SUSTAINABLE DIGITALISATION: A CONCEPTUAL FRAMEWORK, FINAL M40

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KATRINE SOMA (WR), GIANLUCA BRUNORI (UNIPI), EMILS KILIS (BSC), CONSTANTINE ILIOPOULOS (ELGO-DEMETER), FEMKE MEULMAN (WR), CYNTHIA GIAGNOCAVO (UAL), ROSA MARIA HEREDIA HORTIGÜELA (UAL), ELISABETH OBENG (WR), IRENE NAVARRO DEL AGUILA (COEXPHAL), STEFANO GRANDO (UNIPI), MANLIO BACCO (CNR), ALESSIO FERRARI (CNR), CHIARA MANNARI (CNR), REINOUT GODAERT (EV ILVO), ANDREA KNIERIM (UNI HOHENHEIM), BEATRIZ HERRERA (UNI HOHENHEIM), LEANNE TOWNSEND (HUTTON), MARIO PETKOVSKI (AGFT), RAFAEL SERAFIN (ISO-TECH), GORAN KITIĆ (BIOS), SIMONA STOJANOVA (UL), LIVIA ORTOLANI (UNIPI), TIZIANA NADALUTTI (UNIPI), DANIELE VERGAMINI (UNIPI), VIKTORIA MARGIT VONA (SZE), PENNY ZAFIRAKI (AUA), EMILIJA STOJMENOVA DUH (UL), ARGENE SUPERINA (UL), JOANNA STORIE (EMU), MICHAEL PAULUS (UNI HOHENHEIM), VINETA GAILITE (EMU), ZUZANA PALKOVA (NEW EDU), MAIJA USCA (BSC), ALINA SILVI (UNIPI), GLADYS SÁNCHEZ GARRIDO (COEXPHAL), MARK RYAN (WR)

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Authors	Katrine Soma (WR), Gianluca Brunori (UNIPI), Emils Kilis (BSC), Constantine Iliopoulos (ELGO-DEMETER), Femke Meulman (WR), Cynthia Giagnocavo (UAL), Rosa Maria Heredia Hortigüela (UAL), Elisabeth Obeng (WR), Irene Navarro Del Aguila (COEXPHAL), Stefano Grando (UNIPI), Manlio Bacco (CNR), Alessio Ferrari (CNR), Chiara Mannari (CNR), Reinout Godaert (EV ILVO), Andrea Knierim (UNI HOHENHEIM), Beatriz Herrera (UNI HOHENHEIM), Leanne Townsend (HUTTON), Mario Petkovski (AGFT), Rafael Serafin (ISO-TECH), Goran Kitić (BIOS), Simona Stojanova (UL), Livia Ortolani (UNIPI), Tiziana Nadalutti (UNIPI), Daniele Vergamini (UNIPI), Viktoria Margit Vona (SZE), Penny Zafiraki (AUA), Emilija Stojmenova Duh (UL), Argene Superina (UL), Joanna Storie (EMU), Michael Paulus (UNI HOHENHEIM), Vineta Gailite (EMU), Zuzana Palkova (NEW EDU), Maija Usca (BSC), Alina Silvi (UNIPI), Gladys Sánchez Garrido (COEXPHAL), Mark Ryan (WR)
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CODECS

Project Coordinator	University of Pisa

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CONTENTS

EXECUTIVE SUMMARY 4

1 INTRODUCTION – VISIONING TOWARDS SUSTAINABLE DIGITALISATION 9

2 METHODOLOGICAL APPROACH 10

2.1 Participatory theory building 10

2.2 Value-tree analysis of contextual Living Lab sustainability outcomes 11

2.3 CODECS research examples operating at different levels 13

3 THE CODECS CONCEPTUAL FRAMEWORK – CONTEXTUAL FACTORS MATTER 14

4 LIVING LABS TRANSITIONING TOWARDS SUSTAINABLE DIGITALISATION 16

4.1 An overview of the Living Labs in CODECS 16

4.2 Living Labs operating at different levels and different contexts 21

4.2.1 An overview of contextual operations of Living Labs at different digitalisation level 21

4.2.2 Living Lab contributions to business process context level 25

4.2.3 Living Lab contributions to digital ecosystem context level 26

4.2.4 Living Lab contributions to socioenvironmental context level 27

4.3 Main challenges and opportunities towards sustainable digitalisation 27

4.3.1 Sustainable digitalisation as a main objective across Living Labs 27

4.3.2 Main challenges across Living Labs 30

4.3.3 Main opportunities across Living Labs 33

4.4 Main costs and benefits per Living Lab 35

4.5 Main learning contributions per Living Lab 39

5 VISIONING SUSTAINABLE DIGITALISATION ACROSS LIVING LABS 41

5.1 Overall comparison of the relative priorities sustainable digitalisation outcomes 41

5.2 Sustainability outcomes per Living Lab, including value-trees and priority scores 43

5.3 Summary of the participatory theory building outcomes 58

6 CONCEPTUAL ANALYSES OF SUSTAINABLE DIGITALISATION AT MULTIPLE LEVELS 60

6.1 Overview 60

6.2 Conceptual analyses at business process level 61

6.2.1 Selected business process level concepts and their relevance in CODECS 61

6.3 Conceptual analyses at digital ecosystem level 62

6.3.1 Selected digital ecosystem level concepts and their relevance in CODECS 62

6.4 Conceptual analyses at socioenvironmental level 64

6.4.1 Selected socioenvironmental level concepts and their relevance in CODECS 64

7 POLICY IMPLICATIONS AND MAIN ADVICE 66

7. CONCLUDING REMARKS 68

REFERENCES 70

APPENDIX 1. CODECS' ASSESSMENT METHODOLOGIES CARRIED OUT ACROSS WPS, AT DIFFERENT LEVELS 73

APPENDIX 2. POLICY BRIEF: CONCEPTUAL BASIS OF SUSTAINABLE DIGITALISATION 77

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TABLES

Table 1 – A brief overview of the 20 Living Labs in CODECS 19
Table 2 – Living Labs (the 16 taking part in the Teams talks) categorised into main digitalisation levels 24
Table 3 – Summary table of outcomes of the participatory theory building across 14 Living Labs in CODECS engaged in developing a value-tree with relevant context factors including economic, social and environmental sustainability outcomes of digitalisation, and in assigning weights to reflect on relative relevance to the different sustainability outcomes in their specific context (highest priority scores marked in red) 59
Table 4 – Concepts with relevance for business process contexts, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation 61
Table 5 – Concepts with relevance to digital ecosystem context, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation 63
Table 6 – Concepts with relevance to socioenvironmental contexts, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation 65

FIGURES

Figure 1 – A value-tree with explanatory factors leading to outcomes of digitisation at farm process level based on literature review 12
Figure 2 – Example question in VARI survey 13
Figure 3 – The CODECS Conceptual Framework adopts a systems approach for assessments of costs and benefits of agricultural digitalisation across three interrelated dimensions of sustainability: social, economic, and environmental 14
Figure 4 – The relative priority scores of economic, social and environmental sustainability outcomes – comparison across the Living Labs 42
Figure 5 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in the Belgian Living Lab 43
Figure 6 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Belgium 44
Figure 7 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in the Serbian Living Lab 44
Figure 8 – The relative priority scores of economic, social and environmental sustainability outcomes in Serbian LL 45
Figure 9 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this German Living Lab 45
Figure 10 – The relative priority scores of economic, social and environmental sustainability outcomes in the German LL 46
Figure 11 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this North Macedonian Living Lab 46
Figure 12 – The relative priority scores of economic, social and environmental sustainability outcomes in the North Macedonian LL 47
Figure 13 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Polish Living Lab 47
Figure 14 – The relative priority scores of economic, social and environmental sustainability outcomes in the Polish LL 48
Figure 15 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Slovakian Living Lab 49
Figure 16 – The relative priority scores of economic, social and environmental sustainability outcomes in Slovakian LL 49

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Figure 17 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Estonian/Latvian Living Lab 50
Figure 18 – The relative priority scores of economic, social and environmental sustainability outcomes in the Estonian/Latvian LL 50
Figure 19 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Irish Living Lab 51
Figure 20 – The relative priority scores of economic, social and environmental sustainability outcomes in the Irish LL 51
Figure 21 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Scottish Living Lab 52
Figure 22 – The relative priority scores of economic, social and environmental sustainability outcomes in the Scottish LL 52
Figure 23 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Living Lab in Slovenia 53
Figure 24 – The relative priority scores of economic, social and environmental sustainability outcomes in the Living Lab in Slovenia 54
Figure 25 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Spanish Living Lab 54
Figure 26 – The relative priority scores of economic, social and environmental sustainability outcomes in this Spanish LL 55
Figure 27 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Hungarian Living Lab 55
Figure 28 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Hungary 56
Figure 29 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Latvian Living Lab 56
Figure 30 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Latvia 57
Figure 31 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Czech Republic Living Lab 57
Figure 32 – The relative priority scores of economic, social and environmental sustainability outcomes in the Czech republic LL 58

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EXECUTIVE SUMMARY

Introduction

The CODECS Conceptual framework is essential to understand why short and long term costs and benefits of digitalisation not always are positive by means of a system thinking approach. The rapid uptake of digital technologies in European agriculture often leads to productivity gains. However, this is not always the case. While digital agriculture promises efficiency and profitability, its broader economic, social, and environmental outcomes remain uncertain and unevenly distributed. For instance, digitalisation can exacerbate inequalities, reinforce power concentration, and increase technological dependency, while economic constraints and data asymmetries may widen poverty gaps. Environmentally, digital tools do not inherently guarantee climate mitigation, biodiversity protection, or ecosystem resilience. The CODECS Conceptual framework is therefore needed to assess trade-offs, avoid unintended consequences, and ensure that digital transformation supports long-term sustainability beyond individual farm-level gains.

