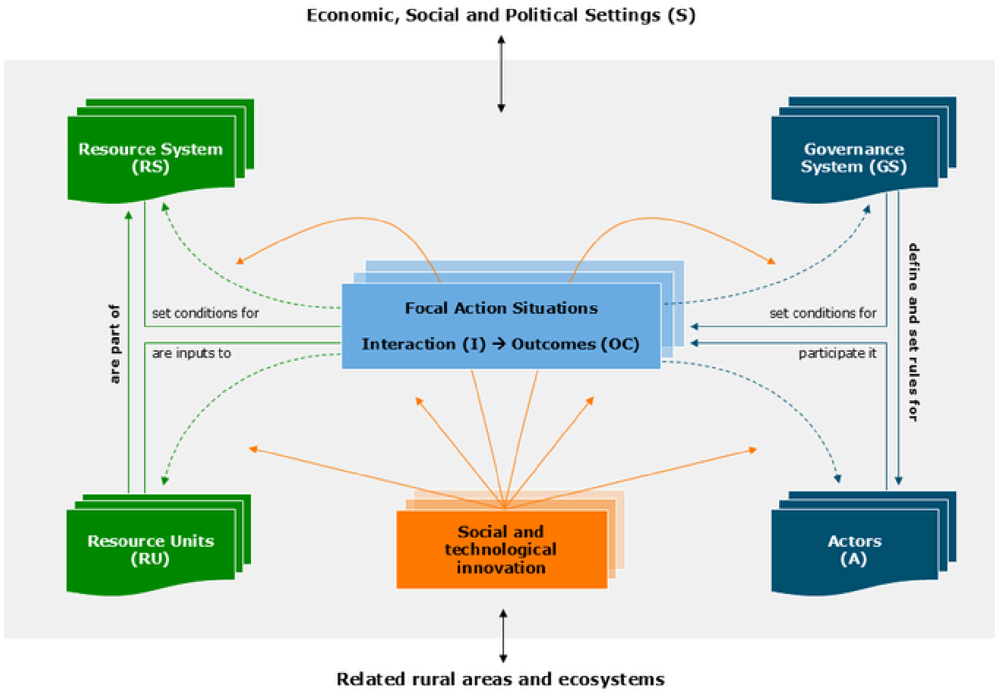

Figure 15. Digitalisation influencing the Socio-Ecological System framework (SESF).

To better understand these interactions, CODECS complements the SESF with the Resources, Capabilities, Collaborations, and Innovations (RCCI) approach.

Future relevance. The SESF will remain important for guiding responsible digital transformation in agriculture. By providing a holistic perspective that integrates social, institutional, technological, and environmental dimensions, it supports better understanding of complex system dynamics. In future research and policy design, SES can help identify conditions that enable sustainable innovation, strengthen digital ecosystems, and improve farmer readiness. It also facilitates comparison across regions and contexts, allowing lessons learned from living labs to inform broader strategies for sustainable and inclusive digitalisation in agriculture.

CODECS D3.1 Report on Digital Ecosystems; CODECS D3.2 Report on Digital Ecosystems (final); Policy brief Digital Ecosystem.

Rosa Maria Heredia Hortigüela (UAL), rhh410@ual.es and Cynthia Giagnocavo (UAL), cgiagnocavo@ual.es

4.3 Multicriteria analyses tool (MCA)

Agricultural systems face increasing pressure to adopt digital technologies, yet their broader impacts on economic, environmental, and social dimensions remain uncertain. Stakeholders often lack a structured way to evaluate how different levels of digitalisation affect the entire system, making it difficult to anticipate trade-offs, risks, and long-term sustainability outcomes.

The aim of the Multi-Criteria Assessment (MCA) is to provide a structured framework to evaluate how different levels of digitalisation influence agricultural systems. By assessing impacts across economic, environmental, and social criteria, the MCA helps stakeholders systematically compare alternative scenarios and better understand potential system-level consequences of digital transformation.

Approach. The MCA supports a transparent and systematic reflection on how digitalisation may influence agricultural systems. The MCA approach is particularly suited to sustainability assessments because it allows the simultaneous consideration of different and often incommensurable evaluation criteria. Economic performance, environmental impacts, and social outcomes cannot always be reduced to a single unit of measurement. Multi-criteria approaches therefore provide a structured way to integrate different "languages of valuation" and make trade-offs between competing objectives explicit (Martinez-Alier, 2002; Munda, 2008). Rather than focusing on individual technologies, the MCA assesses how different levels of digital integration may influence the broader socio-ecological system, including farms, advisory services, supply chains, and rural communities.

The MCA is based on the use of scenarios, which represent different degrees of digitalisation. These scenarios are simplified representations of possible system configurations that assist stakeholders reflect on how the system might function under different conditions. Typically, alternatives and extreme scenarios are considered: a baseline scenario with minimal or no digitalisation, a medium scenario with partial adoption of digital tools, and a strong digitalisation scenario in which technologies are fully integrated and interoperable across the system. The scenarios are not predictions but structured reference points that support consistent comparison across the different living labs.