The main aim of this deliverable is to develop a new upgraded version of the CODECS Conceptual framework based on participatory theory building among researchers and stakeholders, as well as demonstrate applicability by means of the following four research questions:

1. What is the context specific applicability of the CODECS Conceptual framework to each Living Lab?
2. What is the context specific sustainability outcomes of relevance to each Living Lab?
3. What level specific concepts are of relevance to the CODECS Conceptual framework?
4. How can the CODECS Conceptual framework contributes to more responsible policy making?

In this deliverable the CODECS conceptual framework for sustainable digitalisation (Soma *et al.,* 2024) is hence a conceptually upgraded version by means by participatory theory building analyses, including contextual empirical applications in the CODECS Living Labs.

The CODECS Conceptual framework

In order to understanding the costs and benefits of agricultural digitalisation across economic, social, and environmental dimensions of sustainability, a system-based approach has been developed referred to as the CODECS conceptual framework. Although productivity gains in the European agriculture often are linked with technology uptake, the framework recognises that farmers' investments in digital technologies depend on contextual factors. Hence, the benefits emerge within dynamic and context-specific conditions shaped by both external drivers (e.g. policy, environmental pressures, technological change) and internal drivers (e.g. farmers' capacities, motivations, and opportunities).

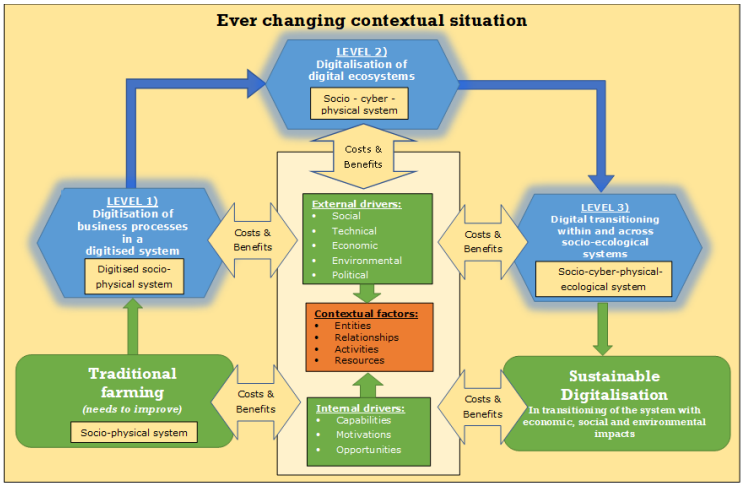

Figure ES1. The CODECS Conceptual framework

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The framework conceptualises digitalisation as a transition across interconnected system levels with increasing digital maturity. At the business process level, digital technologies reshape farm-level decision-making, relationships, and activities, generating costs and benefits that extend beyond financial performance to learning, collaboration, and organisational fit. At the digital ecosystem level, farm-level digitalisation relies on external infrastructures, data systems, expertise, and networks, involving multiple actors and supported by AKIS to address human and organisational capacities. At the broader socioenvironmental level, digitalisation affects governance systems, natural resources, and societal outcomes, addressing risks such as digital divides, interoperability failures, and environmental degradation. By capturing these interacting system levels, the CODECS conceptual framework highlights that the impacts of digitalisation evolve over time and vary by context, underlining the need for holistic assessments of sustainability trade-offs beyond individual farms.

Main outcomes responding to the four specific research questions are briefly addressed in the following.

1) What is the context specific applicability of the CODECS Conceptual framework to each Living Lab?

Across the 16 CODECS Living Labs who took part in an exploratory Teams talks about how they related with the CODECS Conceptual framework, contextual factors vary considerably, reflecting differences in digital maturity, governance settings, farm structures, and socioenvironmental conditions.

In order to analyse the first research question on context specific applicability of the CODECS Conceptual framework to each Living Lab, five investigations have been conducted: 1) contextual differences across the Living Labs, 2) specific contributions by each Living Lab to the business process, digital ecosystem and socioenvironmental levels, 3) main challenges and opportunities, 4) main costs and benefits in each Living Lab, and 5) main learning contributions per Living Lab.

First, the analyses of the **contextual differences** across the Living Labs show that the Living Labs operating at the business process level focus primarily on farm-level optimisation through data availability, automation, and high-tech solutions. These contexts are characterised by relatively high technological readiness, motivated farmers, and clear operational objectives, while facing challenges related to interoperability, data sharing, financial risk, and unequal uptake between farms. Local environmental conditions, market pressures, and regulatory frameworks further influence technology choices and investment decisions. Living Labs operating at the digital ecosystem level function in more networked and actor-rich contexts, relying on advisory systems, producer organisations, education, marketing platforms, and peer-to-peer learning. Here, digitalisation depends less on individual technologies and more on infrastructure, skills, trust, and coordination among stakeholders, with variability shaped by digital literacy, governance support, and AKIS capacity. At the socioenvironmental level, Living Labs address landscape-scale outcomes, biodiversity, and governance, highlighting how digitalisation interacts with environmental stewardship, cultural practices, and public policy. Across all levels, digitalisation pathways are highly context-specific and depend on aligning technologies with local capacities, needs, and values.

Second, the **specific contributions** by each Living Lab to the business process, digital ecosystem and socioenvironmental levels, include that; at the business process level, Living Labs support farm-level optimisation through data-driven decision-making, precision technologies, and automation. They improve efficiency, resource use, risk management, and labour organisation, while advisory services, demonstrations, and peer learning help farmers interpret data and build confidence in digital tools. These contributions strengthen economic viability while linking productivity with sustainability goals. At the digital ecosystem level, Living Labs act as connectors and facilitators within complex, multi-actor environments. They enhance interoperability, data sharing, skills development, and trust among farmers, advisors, technology providers, educators, and market actors. By fostering co-creation, peer-to-peer learning, and platform-based coordination, they improve access to digital tools, support innovation uptake, and strengthen knowledge networks across value chains. At the socioenvironmental level, Living Labs integrate digitalisation with landscape management, biodiversity conservation, governance, and community engagement. They support environmental development, cultural heritage preservation, and social learning, demonstrating how digital tools can contribute to resilient, place-based agricultural systems aligned with societal and ecological values.

Third, addressing main **challenges and opportunities**, this deliverable unravels that sustainable digitalisation is interpreted in multiple, overlapping ways, reflecting different priorities, scales, and contexts across the Living Labs. For instance, in many cases, digital tools support environmental sustainability by optimising water, soil, and nutrient

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use, reducing inputs, protecting biodiversity, and lowering emissions, while also revealing the environmental footprint of technologies. Some Living Labs adopt a triple-bottom-line perspective, enhancing environmental performance, economic viability, and social resilience simultaneously through efficiency, risk reduction, collaboration, and value-chain integration. Others emphasise social innovation and local food systems, empowering small-scale farmers, strengthening local economies, and shortening value chains. Knowledge diffusion, training, advisory services, and digital inclusion address inequalities in access to technology, while sector- and culture-specific applications preserve traditional farming systems, animal welfare, quality products, and regional identities. Key challenges include limited digital skills, complex technologies, insufficient training, high investment costs, uncertain returns, weak market incentives, fragmented governance, poor connectivity, interoperability issues, social and cultural barriers, and hidden ecological costs. Sustaining initiatives beyond pilot phases is also difficult due to funding and scalability constraints. Opportunities include improving efficiency, traceability, and precision, building digital skills and trust through Living Labs, enabling strategic investment via coordinated governance, opening new market channels, supporting short value chains, and fostering community networks. Digitalisation can also advance climate adaptation and resilient, sustainable agricultural systems.

Fourth, main **costs and benefits** extend beyond purely financial considerations and have different meaning in each Living Lab. Benefits include that high-tech efficiency and resource optimisation deliver clear environmental and economic benefits through precision irrigation, input reduction, monitoring, and data analytics. These gains include cost savings, improved yields, biodiversity protection, and labour efficiency, but they require costs in terms of investment, training, reliable infrastructure, and continued human oversight to avoid dependency and misinterpretation of data. Costs are also related with digital adoption which comes expensive technologies, interoperability challenges, and reliance on advisors or consultants. While long-term benefits may include improved animal welfare, regulatory compliance, productivity, and resilience, short-term costs include uncertain returns and governance gaps that can slow uptake and create unequal access. Notably, social, market, and community-based digitalisation generates benefits through short value chains, direct marketing, storytelling, and collective action. These approaches strengthen rural resilience, market access, and social cohesion at relatively low financial cost, but may introduce costs in terms of time burdens, digital fatigue, coordination challenges, and vulnerability to market dominance by large platforms. Further, benefits of capacity building and governance-oriented digitalisation focusing on education, advisory systems, and decision-support tools can reduce knowledge gaps and enhance long-term readiness.

Fifth, main **learning contributions** by the Living Labs, which provide low-risk environments for experimentation and critical evaluation, have shown to include environmental learning demonstrating how precision water management, reduced inputs, and biodiversity monitoring can improve resource efficiency, ecosystem health, and climate resilience, while also revealing trade-offs and hidden impacts of digital technologies. Also, social learning and community building can develop through peer-to-peer exchange, demonstrations, and collaborative experimentation, strengthening trust, farmer confidence, and collective problem-solving across diverse contexts. Governance and institutional learning highlight the importance of coordination among farmers, advisors, cooperatives, researchers, and public authorities to enable interoperability, data sharing, training, and coherent policy support. Further, digital skills and technological learning demonstrated that effective adoption depend on context-specific training, usability, and understanding of data, risks, and system complexity, rather than on a technology alone. Economic and market related learning illustrated how digitalisation can improve efficiency, traceability, and competitiveness, support short value chains, and enable resilient business models, while also exposing limits linked to scale, market power, and consumer behaviour.

2) What is the context specific sustainability outcomes of relevance to each Living Lab?

As part of participatory theory building in CODECS, value-tree analysis was used to identify context-specific sustainability outcomes of digitalisation in each Living Lab. Researchers first developed a preliminary value tree based on literature, covering economic, social, and environmental outcomes. This was then discussed and adapted in participatory stakeholder workshops, allowing each Living Lab to co-create its own context-specific value tree. To assess the relative importance of the identified outcomes, Living Labs completed a VARI survey based on Multi-Criteria Analysis and the Analytical Hierarchy Process. Through pairwise comparisons, participants assigned weights to outcomes, revealing which sustainability outcomes were considered most relevant within each Living Lab context.

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Across the Living Labs, participatory theory building revealed substantial diversity in how sustainable digitalisation is interpreted and prioritised across economic, social, and environmental sustainability dimensions. While all Living Labs addressed all three dimensions, their relative importance varies strongly according to local contexts, challenges, and development trajectories, confirming that there is no single pathway toward sustainable digitalisation in agri-food systems. A first group of Living Labs placed clear emphasis on economic sustainability, including the Living Labs in Belgium, Poland, Latvia, Germany, Serbia, and North Macedonia. In these contexts, digitalisation was primarily understood as a tool to enhance competitiveness, productivity, cost efficiency, and market integration. Social and environmental outcomes remained relevant but are largely framed as supporting conditions that reinforce economic performance rather than as independent objectives. A second group of LL prioritised environmental sustainability, most notably the Living Labs in Slovakia, Estonia/Latvia, and the Czech Republic. These Living Labs focused on water management, soil quality, biodiversity, and climate resilience, reflecting strong ecological agendas. In the Living Labs in Slovakia and Estonia/Latvia, environmental outcomes dominated, while economic benefits are secondary. The Living Lab in the Czech Republic showed a more dual orientation, balancing environmental and economic objectives with limited emphasis on social outcomes.

Social sustainability was most prominent in the Living Labs in Scotland and Ireland, where digitalisation supports community interaction, health, labour conditions, and digital skills. These Living Labs emphasise people-centred transition pathways, with economic and environmental outcomes embedded within broader social goals. The Living Lab in Ireland combined strong social priorities with a focused climate mitigation agenda. Moreover, several Living Labs, including the Living Labs in Spain and Hungary, displayed a balanced sustainability orientation, assigning similar weight to economic, social, and environmental outcomes. This integrated perspective highlights digitalisation as a multifunctional enabler capable of delivering simultaneous sustainability gains.

3) What level specific concepts are of relevance to the CODECS Conceptual framework?

The conceptual analysis is explanatory to ways in which innovation supports economic, social, and environmental outcomes in agriculture, and demonstrate alignments between 1) sustainable digitalisation and 2) technologies, social practices, governance, and learning processes across multiple levels.

The conceptual analysis showed that at the business process level, central concepts include socio-technical processes, decision-making processes, role reconfiguration, learning loops and adaptation, work organisation and wellbeing, process transparency and traceability, inclusion and exclusion dynamics, and dependency and control. These concepts capture how digital tools, such as sensors, drones, farm management software, and decision-support systems, are embedded in farm routines, reshaping workflows, actor roles, and knowledge-sharing. For example, decision-making evolves from individual, experience-based judgement to collective, data-driven processes, while learning loops and adaptive experimentation support resilience and long-term adoption. Work organisation and wellbeing address labour intensity and social sustainability, and transparency, dependency, and inclusion dynamics highlight governance and equity considerations.

At the digital ecosystem level, concepts include socio-ecological systems, digital ecosystems, governmental systems, resource systems, Agricultural Knowledge and Innovation Systems (AKIS), knowledge networks and digital literacy, and interoperability and data integration. These concepts emphasise the interconnected networks of actors, infrastructures, and data flows that enable sustainable digital agriculture. They highlight how coordinated multi-actor engagement, integrated platforms, and effective resource management support regulatory alignment, adoption of innovations, peer-to-peer learning, and system resilience.

At the socio-environmental level, key concepts include socio-ecological resilience, environmental stewardship, cultural landscape preservation, social embeddedness and community, governance and accountability, territorial cohesion and rural vitality, and collective learning and systemic awareness. These concepts show how digitalisation extends beyond efficiency to enhance adaptive capacity, ecological management, social legitimacy, rural development, and systemic understanding, linking technological change to long-term sustainability.

5) How can the CODECS Conceptual framework contributes to more responsible policy making?

The CODECS framework can guide policies to ensure integrated, inclusive, and resilient digital transformation in European agriculture. The CODECS conceptual framework highlights that sustainable digitalisation in agriculture is a socio-technical process delivering economic, environmental, and social outcomes, rather than a goal in itself.

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Highly relevant policy areas include infrastructure and connectivity, data governance, AKIS and skills, legal and financial frameworks, technologies, and social aspects, although a persistent implementation gap has been addressed despite a decade of policy recommendations. Effective policy requires coordination across ministries, EU, national, and regional levels, aligning governance, regulation, and funding to support systemic digital transformation. Policies must recognise the multi-level, context-specific nature of digitalisation, shaped by factors such as governance, farm structure, connectivity, and human capital. Enhancing digital skills among farmers, advisors, and AKIS actors is critical, requiring accessible training, demonstration farms, and peer-to-peer learning. Policies should be farmer-centred, supporting small and large farms alike with practical, time-saving, and context-appropriate tools while fostering collaboration with technology providers. Evidence-based decision-making is essential, but data on farm-level digitalisation remains limited. Finally, while the CAP supports digitalisation through strategies, investments, and advisory services, it cannot alone address structural challenges such as bureaucracy, insufficient indicators, or lack of baseline data.

Concluding remarks.

The analyses conducted in this deliverable demonstrate the value of the CODECS Conceptual framework for understanding the complex, context-specific impacts of digitalisation in European agriculture. Across the CODECS Living Labs, digitalisation has been shown to operate as a multi-level, socio-technical process, generating outcomes that extend beyond productivity and financial performance to encompass social, environmental, and institutional dimensions. While some Living Labs emphasised economic sustainability, others prioritised environmental progress or social well-being, and several adopted integrated approaches combining multiple dimensions. This diversity highlights that there is no single pathway to sustainable digitalisation; instead, outcomes depend on local governance, farm structures, connectivity, skills, and socio-cultural contexts.

The framework's multi-level perspective covering business processes, digital ecosystems, and socioenvironmental levels, clarifies how digital technologies interact with actors, routines, infrastructures, and governance. At the farm level, socio-technical processes, decision-making, role reconfiguration, learning loops, and work organisation shape efficiency, resilience, and inclusivity. At the digital ecosystem level, AKIS, knowledge networks, digital literacy, and interoperability facilitate coordination, innovation adoption, and resource efficiency. At the socioenvironmental level, concepts such as socio-ecological resilience, environmental stewardship, cultural landscape preservation, and collective learning illustrate how digitalisation contributes to broader societal and ecological goals.

Participatory theory building and empirical Living Lab observations also reveal critical challenges and opportunities. Barriers such as limited digital skills, high investment costs, fragmented governance, and technological complexity coexist with opportunities for precision agriculture, peer-to-peer learning, strengthened knowledge networks, and socially embedded innovations. Importantly, digitalisation benefits are context-dependent and often require supportive governance, advisory services, and multi-actor coordination to realise sustainable outcomes.

Finally, the framework offers actionable guidance for policy. By highlighting the multi-level system approach, and context-specific dependencies of digitalisation, it informs farmer-centred, evidence-based, and coordinated policies that align infrastructure, data governance, skills, and advisory systems with sustainability objectives. While policy instruments such as the CAP provide a foundation, the framework underscores the need for adaptive, integrated, and inclusive approaches that anticipate trade-offs and foster long-term resilience, equity, and environmental stewardship in European agriculture.