	Scenario	Impact judgement	Certainty level	Short rationale
Indicator 1 (i.e. support rural vitalisation)	S0 Baseline	(Very negative to Very positive)	(Very uncertain to Very certain)	(1–2 sentences)
	S1 partial digitalisation			
	S2 full digitalisation			

Table 2. *Illustration of how scenarios are evaluated against a set of criteria, specified as indicators.*

The participatory assessment evaluates each scenario against a set of economic, environmental, and social criteria (Table 2). Economic criteria examine aspects such as production costs, revenues, market access, labour productivity, and business resilience. Environmental criteria focus on issues including soil and water quality, biodiversity, resource efficiency, emissions reduction, and climate resilience. Social criteria consider factors such as labour conditions, knowledge exchange, inclusiveness, trust, digital skills, and rural development. For each criterion, stakeholders assess the expected direction and magnitude of impact under the given scenario, typically ranging from very negative to very positive. They also indicate their level of certainty and provide a short explanation of the reasoning behind their judgement. This structured evaluation allows diverse perspectives and knowledge to be incorporated into the analysis.

Future relevance. In the future, the MCA can support strategic planning for digital transformation in agriculture and rural development. By enabling stakeholders to reflect on system-level impacts, the MCA can help identify balanced pathways that maximise economic benefits while safeguarding environmental sustainability and social inclusion, or potential conflicts across stakeholders due to divergence on the importance of different MCA dimensions. It can also inform policy design, research priorities, and investment decisions. As digital technologies evolve, the MCA framework can be adapted to include new criteria, helping stakeholders continuously evaluate emerging opportunities and risks associated with digitalisation.

CODECS Multicriteria Assesment Tool (MAT).

Daniele Vergamini (UNIPI), daniele.vergamini@unipi.it and Fabio Bartolini (UNIPI), brtfba@unife.it

5.1 Introduction - Costs and benefits acrosss Living Lab

Digitalisation in agriculture is often examined through individual technologies or isolated case studies, making it difficult to understand broader transformation processes. Without integrating practical experiences, stakeholder interactions, and conceptual perspectives, knowledge about how digital tools influence farm practices, innovation networks, and sustainability transitions remains fragmented across different levels.

Main aim. The aim of this chapter is to provide an integrated understanding of sustainable digitalisation in agriculture by analysing Living Lab practices, collaboration processes, demonstration activities, and conceptual perspectives across multiple system levels. The chapter explores how digital technologies influence farm operations, innovation ecosystems, and broader socio-environmental transformations.

Approach. This chapter combines empirical insights from Living Labs' activities with analytical and conceptual perspectives to explore digitalisation across multiple levels of agricultural systems. First, Living Labs are mapped according to the level at which farm-level digital technologies generate broader transitions: farm process, digital ecosystem, or socio-environmental systems. This mapping helps clarify how costs and benefits of digitalisation are perceived and experienced across different contexts.

Second, coordinated stakeholder engagement supports data collection and knowledge exchange across the Living Labs are examined. Annual workshops and structured collaboration between researchers, Living Lab coordinators, and stakeholders provide opportunities to gather comparable insights on digitalisation impacts while integrating local perspectives.

Third, Living Labs are analysed as innovation communities that strengthen collaboration networks around digital agriculture. Demonstration farms and participatory activities create environments where farmers, researchers, advisers, and technology providers can jointly explore digital tools and exchange practical experiences.

Fourth, virtual demonstration farms are presented as an additional method to expand knowledge exchange. Interactive virtual tours allow stakeholders to explore digital technologies in real farming environments remotely, improving accessibility and transparency.

Fifth, the chapter develops a conceptual analysis of sustainable digitalisation at business process, digital ecosystem, and socio-environmental levels, identifying key concepts that explain how digital technologies reshape agricultural systems and sustainability transitions.

Future relevance. By combining empirical Living Lab experiences with conceptual analysis, this chapter contributes to a more comprehensive understanding of sustainable digitalisation in agriculture. The approaches presented demonstrate how practical experimentation, stakeholder collaboration, and conceptual reflection can jointly inform digital innovation strategies. In future research and policy development, such integrated perspectives can support more effective digitalisation pathways that strengthen farm resilience, foster inclusive innovation ecosystems, and ensure that technological progress contributes to long-term environmental and societal sustainability.

5.2 Mapping of Living Lab across levels of digitalisation

Digital technologies are increasingly introduced on farms, yet their impacts extend beyond farm operations. Without distinguishing the system levels at which digitalisation drives change; farm processes, digital ecosystems, or socio-environmental systems, it becomes difficult to interpret costs and benefits, compare Living Lab experiences, and understand broader sustainability implications of digital transformation.

The aim of this section is to categorise CODECS Living Labs according to the system level at which farm-level digital technologies contribute to wider transitions: farm process, digital ecosystem, or socio-environmental systems. This helps clarify how costs and benefits of digitalisation are understood and experienced differently across these interconnected levels. (See examples of costs and benefits across different digitalisation levels in Figure 16).

Approach. Based on in-depth interviews with each Living Lab, the approach maps the CODECS Living Labs according to the level at which digital technologies introduced on farms trigger broader system transitions. While most technologies are applied within farm operations, their impacts extend to wider networks and governance structures. Living Labs participating in the analysis were examined using qualitative information on technologies applied, stakeholder interactions, governance arrangements, and reported costs and benefits.