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1 Introduction – visioning towards sustainable digitalisation

The agricultural sector in Europe is digitalising rapidly, leading to digital transformation of our societies (Butt *et al.,* 2024; Omol, 2024). In Europe, 93% of existing farms use at least one IT/software tool, while 79% use at least one crop-specific digital tool and 82% use at least one livestock-specific digital tool (Tur *et al.,* 2025). The overall process of digital transformation is referred to as digitalisation (Mäkitie *et al.,* 2023; Jabłoński and Jabłoński, 2022). Digitalisation refers to people's routines and way of life that are redefined according to the digital transformation of new economic, environmental, social and governance domains (Rolandi *et al.,* 2021). Digitisation is an important component of digital transformation, and is a component of digitalisation, and can be understood as 'the technical conversion of analogue information into digital form' (Autio, 2017), or in other words 'a process of representing the physical world through numbers' (Bacco *et al.,* 2020). Similarly, for the agricultural sector, while precision agriculture refers to digitisation, digital agriculture refers to both digitisation and digitalisation (Hackfort, 2021; Balasundram *et al.* 2023).

Digital agriculture has been referred to as transformation leading to increased profitability and sustainability in agriculture (Ozdogan *et al.,* 2017). Technology advancements in digital agriculture are expected to transform the traditional farming practices to a highly automated and data intensive industry (Fountas *et al.* 2020). However, the overall impacts of agricultural digitalisation at a broader societal level are sometimes unclear. Digitalisation can cause societal costs by increasing disparity and risks of power concentration, excessive standardisation and technological dependency leading to exclusion. Moreover, from an economic perspective, information biases, network limitations, no access to finance and lack of investments opportunities, can lead to increased poverty gaps (Bellon Maurel *et al.,* 2022). Also, from an environmental point of view, there is no assurance that digitalisation will lead to climate adaptation and mitigation, increased biodiversity, enhanced nutrient and hydrological cycles, or resilience of natural ecosystems (Gailhofer *et al.* 2021, Lorenz *et al.,* 2025). Existing impact analyses tend to focus on individual farms, not comprehending the impacts digitalisation has on a larger scale. An urgent research gap refers to biases in prediction of potential costs and benefits with digitalisation.

Different insights exist linking digitalisation and sustainability based on different perspectives (e.g. Niehoff, 2022; Sacco *et al.* 2021; Rolandi *et al.* 2021; Mondejar *et al.* 2021; van der Burg *et al.,* 2019). Sustainable digitalisation has been specified as; "sustainable digitalisation is the compass that guides us toward a future where technology empowers society while minimising its environmental footprint" (UN, 2015). In this definition, 'empowering society' addresses social impacts, and 'environmental footprint' addresses the ecological impact of digital technologies. From a system perspective, sustainable digitalisation can be seen as 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 (Soma *et al.,* 2024a).

Accordingly, this Deliverable 2.2. is further develop by means of participatory theory building the CODECS Conceptual framework (Soma *et al.* 2024a). In order to deal with the mentioned limitations as well as to provide a baseline for understanding context specific differences and changes leading to transition, in this research we apply a system approach for sustainable digitalisation. Hence, linking digital technology with sustainable digitalisation can be approached by means of system thinking (Clancy, 2013; Brouwer *et al.* 2020). A system can be defined as an "organised set of elements", which interconnect and interact to perform activities, and these activities generate outputs. The social activities in a system are regulated by rules, which regulate the use of resources, the type of actors that can carry out the activities, and the interaction among them. Formal rules and regulations, and informal rules, values and norms, which encourage or restrain actors in their activities are referred to as institutions (Ostrom, 2009a). Transformation involves long term changes in institutional settings, which influence actor's behaviour. When new rules and resources are generated through transitions, system activities contribute to produce and to reproduce some of them, while others are affected by the system, which involve feedback-loops, before the activities eventually lead to multiple outputs across economic, social and environmental dimensions.

The main aim of this deliverable is to develop a new upgraded version of the CODECS Conceptual framework based on participatory theory building among researchers and stakeholders, as well as demonstrate applicability by means of the following four research questions:

1. What is the context specific applicability of the CODECS Conceptual framework to each Living Lab?

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2. What is the context specific sustainability outcomes of relevance to each Living Lab?
3. What level specific concepts are of relevance to the CODECS Conceptual framework?
4. How can the CODECS Conceptual framework contributes to more responsible policy making?

This Deliverable 2.2 – Sustainable digitalisation: a Conceptual framework (final), provides the final version of the Conceptual Framework (M40), which has been under development since the first version was submitted (M18) (Soma *et al.,* 2024a). Following up of the first version, a Policy brief and a scientific article in the Agricultural Systems journal were published (Soma *et al.,* 2024b; Soma *et al.,* 2026), which also have contributed to this Deliverable 2.2.

This last version of the CODECS Conceptual framework has been co-developed with the entire consortium by means of participatory theory building (See Chapter 3). The CODECS Conceptual framework contributes with a shared vision of sustainable digitalisation and a conceptual and analytical framework to support it. It establishes economic, social and environmental visions of sustainable digitalisation in the agri-food sectors.

The new aspects of the Deliverable 2.2 (Final Version) compared with the draft version (D2.1) include the operationalisation of the CODECS Conceptual framework to analyse empirically across Living Labs:

- Context specific applicability of the CODECS Conceptual framework to each Living Lab (Chapter 4) based on Teams talks, involving contextual differences across the Living Labs, specific contributions by each Living Lab to the business process, digital ecosystem and socioenvironmental levels, main challenges and opportunities, main costs and benefits in each Living Lab, and main learning contributions per Living Lab.
- Multi-level sustainability outcomes of relevance to each Living Lab context (Chapter 5) based on participatory theory building of Living Lab specific value-trees, for which each Living Lab also assigned relative relevance of the listed environmental, economic and social sustainability outcomes.
- Level specific relevance of different concepts (Chapter 6) based on research contributions within CODECS and a literature review
- Policy relevance of the CODECS Conceptual framework (Chapter 7).

In addition to these four Chapters mentioned, this Deliverable begins with a methodological approach (Chapter 2), followed by the introduction the CODECS Conceptual framework which is slightly edited (Chapter 3), and finalises by providing some concluding remarks (Chapter 6).

Note that this deliverable is intentionally extensive, as it provides essential background information for multiple Living Labs that differ substantially. It is not intended to function as a scientific article; rather, it supplies context-specific data to support subsequent scientific publications. Condensation would have compromised data quality and contextual integrity.

2 Methodological approach

2.1 Participatory theory building

While the Deliverable 2.1. Sustainable digitalisation: a conceptual framework draft, was designed based on a literature review and theoretical insights and analyses, the Deliverable 2.2. is investigating its relevance based on empirical analyses, particularly related with the insights provided on context specific factors and the multi-level approach. Participatory theory building is central as an overall methodological approach to the empirical analyses in this deliverable, which typically involves co-creation with multi stakeholders for development of conceptual frameworks, models, or explanations (European Commission CAP Network, 2023). In this way, not only academic researchers develops theories, but collaboration, learning, dialogue, and exchange of practical and contextual knowledge are ensuring relevance to reality as a bottom-up contribution of insights.

In particular, the participatory theory building has been used to improve the CODECS Conceptual framework at different stages. Based on the insights of the diverse WPs, it has evolved dynamically as the project unfolded. The first period of theory building involved the researchers in other work packages who contributed to co-development during a set of informal meetings before the Deliverable 2.1. CODECS Conceptual framework was submitted (M18) (Soma *et al.,* 2024a). After this, in a second period of participatory theory building, the CODECS Conceptual

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framework was developed towards the policy brief submission (Soma *et al.,* 2024b), and further towards submission of 3) a scientific article (published 10.10.2025) (Soma *et al.,* 2026). These three documents all present the CODECS Conceptual framework.

Whereas these three first phases involved participatory theory building among research partners in CODECS working in multiple tasks in the project, the fourth phase involved the Living Labs, and hence, the contributions in theory building were truly multi-stakeholder based in two separate but interlinked activities. Following a participatory theory building approach, a bottom-up activity was carried out with multi-stakeholders during the second Annual Living Lab workshops organised by the Living Labs (2024). Atter a training session held on 18/02/2025, a total of 14 Living Labs of the 20 took part in this activity. The intention with first activity was to identify which sustainable digitalisation outcomes would be of relevance to the specific Living Lab, with the assumption that this will differ across the very heterogenous Living Labs. We refer to this as the value-tree analyses, and this is described more in details in the next section. Not only were the Living Lab coordinators involved, but also stakeholders in the Living Labs who took part in the Annual Living Lab workshop (2024) that included this session for WP2 (See Chapter 5)

The intention with the second participatory theory building activity with the Living Labs was to broaden the scope from looking solely at the sustainable digitalisation outcomes to addressing relevant context factors and steps in the CODECS Conceptual framework to each Living Lab. This took place in the form of a one hour Teams talk per Living Lab, recording and summarising a script of each of them, leading to the content of Chapter 4.