At the farm process level, digitalisation mainly affects production activities and resource management. Living Labs such as Slovakia, Hungary, Slovenia, Serbia, Spain, and Estonia/Latvia demonstrated how sensors, drones, artificial intelligence, and precision irrigation improve irrigation management, input efficiency, biodiversity monitoring, and farm decision-making. These initiatives often generate clear economic and environmental benefits through increased efficiency and reduced resource use. However, they also involve costs related to technology investments, training, maintenance, and the need to interpret complex data.

At the digital ecosystem level, the impacts extend beyond individual farms to the networks of advisors, technology providers, markets, and institutions that support digital agriculture. Living Labs in France, Belgium, and Italy (Puglia and Tuscany) highlighted that the adoption of costly digital tools depends on advisory services, interoperability between technologies, training systems, and governance structures. In these contexts, benefits and costs were strongly influenced by collaboration, institutional coordination, and access to knowledge.

At the socio-environmental level, digitalisation contributes to broader societal, community, and governance outcomes. Living Labs in Scotland, Poland, Ireland, and Latvia demonstrate how digital platforms and communication tools support short supply chains, local markets, community engagement, and rural resilience. In Germany and North Macedonia, digitalisation primarily strengthens education, decision-support systems, and governance structures, building capacity for long-term sustainable digital transformation.

Future relevance. Distinguishing the system level at which digitalisation drives change helps policymakers and researchers better understand how farm-level technologies shape broader agricultural transitions. This perspective enables more targeted interventions, ensuring that investments address not only farm efficiency but also ecosystem coordination and socio-environmental sustainability. In future research and policy design, analysing digitalisation across system levels can support integrated strategies that strengthen knowledge exchange, governance arrangements, and community engagement while promoting resilient and sustainable agricultural systems.

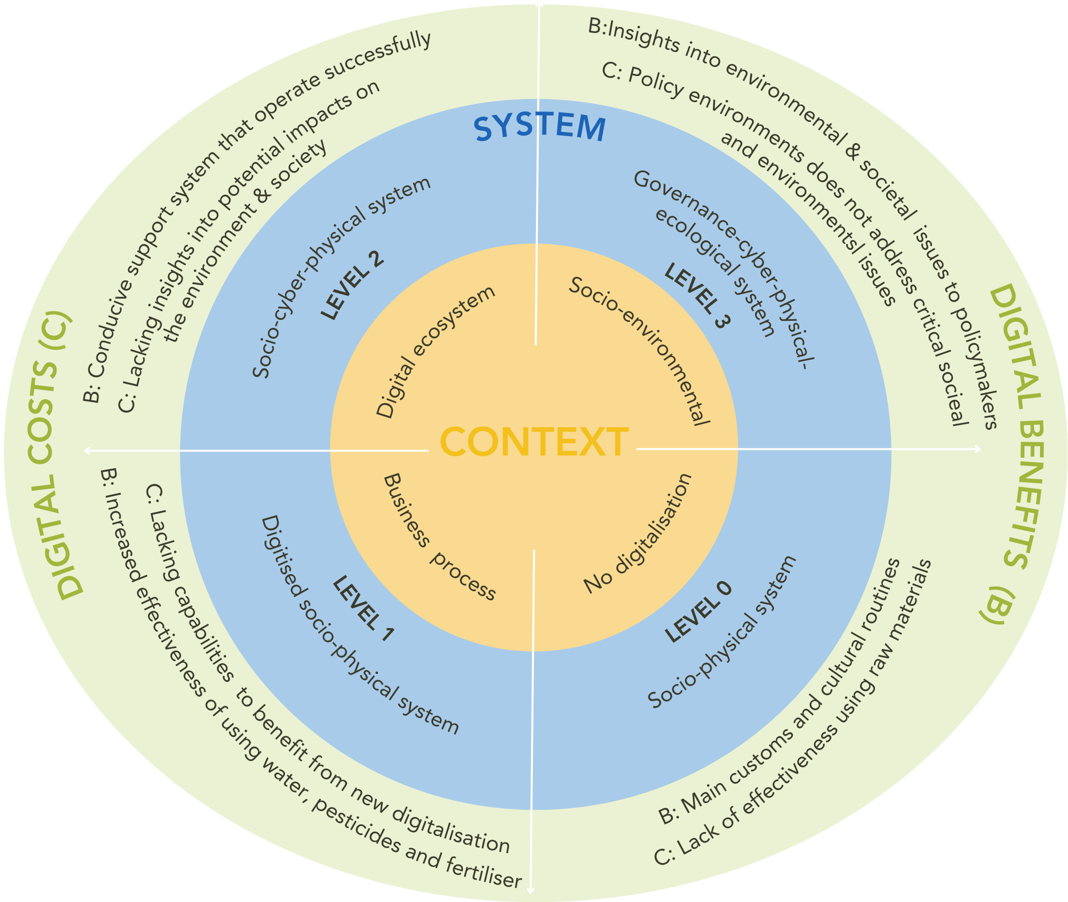

Figure 16. Examples of digital costs and benefits identified across de CODECS Living Labs in different contexts and digitalisation system levels (Soma et al., 2016).

Scientific article: Sustainable digitalisation - a system thinking approache; CODECS D2.1. Conceptual Framework (draft); CODECS D2.2 Conceptual Framework (final); CODECS Policy Brief Conceptual Framework

Katrine Soma (WUR), katrine.soma@wur.nl/ and Gianluca Brunori (UNIPI), gianluca.brunori@unipi.it

5.3 Annual Living lab workshops with multistakeholder interactions

Collecting consistent and high-quality data across multiple Living Labs and research tasks is challenging. Diverse stakeholders, methodological requirements, and local contexts can lead to misalignment, communication gaps, and uneven data quality. Without structured coordination and engagement mechanisms, insights on digitalisation costs, benefits, and sustainability impacts risk becoming fragmented or unreliable.

The aim was to establish an effective coordination structure that ensures reliable, consistent, and context-sensitive data collection knowledge exchange and co-creation across the CODECS Living Labs. Through structured training, collaboration, and stakeholder engagement, the approach supports cooperation between researchers, task leaders, and Living Lab coordinators while generating comparable insights on digitalisation impacts.

Approach. The coordination approach combined structured training, iterative learning, and continuous communication to manage data collection across 20 Living Labs and more than 30 research tasks. The coordination team, led by the University of Pisa (UNIPI) and Wageningen University & Research (WUR), facilitated collaboration between task leaders and Living Lab coordinators through regular trainings, monitoring activities, and feedback mechanisms.

Data collection followed a sequential process including training, fieldwork, reporting, monitoring, and analysis.

LEach new phase began with online training sessions introducing the objectives, methods, and tools required for specific research tasks, such as Agricultural Knowledge and Innovation Systems (AKIS) mapping, process modelling, socio-ecological assessments, and evaluations of digital technologies. Coordinators then implemented these activities locally with stakeholders, collecting qualitative and quantitative data through workshops, surveys, and field observations.

Annual Living Lab workshops formed a central component of this process. Over three years, 20 workshops were organised annually across the Living Labs, creating a total of 60 workshops. These events facilitated knowledge exchange, stakeholder engagement, and reflection on methodological challenges. Interactive tools, such as online collaboration boards, supported dialogue and feedback. Continuous monitoring and individual meetings between researchers and coordinators helped address delays, clarify methodological questions, and adapt procedures to local contexts while maintaining comparability across sites.

Future relevance. The coordination model developed in CODECS demonstrates how structured training, iterative learning, and regular stakeholder engagement can support large-scale, multi-actor research on agricultural digitalisation. Annual Living Lab workshops strengthen collaboration, integrate local knowledge, and improve the quality and relevance of collected data. In future initiatives, similar coordination frameworks can support inclusive innovation processes, enhance cross-regional learning, and generate robust evidence for policy and practice. Such approaches are essential for guiding sustainable digital transformation in Europe's diverse agricultural systems.

CODECS D8.5 Report abour Living Labs setup and results (draft); CODECS D8.6 Report about the Living Labs setup and Results (final).

Livia Ortolani (UNIPI), livia.ortolani@agr.unipi.it, and Femke Meulman (WR), femke.meulman@wur.nl

5.4 Living Labs as innovation communities and collaboration networks

Agricultural digitalisation faces challenges related to fragmented knowledge exchange, limited farmer engagement, and insufficient collaboration among actors in the agricultural innovation ecosystem. Farmers often lack opportunities to observe technologies in real contexts or discuss impacts with peers. Strengthening local networks and shared learning environments is therefore essential to support informed digital adoption.

Main Aim. Agricultural digitalisation faces challenges related to fragmented knowledge exchange, limited farmer engagement, and insufficient collaboration among actors in the agricultural innovation ecosystem. Farmers often lack opportunities to observe technologies in real contexts or discuss impacts with peers. Strengthening local networks and shared learning environments is therefore essential to support informed digital adoption.

Approach. Demonstration activities organised within the CODECS Living Labs were designed to strengthen local networks around agricultural digitalisation by bringing together farmers, researchers, advisers, students and other stakeholders. Through a network of demonstration farms and participatory exchanges, these activities created opportunities for peer-to-peer learning, dialogue and collective reflection on the adoption of digital technologies in real farming contexts**.**

Living Labs function as multi-actor innovation communities organised around specific challenges, where farmers, knowledge intermediaries and other stakeholders collaborate to explore opportunities and constraints related to digital tools.

Within the CODECS project, a network of demonstration farms focusing on agricultural digitalisation was established across the 20 Living Labs and progressively expanded during the project. As demonstration activities developed, additional farms joined the initiative, increasing the diversity of the network across regions and agricultural sectors and reaching 27 demonstration farms by the end of the project.

Figure 17. *The CODECS assesment grid.*

Living lab identification of costs and benefits

Demonstration events mobilised a wide range of stakeholders, including researchers, students, farmers, technology providers, advisers, policy actors and representatives of farmers' organisations. To support structured reflection, Living Labs applied the CODECS assessment grid, which collects participant observations on ecosystem readiness, perceived costs and benefits of technologies, and the demonstration process itself (Figure 17). The insights gathered contribute to understanding farmers' readiness to adopt digital technologies and the functioning of agricultural digital ecosystems.

Future relevance. The networks and collaborations developed through the Living Labs have the potential to continue beyond the project and support long-term innovation communities around digital agriculture. Demonstration farms can remain focal points for peer-to-peer learning, experimentation and dialogue among agricultural stakeholders. In addition, the methods and guidelines developed in the CODECS project, including the demonstration handbook and assessment tools, offer a replicable framework that can be adopted by other regional, national or European organisations seeking to organise demonstration events and strengthen knowledge exchange on agricultural digitalisation.