Besides participatory theory building, the CODECS Conceptual framework is developed by means of a comprehensive literature review (Soma *et al.,* 2024). The literature review addresses relevant multiple theoretical perspectives relevant for exploring what sustainable digitalisation means in a variety of agricultural contexts. This does not only refer to how digital technologies can impact business process level, but also digital ecosystem level and socioenvironmental level, in terms of short and long term costs and benefits, advantages and disadvantages. Capabilities, motivations and opportunities are explored as internal drivers to change, while the external drivers such as political, economic, social, technical, economic, environmental and political drivers are also explored as influential. The final version of the CODECS Conceptual framework will be presented at the CORDIALL conference in France April 2026.

Although most Living Labs took part and contributed with excellent information, not every Living Lab took part in all exercises. A brief overview of the 20 Living Labs in CODECS is provided in Table 1 below, including information about which Living Lab took part in which exercise. Marked in blue are the ones who took part in both the value-tree analyses and Teams talk (13); green informs of who took part in the Teams talk only (3); purple informs of who took part in the value-tree analyses only (1), and grey informs of who did not take part in any of these exercises (3). Compared with other EU projects, 20 Living Labs is a relatively large number to coordinate, and the Living Labs were given some flexibilities to make choices to contribute across the highly demanding requests from all the WPs in CODECS, which explains why not every Living Lab took part.

2.2 Value-tree analysis of contextual Living Lab sustainability outcomes

In this section, the value-tree analysis conducted by the Living Labs are explained in more detail, as mentioned above. With the intention to clarify which sustainable digitalisation outcomes are of relevance to each Living Lab, a bottom-up approach to participatory theory building has been conducted for specific Living Labs in the form of building an own value-tree, with overall ambition to reach at sustainable digitalisation outcomes in agriculture, which further is specified to economic, social and environmental digitalisation outcomes. The criteria of relevance to each of these three categories are thus different and built into specific Living Lab value-trees. The whole exercise consists of three main steps:

1. Constructing a preliminary show-case value-tree for economic, environmental and social outcomes of digitalisation (based on a literature review)
2. Reflecting on this value tree in the CODECS Living Labs by means of participatory theory building during stakeholder workshops with the aim to create context-specific value trees for each of the CODECS Living Labs

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3. Assessing the relative importance of economic, environmental and social outcomes of digitalisation for each Living Lab.

In principle, steps 1-2 are all conducted to eventually be able to assess the relative importance of sustainability outcomes of digitalisation. To assess the sustainability outcomes of digitalisation in step 3, CODECS Living Labs responded to a survey that was distributed to them to assess which of the sustainable digitalisation outcomes were relevant to them. This survey follows the principles of Multi-Criteria Analysis (MCA) and Analytical Hierarchy Process (AHP) (Saaty, 2001), which makes use of designing relevant outcomes into a value-tree and comparing them to find relative relevance by means of a pairwise comparison technique (assigning relative importance by weighting). Specifically, the assessment of the value-tree components was done by applying the method Value-Analysis of Relative Importance (VARI). By assessing the relative importance of different criteria, VARI prioritises different sustainability outcomes of digitisation by estimates of shares adding up to 100%. This approach facilitates the involvement and input of CODECS Living Lab stakeholders, ensuring the inclusivity of diverse perspectives and insights in the VARI results, in the form of assigning weightings to different digitalisation outcomes to reveal what outcomes are relatively more relevant to the specific Living Lab.

First, constructing a show-case value-tree based on literature. In order to assess the relative importance of sustainability outcomes of digitalisation in CODECS Living Labs, a value tree with carefully identified outcomes has been constructed and arranged into hierarchies. A value tree can structure the different outcomes imaginable into categories and subcategories. Therefore, a predefined value tree is created by CODECS researchers, which has been evaluated by the Living Labs in a participatory workshop setting. This predefined value tree has been iteratively constructed on the basis of literature review and consultations with the CODECS Living Labs. The value tree can be read as a theory of change: as a result of digitalisation at the farm business process level, including a diversity of outcomes identified. Figure 1 presents the conceptual value tree created for the identified outcomes of digitisation.

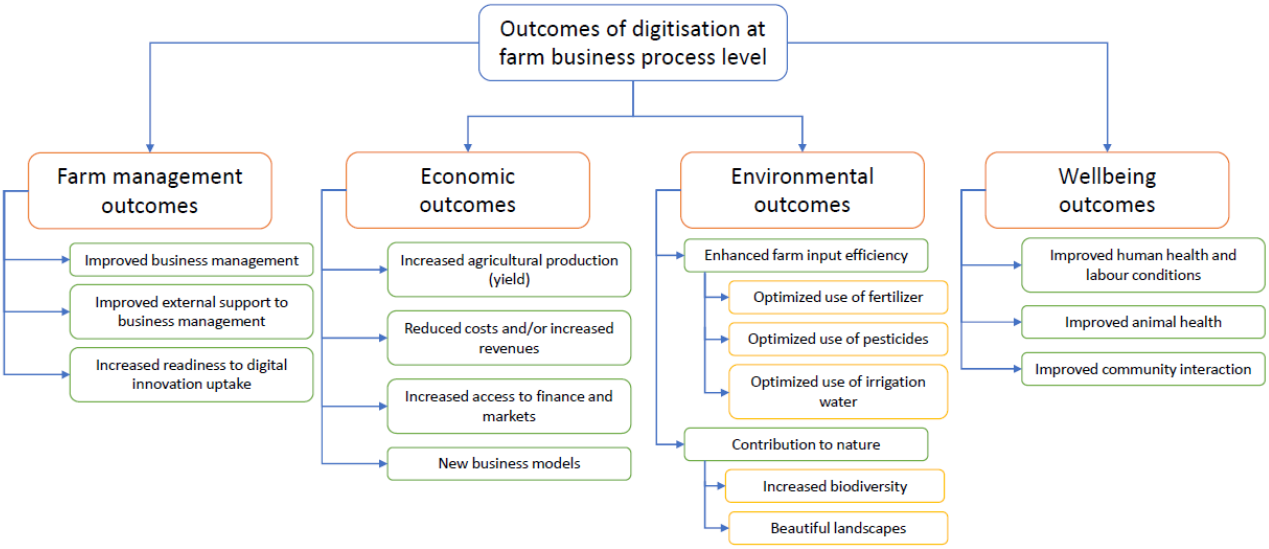

Figure 1 – A value-tree with explanatory factors leading to outcomes of digitisation at farm process level based on literature review

Second, participatory stakeholder workshops. The main aim of the participatory stakeholder workshops was to discuss and gain feedback on the predefined value tree from each Living Lab. The Living Lab participants hence have reflected by means of participatory theory building on how to redesign the value trees given the context of their Living Lab. They were also suggesting further additions or adaptations to the value trees. This supported the bottom-up creation of context-specific value trees and ultimately contributes to finding the most important sustainability outcomes of digitalisation for the CODECS Living Labs.

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The participatory stakeholder workshops in the Living Labs took place in November-December 2024 and January 2025 in 14 CODECS Living Labs. The workshop was part of the CODECS annual workshop that each Living Lab organises to support data collection in the Living Labs for the CODECS work packages. For the value tree discussion in the workshop, CODECS researchers provided materials for either in-person or online workshops. The key material provided was the predefined value tree, both as poster to be printed for an in-person workshop or as framework on a MIRO board for an online workshop in case a face-to-face workshop was not possible.

Third, assessing relative importance of sustainability outcomes. The context-specific value trees were inserted in the VARI survey tool. The VARI survey was then sent to the Living Lab coordinators. They were instructed to give a minimum of one response as a Living Lab, either by the Living Lab coordinator or by another stakeholder that was found representative of the Living Lab and deemed able to give a good representation of the relevance of sustainability outcomes for the Living Lab.

In the VARI survey, respondents had to conduct a pair-wise comparison. Each of the sustainability outcomes were compared to each other, and respondents had to add a weighting from 1-5 indicating whether they thought the outcomes were equally important (1) or which outcome was little more important (2) to much more important (5) (see Figure 2 for an example).

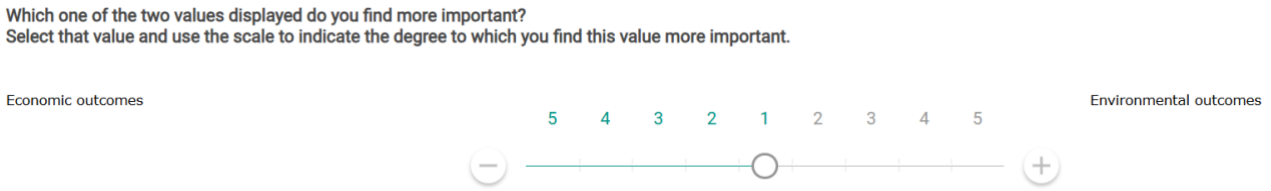

Figure 2 – Example question in VARI survey

The results of the VARI survey give an indication of the relative importance of sustainability outcomes in the CODECS Living Labs.

2.3 CODECS research examples operating at different levels

In this section, relevant concepts addressed in CODECS are addressed at business process level, digital ecosystem level and socioenvironmental level. Most of these concepts were addressed in the Deliverable 2.1, whereas more concepts have been identified based on theoretical insights during the CODECS project, and then discussed with each Living Lab in the Teams talks. Explanations to the concepts are proved in terms of; meaning of the conceptual terms, how they appear in the Living Labs in practice (4.2), type of techno-social change observed and relevance for sustainable digitalisation.