CODECS Living Labs; CODECS demonstration farms; Past and upcoming CODECS demonstration events; CODECS D5.3 Handbook of demonstration of digital technologies.

Julie Menadi (ACTA), julie.menadi@acta.asso.fr and Ninon Violeau (ACTA), ninon.violeau@acta.asso.fr

5.5 Virtual demonstration farms

Farmers often hesitate to adopt emerging digital technologies due to limited evidence of their practical benefits and concerns about costs and technical reliability. Existing information is frequently difficult to access or poorly communicated, limiting trust and understanding. As a result, knowledge exchange between farmers, researchers, advisers, and technology providers remains insufficient.

The aim is to develop accessible and engaging tools that demonstrate digital agricultural technologies virtually, based on real farming conditions. Virtual tours were designed to improve knowledge exchange and allow farmers, students, advisers, and other stakeholders to remotely explore farms and technologies, supporting informed decision-making regarding the adoption of digital solutions.

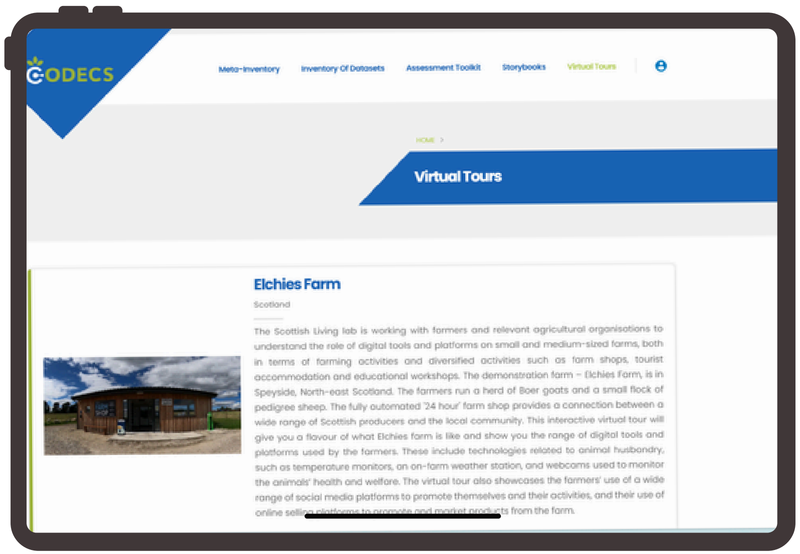

Figure 18. *The virtual tours available on the CODECS website.*

Approach. The approach involved developing a series of interactive virtual tours that showcase digital agricultural technologies in real farming environments. Within the CODECS project, five virtual tours were created across five European Living Labs: remote rural farming communities in Scotland, agri-food technology in Belgium, automated orchard management in Czechia, agri-digital education in Germany, and grassland management using drone technology in Estonia. Each tour provides an immersive digital experience using 360° images, video, audio, and interactive elements that allow users to explore farms and technologies remotely (Figure 18).

The development process followed a collaborative and iterative approach. Living Lab coordinators worked closely with researchers from the James Hutton Institute to design the tours. Each Living Lab first developed a storyboard outlining the narrative, structure, and key technologies to be featured. Storyboards helped organise visual ideas and ensure that the final virtual tour clearly communicated the intended story and learning objectives.

Living Lab teams collected the required materials, including 360° photographs, videos captured using fisheye-lens cameras, conventional images, text descriptions, and audio recordings. These materials were then assembled into immersive environments through digital processing, where images were stitched together and interactive hotspots were added. Regular consultations ensured the tours accurately represented farming practices, while feedback from farmers and Living Lab participants supported continuous refinement.

Future relevance. Virtual demonstration farms offer a scalable and accessible way to support learning and knowledge exchange about digital agriculture. By enabling remote exploration of real farming environments, virtual tours complement physical demonstrations and broaden access for farmers, students, advisers, and policymakers. In the future, such tools can strengthen cross-regional learning, improve transparency around digital technologies, and support more informed adoption decisions. As digital education and advisory services expand, virtual demonstrations may become an important component of innovation ecosystems in agriculture.

CODECS demonstration farms virtual tours

Leanne Townsend (Hutton) leanne.townsend@hutton.ac.uk, Niamh Mahon (Hutton), niamh.mahon@hutton.ac.uk, Tim Pittaway (Hutton), tim.pittaway@hutton.ac.uk

5.6 Conceptual analyses of sustainable digitalisation at multiple levels

Digitalisation in agriculture is often analysed mainly through technological adoption or economic performance, overlooking how it reshapes farming processes, actor relationships, governance arrangements, and environmental interactions. Without a multi-level conceptual perspective, it is difficult to understand how digital tools influence broader socio-technical transitions and sustainability outcomes in agricultural systems.

The aim of this section is to identify and analyse key concepts relevant to sustainable digitalisation across three analytical levels in the CODECS conceptual framework: business process, digital ecosystem, and socio-environmental systems. This multi-level conceptual analysis helps explain how digitalisation influences agricultural practices, actor interactions, governance arrangements, and sustainability outcomes.

Approach. The approach consists of a conceptual analysis of sustainable digitalisation across three analytical levels in the CODECS conceptual framework: business process, digital ecosystem, and socio-environmental systems. The analysis identifies and interprets key techno-social concepts that explain how digital technologies reshape agricultural systems beyond their technical functions.

At the business process level, the focus is on how digital tools transform everyday farm practices and organisational routines. Concepts such as socio-technical processes highlight that farming operations combine technologies, actors, and rules.

Decision-making processes shift from individual experience-based judgement to collective, data-informed decisions supported by sensors, monitoring systems, or decision-support tools.

Role reconfiguration reflects how farmers increasingly act as data managers while advisors and technology providers become integral operational partners. Other relevant concepts include learning loops and adaptation, where experimentation and feedback improve practices over time, as well as process transparency, inclusion and exclusion dynamics, and dependency and control over digital platforms and expertise.

At the digital ecosystem level, the analysis examines concepts that explain interactions among actors and infrastructures surrounding farms. Socio-ecological systems capture relationships between actors, resources, and governance structures. Digital ecosystems describe networks of digital infrastructures, data platforms, and service providers. Concepts such as resource systems, AKIS, knowledge networks, and interoperability help explain how knowledge flows, collaboration, and data integration enable or constrain digitalisation.

Living lab identification of costs and benefits

At the socio-environmental level, concepts such as socio-ecological resilience, environmental stewardship, cultural landscape preservation, social embeddedness, governance and accountability, territorial cohesion, and collective learning explain how digitalisation contributes to broader sustainability transitions across communities and landscapes.

Future relevance. This conceptual analysis helps clarify how digitalisation affects agricultural systems at multiple levels, from farm practices to broader social and ecological dynamics. By identifying key concepts shaping sustainable digitalisation, the framework supports more systematic interpretation of Living Lab experiences and digital innovation pathways. In future research and policy design, such conceptual clarity can guide the development of digital strategies that consider not only technological efficiency but also governance, social inclusion, knowledge systems, and long-term environmental sustainability in agricultural landscapes.

Scientific article: Sustainable digitalisation - a system thinking approache; CODECS D2.1. Conceptual Framework (draft); CODECS D2.2 Conceptual Framework (final); CODECS Policy Brief Conceptual Framework

Katrine Soma (WUR), katrine.soma@wur.nl/ and Gianluca Brunori (UNIPI), gianluca.brunori@unipi.it

Understanding the policy environment and areas of intervention

Despite extensive policy initiatives and repeated recommendations, agricultural digitalisation across Europe remains uneven and slow. Structural barriers, such as fragmented governance, limited connectivity, insufficient digital skills, weak data availability, and misalignment between policy design and on-the-ground realities, continue to hinder effective implementation and the development of coherent, farmer-centred digital transformation strategies.

Main aim. The overall objective of policy-related research activities in CODECS was to develop an evidence-based policy strategy for sustainable digitalisation, consider alternative future scenarios and deliver policy recommendations. This was done by analysing the existing policy environment and policy initiatives in the field of digitalisation, exploring the role of innovation intermediaries and discussing future scenarios with agents of change. This has laid the groundwork for proposing policy tools and policy interventions that will aid policymakers in making decisions conducive to sustainable digitalisation.

A multi-method approach. A multi-method approach. A three-pronged approach was used to assess the EU policy environment for agricultural digitalisation. First, a systematic review of around 150 EU-funded projects via the CORDIS database established a strong evidence base. Second, EU and national policies were mapped, cataloguing legislation, strategies, and programmes and linking them to CODECS Living Labs. Third, 101 semi-structured interviews (2024-2025) with policymakers, experts, and industry representatives across 18 EU and three non-EU countries provided in-depth insights.

These qualitative findings were combined with four quantitative pillars: These qualitative findings were combined with four quantitative pillars: 1) digital readiness (DESI), 2) farm structure, 3) farmer demographics, and 4) policy momentum, to produce a composite digitalisation score for each country. This design captures both policy frameworks and on-the-ground realities shaping digital transformation.

Moreover, to analyse innovation intermediaries within Agricultural Knowledge and Innovation Systems (AKIS), a dedicated three-step approach was applied. First, policy documents and EU projects (AgriLink, i2connect, LIAISON, PRO AKIS) were reviewed to examine how intermediaries are positioned within digitalisation processes. Second, findings from CODECS Living Labs mapped the AKIS actors with whom stakeholders interact. Third, a survey of actors in Germany, Italy, Latvia, and France explored perceptions of AKIS policies, Living Labs, and the roles, resources, and services of intermediary organisations. Results highlight the growing importance of intermediaries, especially private firms, in connecting farmers, advisors, and technology providers, though their roles remain unevenly recognised and supported.

Main findings and outcomes. Agricultural digitalisation largely mirrors overall digital development, influenced by connectivity, human capital, governance, and economic conditions. Significant variation exists within and between countries, leading to four distinct clusters with different levels of farm digital maturity. There is no single pathway: outcomes depend on how structural factors interact. Strong enabling conditions, such as effective institutions, infrastructure, skills, and access to finance, can support more successful transitions.

Despite consistent focus on infrastructure, data, skills, and regulation, recommendations have changed little over time, pointing to an implementation gap. Intermediaries play a crucial role in bridging this gap by translating policy into practice and facilitating knowledge exchange. However, fragmented governance, uneven skills, and limited coordination constrain their effectiveness. Persistent data gaps at various levelss also limit monitoring and evaluation.