Most of these concepts have been addressed and analysed during activities across the CODECS work packages (Appendix 1). Notably, not all research efforts have been finalised. Therefore, the contributions from already submitted Deliverables are briefly addressed in this Deliverable 2.2, where we make a clear distinction between analyses operating at different levels. The Deliverables include (Hurtado *et al.,* 2025; Contreras and Guichaoua, 2023; Giagnocavo *et al.,* 2024; Gobrecht *et al.,* 2024; Šimek, *et al.,* 2024; Soma *et al.,* 2024a and b; 2026).

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3 The CODECS Conceptual framework – contextual factors matter

Since 2015-2024 labour productivity in Europe overall increased with a total of 37%, which can be explained by extensive uptake of technologies in food production (Eurostat, 2024). For farmers to invest in digital technologies they must anticipate a benefit. Anticipated benefit can, for instance, be in the form of increased income, advanced farm management, or enhanced sustainability by improving farming by responding to economic, ecological or social challenges (Kernecker *et al.,* 2020). As a way of identifying the costs and benefits of digitalisation in the European agricultural sector, the CODECS conceptual framework for sustainable digitalisation is introduced. The CODECS conceptual framework, presented in Figure 3, operates in an ever-changing contextual situation, transitioning towards enhanced sustainable digitalisation, impacted by external drivers (e.g., social, technical, environmental and political drivers) and internal drivers (e.g., capacities, motivations and opportunities). The external and internal drivers influence the contextual factors' resources as well as entities, relationships and activities in a particular context. These contexts are in continuous change due to extended digitalisation impacts, covering contexts of no digitalisation as a starting point, moving towards contexts covering business processes, digital ecosystem context and a socio-environmental context. The CODECS conceptual framework refers to the extended visions of digital influence as the socio-physical-system level (level zero), the digitised socio-physical system level (level 1), the socio-cyber-physical system level (level 2), and the governance-cyber-ecological system level (level 3). The system levels are adapted from Klerkx *et al.* (2019), Rijswijk *et al.* (2021) and Metta *et al.* (2022), among others. The costs and benefits of digitalisation in a given context evolve during the transition towards higher levels of digitalisation, spanning three interrelated dimensions of sustainability: social, economic, and environmental (Soma *et al.,* 2024a).

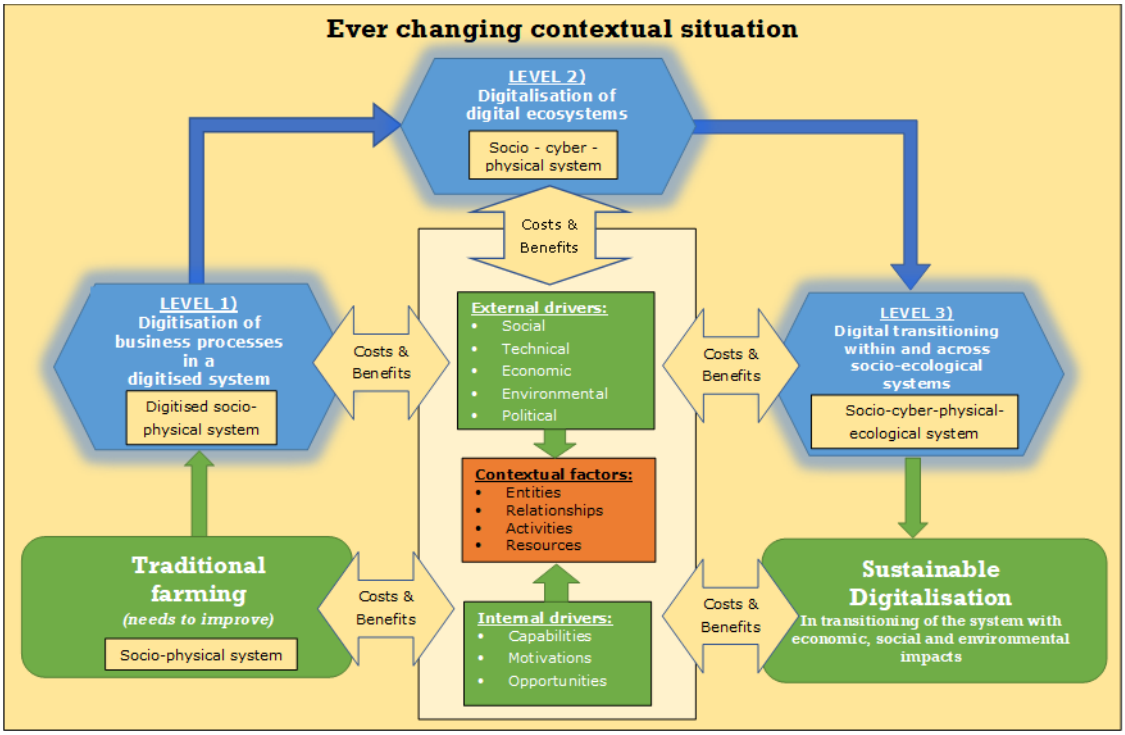

Figure 3 – The CODECS Conceptual Framework adopts a systems approach for assessments of costs and benefits of agricultural digitalisation across three interrelated dimensions of sustainability: social, economic, and environmental

The CODECS Conceptual framework contribute with addressing different levels of digitalisation which ideally should transition our societies into enhanced economic, social and environmental sustainable digitalisation. These transitions are not linear, as in practical terms, one Living Lab can operate at different levels, even when focus is at

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a specific level. The transition pathways can be different and discrepant, and will fully depend on the contextual factors. Hence, the transitions are not linear but contextual.

All system levels in Figure 1 target sustainable digitalisation but vary in their digital maturity, representing distinct stages of technology adoption and contextual impact. The contexts consist of different external drivers, internal drivers, entities, relationships, and activities. The system levels take account of context specific economic, environmental, social, and political drivers, as well as capabilities, motivations and opportunities, which are influential to context specific resources, as well as entities, relationships and activities (Metta *et al.* 2022). Because the digital technologies cause change, there are risks for non-intended outcomes, such as digital mistrust, lack of interoperability, digital divide, environmental degradation and climate change. The costs and benefits that people attribute to the outputs generated in terms of economic, social, and environmental nature, depend on contextual factors and at which level digitalisation is operating. This divergence is explained by each of the three levels, because costs and benefits will differ in scope and character.

Costs and benefits in business process context level. The costs and benefits measuring the value that people attributes to the outputs generated in business process contexts are hence not only about measurable financial costs and benefits but encounter more aims than profitability (e.g. learning), and fit to farmer's needs (e.g. collaboration across value-chains). The scope of costs and benefits in this research is hence broader than purely looking at numbers within the financial scheme in a business. Such digitalisation at the farm with introduction of sensing, actuation devices, or replacement of face-to-face advisory services with digital services, transform the farm with new opportunities to the business processes (Rijswijk *et al*. 2021). The business processes refer to farmers' investments in new technologies that advance decision-making, farm activities and/or financial arrangements, among others. At this digitised socio-physical system level, advanced digitalisation influences contextual entities, relationships, and activities at the farm because of the use of the new technologies.

Costs and benefits of digital ecosystem context level. The digitalised farm processes need external network support, referred to as digital ecosystems, to be able to operate. For example, a decision-support system at farm level requires databases, models, storage units, and expertise outside the farm. CODECS defines digital ecosystems as organised sets of digital, socio-economic, organisational, and physical components that support the use of digital technologies and the production, storage, communication of data (Soma *et al.,* 2024a). At this socio-cyber-physical system level, cyber' refers to digital constructs such as software, big data, cloud computing and IoT, as well as digital reproduction of the physical sphere (Rijswijk *et al.* 2021). The digital ecosystems operate in so-called 'socio-cyber-physical systems' (*ibid.),* involving multiple actors, impacting networks of farmers, businesses, extension services, researchers, policy makers, and citizens. At this level, the Agricultural Knowledge and Innovation System (AKIS) concept supports the engagement with digitalisation-specific human and organisational development aspects (Ingram and Maye 2020; Kernecker *et al.* 2021).

Costs and benefits across socioenvironmental context level. The broader frame, i.e. the socioenvironmental context, is the outer layer for which digitalisation is influential. Costs and benefits with digital technologies in the socioenvironmental context include outcomes of natural ecosystems and governance systems influenced by digital ecosystems, digital resources (data, application systems, etc.), digital resource systems (platforms, infrastructures, clouds, etc.), digital governance systems (data sharing and use regulation), and actors that are involved in digitalisation, among others. The socio-environmental context has been developed extensively through the work of Ostrom (1990, 2009b), Hess and Ostrom (2003, 2007), and McGinnis and Ostrom (2014). Operating within such an extended context, transitioning towards sustainable digitalisation encounter different resources, entities, relationships and activities. For instance, societal costs of digital divide and climate change are relevant when addressing extraction of natural resources and exclusion of societal groups from benefitting from digitalisation. In such contexts, the complexities have reached new levels of interactions and feedback loops, which can be referred to as a governance-cyber-ecological system level with emphasis on the governance and environmental dimensions.