Overall, there is no single trajectory toward agricultural digitalisation. Distinct pathways arise from the interaction between several factors. Successful and sustainable digitalisation in agriculture is more readily achieved where foundational conditions are strong. These include effective governance and institutions, connectivity, skilled labour force, competitive markets, access to finance, but also the absorptive capacity at farm, regional and national levels to identify, acquire and integrate new knowledge and technologies (Figure 19).

Despite consistent focus on infrastructure, data, skills, and regulation, recommendations have changed little over time, pointing to an implementation gap. Intermediaries play a crucial role in bridging this gap by translating policy into practice and facilitating knowledge exchange. However, fragmented governance, uneven skills, and limited coordination constrain their effectiveness. Persistent data gaps at various levelsfarm level also limit monitoring and evaluation.

Over the last decade, policy recommendations have tended to focus on similar issues. These recommendations generally converge on six thematic areas: infrastructure and connectivity; data and governance; AKIS, skills, and capacity building; political, financial, and legal frameworks; tools and technologies; and social aspects.

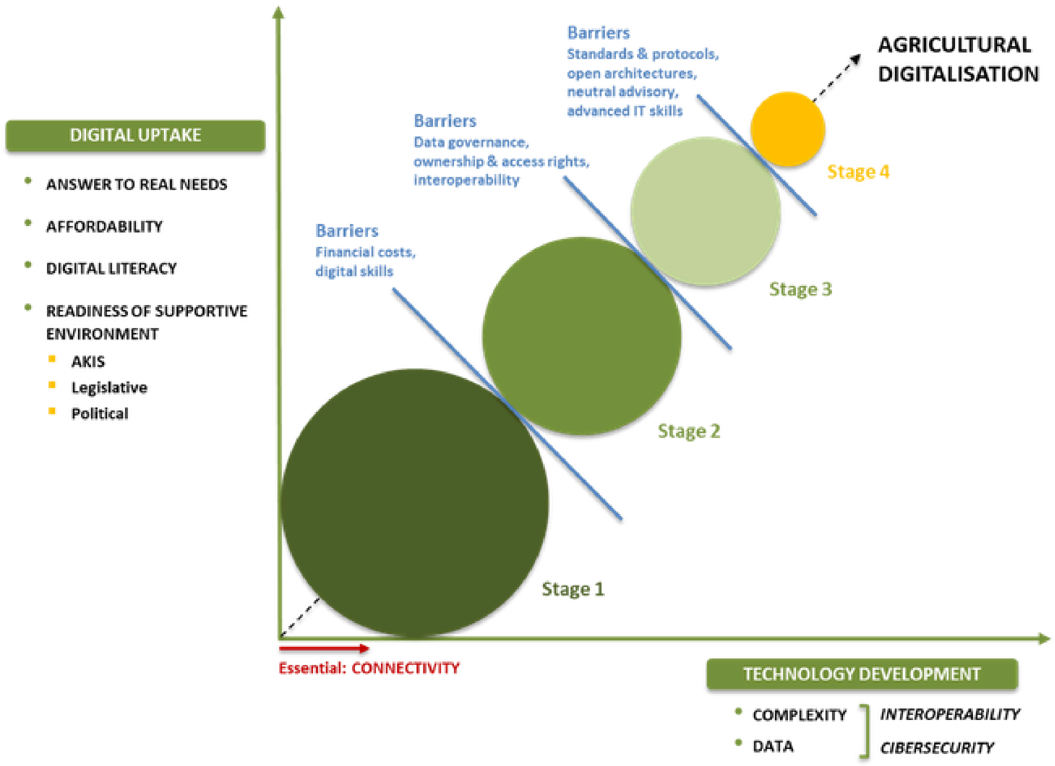

Figure 19. *Agricultural digitalisation.*

Crucially, the core recommendations remain largely unchanged, indicating an implementation gap, rather than a knowledge gap.e last decade, policy recommendations have tended to focus on similar issues.

Facilitation of sustainable digital transformation requires good governance, strong institutional capacity and a systematic approach A proactive policy vision and coordination of efforts across all policy layers to ensure alignment and continuity of digitalisation efforts is essential.

his needs to be supported by robust EU-level regulation on data and cybersecurity. Furthermore, informed decision making is fundamental to ensure that policy interventions are fit for purpose. Currently, a lack of granular data on digitalisation at the farm level and digitalisation-related expenses is a persistent major barrier for the design and evaluation of digitalisation policies in agriculture. Existing indicators on digitalisation in agriculture often leave decision makers with an incomplete picture of digital readiness and use.

Relevance for policymakers: CODECS combined a systematic review of EU funded research, a comprehensive mapping of EU and national level digital agriculture policies, and semi structured interviews with policymakers, experts, and industry representatives. It was concluded that effective digital transformation requires coherent governance, institutional capacity, and coordinated action across EU, national, and regional levels. No single policy instrument is sufficient; integrated approaches are needed to address structural barriers. Policies must better recognise and support intermediaries as core actors, ensuring coordination between public and private services.

Closing the digital skills gap remains critical, requiring stronger advisory systems, education, and lifelong learning. A farmer-centred design, through co-design, demonstration farms, and peer learning, can ensure relevance and uptake. While the Common Agricultural Policy (CAP) is an important driver, it is not sufficient on its own due to limitations in indicators and bureaucracy. Hence, a more coordinated, data-informed, and farmer-focused policy approach, combined with stronger support for intermediaries, is essential to achieve sustainable digitalisation in the European agriculture.