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4 Living Labs transitioning towards sustainable digitalisation

4.1 An overview of the Living Labs in CODECS

In this Chapter, the first research question is addressed; What are the context specific applicability of the CODECS Conceptual framework to each Living Lab? This involves the analyses of: 1) contextual differences across the Living Labs, 2) the specific contributions by each Living Lab to the business process, digital ecosystem and socioenvironmental levels, 3) the main challenges and opportunities, 4) the main costs and benefits in each Living Lab, and 5) main learning contributions per Living Lab.

Before going into the context specific analyses, in this section, an overview of the Living Labs (LL) in CODECS who contributed to the Teams talks addressing this research question are presented briefly. Moreover, they are categorised into clusters with the following focus areas of operation in terms of the following overlapping categories: 1) Data focus in precision agriculture, 2) high-tech focus in precision agriculture, 3) awareness building with high tech, 4) farmer advisers on use of high tech, 5) platform for reaching consumers, and 6) landscape perspectives.

First, three Living Labs have a specific focus on data as means to enhance precision agriculture. On the one hand, in the Slovakian Living Lab, the focus in on minimising water use in irrigation systems, the LL in France, improved data provide farmers with actionable, individualised data to improve herd management, feeding, and animal welfare, and the LL in Hungary with focus on soil data to minimise use of fertiliser.

More precisely:

- **The LL in Slovakia.** The Slovak Living Lab aims to develop a predictive irrigation model that ensures minimal water use while meeting crop needs. By combining high-level digital technologies, real-time climate data, and sensor information, the project seeks to move beyond traditional, experience-based irrigation practices. Machine learning and AI are employed to predict the optimal water requirements during different vegetable growth stages. The goal is to improve efficiency, reduce waste, and support climate resilience. Initially applied on two farms, the model aspires to provide scalable solutions for broader adoption across similar large-scale agricultural operations.
- **The LL in France**. The Living Lab in France aims to experiment with sustainable digitalisation in small ruminant dairy farms, particularly focusing on individual milk meters and associated software. Its core goal is to provide farmers with actionable, individualised data to improve herd management, feeding, and animal welfare. By integrating real-life testing with advisory services and collective stakeholder organisations, the Living Lab seeks to co-develop technological solutions that are user-friendly, affordable, and adaptable to small-scale dairy sheep operations. The broader objective is to enhance farmers' autonomy while fostering system-level learning, supporting innovation in dairy practices, and promoting sustainable agroecological transitions.
- **The LL in Hungary.** The Hungarian Living Lab aims to support sustainable agriculture by providing farmers with detailed soil and nutrient data to optimise fertiliser and input use. This enables more precise, environmentally conscious farming, reducing over-fertilisation, pollution, and carbon emissions. By integrating digital solutions, the lab increases farmers' confidence in decision-making, optimises costs and risks, and engages younger generations in agriculture. It also promotes a broader value chain approach, connecting farms, advisors, food producers, and consumers, fostering social, economic, and environmental sustainability while supporting long-term viability and rural community retention.

Second, two Living Labs are particularly focusing on the high-tech as means to enhance precision agriculture. These include the LL in Slovenia, which by means of sensors, among others, contribute to reduction in use of pesticides, and Belgium which make use of high-resolution drones and digital technologies.

More precisely:

- **The LL in Slovenia.** The Living Lab in Slovenia aims to foster sustainable digitalisation in agriculture by working closely with two demo farms: a winery and a beekeeper. Building on prior projects and established trust, this Living Lab reactivates a collaborative network to introduce advanced technologies adapted to local conditions, including precision sensors and LoRaWAN connectivity. Its main goals are environmental, economic, and social

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sustainability by means of reducing pesticide use, optimising farm performance, lowering costs, and freeing farmers' time for other tasks. The lab leverages prior experience, existing relationships, and increased digital readiness to efficiently implement technology, while considering local context, connectivity, and broader policy and ecosystem factors.

- **The LL in Belgium.** The Living Lab in Belgium investigates the use of high-resolution RGB imagery on drones and AI models in agriculture to optimise crop protection. Its primary goal is to evaluate whether site-specific applications of technology can deliver economic, environmental, and social benefits for farmers. The lab focuses on supporting sustainable digitalisation by enabling pesticide reduction while maintaining yields, exploring innovations in crop management, and understanding adoption barriers. Multi-stakeholder collaboration ensures insights reflect operational, technological, and regulatory realities in conventional farming systems.

Third, three Living Labs concentrate on awareness building about precision technologies. Whereas the LL in Scotland focuses on the small-scale farmers making use of a demo farm and a virtual farm, the LL in Serbia focuses on both small and large scale farmers in meeting gathering, and co-create solutions that fit local conditions.

More precisely:

- **The LL in Scotland.** The LL in Scotland works with small-scale and diversified farms in the North-East of Scotland, to understand and support their use of small-scale technologies and digital platforms. Activities are centred around the annual workshops and the demo farm. The demo farm creates strong social value through its digitally enabled 24-hour farm shop and community space. The shop offers a warm, accessible place for night-shift workers, teenagers, and visitors to gather, enjoy refreshments, and watch a live webcam of animals. It also supports local producers by selling their goods in refrigerated cabinets. These features strengthen community ties, enhance wellbeing, and contribute to local economic and social sustainability.
- **The LL in Serbia.** The Living Lab in Serbia aims to explore the adoption of digital technologies in agriculture, focusing on farmer-centred innovation and sustainable practices. Its main intention is to provide practical, evidence-based demonstrations of sensor technologies in greenhouses, enabling farmers to optimise inputs like water, fertilisers, and pesticides. The Living Lab seeks to motivate farmers through awareness-building, hands-on trials, and demonstrations, while also fostering collaboration among diverse stakeholders, including farmers, advisors, researchers, technology providers, and policy makers, to understand real-world challenges, co-create solutions, and evaluate the effectiveness, usability, and socio-economic impacts of digital agricultural innovations.
- **The LL in Spain.** The Almería Agro-Ecological Living Lab aims to integrate sustainable digitalisation within small- and medium-scale greenhouse farming. Its primary goal is to support farmers in making more informed decisions through interoperable digital technologies, while simultaneously enhancing traceability, certification compliance, and productivity. The lab functions as a practical demonstration site where farmers, cooperatives, advisory services, and tech providers collaborate to test, adapt, and co-create digital solutions that fit local conditions. By bridging farm-level practices with the broader value chain, the Living Lab seeks to optimise resource use, reduce environmental impacts, and increase profitability, all while preserving the diversity and cultural identity of local farming communities.

Fourth, four of the Living Labs operate as farmer advisers on use of high tech on farm. While the two Living Labs in Italy, in Puglia and Tuscany, advise on very specific digital solutions to organic table grapes and sheep milk, respectively, the Living Labs in North Macedonia and Germany advice about diverse technology solutions, for which needs of farmers with a remote agricultural monitoring and advisory system and of young and small-scale farmers are targeted, receptively.

More precisely:

- **The LL in Italy, Puglia.** In this Living Lab, large-scale farmers, particularly those producing high-quality organic table grapes with short seasonal cycles, adopt digital technologies to maintain production standards and ensure optimal yields. Technology supports precise field management, especially irrigation, often remotely, enhancing both crop quality and farmer confidence. Beyond productivity, digital tools contribute to farmers' quality of life, reducing stress and enabling better work-life balance. The Living Lab provides a structured environment for implementing, testing, and refining these technologies, allowing farmers to compare approaches, analyse data,

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and explore new methods. This integration of digital systems improves operational efficiency while offering social and personal benefits, highlighting the multifaceted value of technology in large-scale farming.

- **The LL in Italy, Tuscany.** The Living Lab in South Tuscany focuses on supporting the sustainable digitalisation of sheep milk and Pecorino cheese production. Its main aim is to improve farm efficiency and management through accessible, user-friendly digital solutions, while addressing the economic challenges farmers face. The lab targets both existing and young farmers, with the intention of attracting new generations to livestock farming, ensuring continuity in production, and enhancing coordination between the cheese factory, farmers, and other stakeholders in the network.
- **The LL in North Macedonia.** The main intention of this Living Lab in North Macedonia is to provide farmers with a remote agricultural monitoring and advisory system (RAMAS) tailored to their needs. It aims to introduce farmers to farm management information systems, digital tools, and relevant data, helping them make informed decisions. The Living Lab combines training, knowledge transfer, and user-friendly digital solutions to address gaps in digital literacy. By connecting farmers with advisors, the system seeks to improve productivity, facilitate communication, and support adoption of digital technologies that are practical, accessible, and responsive to local farm requirements.
- **The LL in Germany.** The main intention of the German Living Lab (AgDiBi) is to improve equitable access to knowledge about digital and precision agriculture technologies, especially for young and small-scale farmers who are often excluded from early adoption. By offering field days, demonstrations and educational modules, the lab provides a first practical opportunity to understand what technologies exist, what skills are required to use them, and how they may fit different farm types. Rather than driving technology adoption directly, the Living Lab focuses on reducing knowledge inequality, enabling informed decision-making, and strengthening the educational infrastructure around digital agriculture.