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Future relevance. Work done in CODECS shows that the policy environment is heterogeneous and agricultural digitalisation is a gradual, multi-stage process shaped by technical, economic, social, and institutional factors that vary significantly across farms and member states. This challenges the assumption that policy, applied uniformly, will produce broadly equivalent results across agriculture in the EU. A more contextually literate policy approach would start from the opposite premise: the same intervention and digital tool, deployed in two different contexts, may succeed in one and fail in the other not because of the technology itself, but because of the surrounding conditions and absorptive capacity - connectivity, advisory capacity, social trust, farm structure, and institutional quality.

CODECS D6.2 report on policy environments

María del Mar Delgado-Serrano (UCO), es2desem@uco.es and Pierre Labarthe (INRAE), pierre.labarthe@inrae.fr

A roadmal of costs and benefits of sustainable digitalisation

The baseline of the CODECS Methodological Handbook is to support pathways towards sustainable digitalisation in the European agri-sector, balancing innovation with environmental, economic, and societal objectives. Insights from Living Lab demonstrations inform analyses of farm processes, digital ecosystems, and broader socio-environmental systems.

Integrated within the CODECS Conceptual Framework, these multi-level analyses support informed decision-making, stakeholder engagement, and evidence-based policymaking (Figure 20).

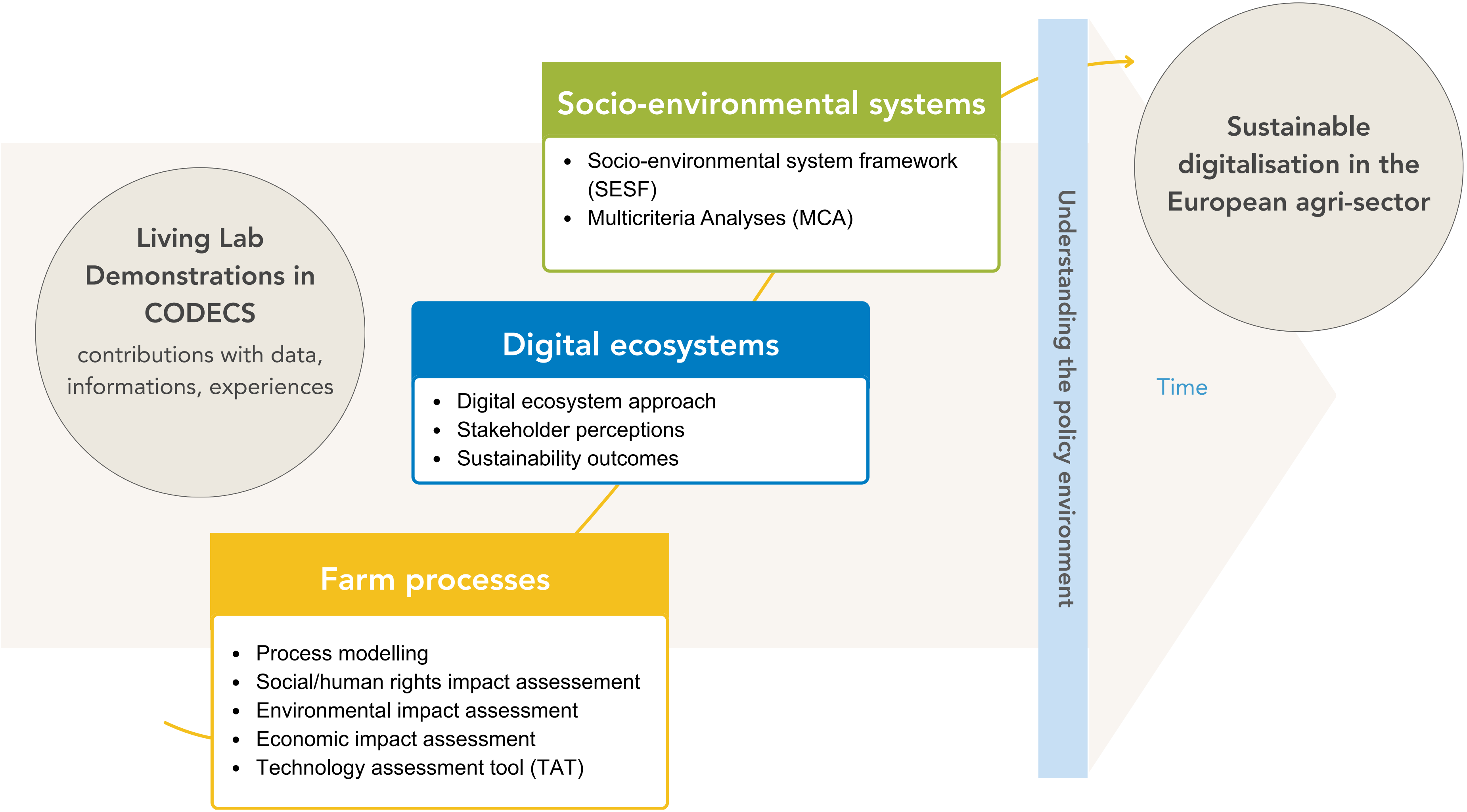

Figure 20. *A roadmap towards sustainable digitalisation in the European agri-sector.*

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