Fifth, two of the Living Labs are working on short food supply chains marketed by means of a platform for reaching consumers. They both have established logistics of food marketing, however, they differ in the sense that the Living Lab in Poland target more consumers and hence has established a more advance service and goods logistics system, while in Ireland, the consumers are living in rural areas and few in numbers.

In particular:

- **The LL in Poland.** This Living Lab aims to scale local food markets by integrating farmers, customers, and software developers through the Appetit platform. It operates as an iterative, evolving system where four pilot food markets test and refine functionalities. Farmers actively use the platform to self-organise, while developers continuously gather feedback to improve automation, user experience, and organisational solutions. The lab encourages experimentation, knowledge sharing, and co-creation, balancing the roles of intermediaries and self-managed farmers. The long-term goal is to expand the platform, increase user engagement, and optimise transactions across multiple locations.
- **The LL in Ireland.** The main intention of this Living Lab is to support local food economies by using a non-proprietary digital farmers-market platform, the Open Food Network, to create short food supply chains. It provides farmers with an efficient, diversified route to market that reduces reliance on traditional physical markets where demand is uncertain. By enabling consumers to pre-order and collect products at a central point, the platform streamlines distribution and strengthens connections between producers and local consumers. This Living Lab aims to build resilient, community-centred food systems through digital innovation.

Sixth, two of the Living Labs are engaged in a landscape perspective linked with digitalisation. Whereas in the Latvian Living Lab, the landscape perspective is used as a branding and quality aspect of the beef product, in the Estonian/Latvian case, landscapes are monitored and data collected by means of high-resolution drone and satellite mapping to provide data for responsible decision making taking nature values into account. They are introduced as follows:

- **The LL in Latvia.** The Latvia Living Lab aims to support farmers in adopting digital tools to enhance direct sales, communication, and marketing of locally produced beef, particularly under the Grassland Product Label. Its main intention is to explore sustainable digitalisation in agriculture by integrating low-cost online tools that are accessible and practical for farmers' workflows. The lab seeks to improve outreach to consumers, strengthen connections within farming communities, and promote environmentally conscious livestock

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practices. Beyond technical implementation, it fosters learning and experimentation, enabling farmers to navigate digital ecosystems while critically reflecting on environmental claims and the cultural, economic, and social dimensions of sustainable beef production.

- **The LL in Estonia/Latvia**. The Living Lab in Estonia and Latvia aims to integrate digital technologies, primarily high-resolution drone and satellite mapping, to support farmers in environmentally sensitive and landscape-protected areas. Its main goal is to facilitate precise monitoring of vegetation, biodiversity, and land use, enabling sustainable decision-making. By combining university research, farmer engagement, and potential private-sector collaboration, the Living Lab seeks to create an adaptive digital ecosystem that balances environmental protection, agricultural productivity, and social values, fostering knowledge sharing and informed governance at farm, community, and national levels.

Table 1 provides an overview of all the 20 Living Labs in CODECS, for which 16 took part in the Teams talks, 14 took part in the Value-tree analyses. The Living Labs taking part are market in blue, and the once not taking part are marked in grey.

Table 1 – A brief overview of the 20 Living Labs in CODECS
(Blue: Value-tree analyses & Teams talk; Green: Teams talk only; Purple; Value-tree analyses only; Grey: none)

#	Part	Country	Title	Technology (TRL)	Main goal
1	Yes	Italy, Tuscany	Pecorino Toscano DOP - Extensive dairy sheep farms	Farm Management Information System (FMIS) - TRL6	To facilitate farmers in the data collection of data related to farm processes
2	Yes	Serbia	Greenhouse smart sensor lab - Vegetable greenhouse production	IoT sensors node, combine with a web platform suitable for pc, tablet and smartphone - TRL 7	To monitor the conditions in the greenhouse (soil moisture, soil pH, CO2 sensor, etc.), and leaf wetness
3	Yes	Italy, Puglia	Organic Table Grape - Organic table grape production	Sensors in orchard at field level (soil, environment, and crop) interconnected and in communication with a Decision Support System –TRL 8	To manage the key factors of production: irrigation, fertilisation patterns, pest and disease control
4	Yes	Poland	Appetit Living Lab - Short food chains	APPETIT IT-enabled platform for collaborative organisational arrangements - TRL 4	To connect many producers to many consumers directly to one another via a virtual marketplace
5	Yes	Scotland	Scottish farms and digital platforms - Small farmers and crofters	Digital platforms for selling, promotion, advertising, training and collaboration, online social media - TRL 3	To exchange knowledge and peer-to-peer learning for small farmers understanding the potential of digital technologies
6	Yes	Ireland	Cloughjordan Food Hub,Local communities and small farmers	Opensource digital platform - TRL 7	To develop an online marketplace to facilitate small scale food producers and people in rural areas in accessing local markets, supporting local economies

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#	Part	Country	Title	Technology (TRL)	Main goal
7	Yes	Belgium	Agrifood Technology - Arable crops	Ultra-high resolution RGB on drones and AI models, task map generation, label tools - TRL 7	To detect weed, disease and pest in commercial farms of arable crops
8	Yes	Spain, Almeria	Almeria Agroecology - Vegetable greenhouse production	Sensors, actuators, centralised platform for data management - TRL 5	To facilitate interoperability of heterogeneous data from different sources
9	Yes	Slovenia	Smart Villages Network - Sustainable viticulture and apiculture	IoT and data analytics, sensors, server storing collected data, web platform, app for smartphone - TRL 7	To find the best IoT infrastructure for winemakers with different microclimate in the same vineyard. And foster IoT innovation in beekeeping
10	Yes	Slovakia	Artificial Irrigation management system- Vegetable greenhouse production	A sensor-based irrigation system using soil moisture sensors and weather data, to support optimal irrigation scheduling - TRL 7	To optimise irrigation doses based on real-time soil moisture levels, local weather conditions, and crop growth stage (phenophase), to improve water use and sustainable farm management
11	*No*	*France, Grand Ouest*	*LIT Ouesterel- Pig meat production*	*Platform linking farm and equipment data - TRL 6*	*To facilitate data sharing between equipment and management software*
12	Yes	Latvia	Grassland product label - Grassfed beef cattle production	ZSA GEO map environment (https://app.smartagro.lv) - TRL 7	To provide an effective and easy-to-use marketing tool to promote an emerging food product from semi-natural grasslands characterised by high biodiversity
13	Yes	France, Occitanum	Open Lab – Sheep Dairy sheep farms	Digital milk counter and connected weight milk tank - TRL 7	To collect automatically herd production data through tank weight measurement
14	*No*	*France, Occitanum*	*Occitanum Viti-Vineyards sustainable agriculture*	*Satellite images, vigour maps, user-friendly web interface - TRL 7*	*Modulating rate of applied fertilisers*
15	*No*	*Greece*	*Spray drones-Vineyards sustainable agriculture*	*Spraying UAVs (drones), GIS, sensors, IoT station, LiDAR for altitude adjustment, vision system - TRL 9*	*To obtain qualitative data on the spraying applications and droplet displacement, applying agrochemicals at a desired rate close to the canopy (commonly <5m).*

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#	Part	Country	Title	Technology (TRL)	Main goal
16	*No*	*Czech Rep*	*Automation of orchard management- Fruit crop production*	*A new sensor-based orchard management system for crop protection, remote control of the irrigation system, frost and pollination monitoring and an end-user application for the farmer - TRL 6*	*To collect, store and analyse on farm data*
17	Yes	Germany	Agri-digital Bildung (AgDiBI) - Knowledge transfer	Digitally related educational format – TRL 8	To support knowledge building on digitalisation in vocational education for prospective farmers and agricultural educators
18	Yes	Estonia/ Latvia	Grassland Management	Drones, machine learning, web app TRL 5/6	To capture changes in vegetation/tree cover, support farmers with data in appropriate format
19	Yes	North Macedonia	RAMAS - Crop production	Farm accountancy form, field repository, user-friendly dashboard, earth observation data, environmental monitoring data. - TRL5	To generate real-time field data that will be used by experts/advisors for delivering tailor-made advice
20	Yes	Hungary	Innovative Soil Scanner - Arable crops	Soil scanner, NIR sensor, cloud, database, soil analysis, mobile phone - TRL9	To analyse nutrients in soil in a fast, affordable, and reliable way

4.2 Living Labs operating at different levels and different contexts

4.2.1 An overview of contextual operations of Living Labs at different digitalisation level

In the CODECS Conceptual framework, three levels of digitalisations have been distinguished for 1) business process level, 2) digital ecosystem level, and 3) socioenvironmental level. Contexts differ not only in different locations, but also in the same locations with different levels of digitalisation. In this section, a short description of the variability of contexts across the 16 Living Labs are provided of each Living Lab, which also are categorised into digitalisation level from which they are carrying out activities.

A total of five Living Labs have been categorised as active at the business process level, including Slovakia, France and Hungary which are advancing digitalisation by means of enhanced data availability, as well as Slovenia and Belgium who enhance digitalisation by focusing on the high tech itself. Obviously these two categories are highly overlapping. Brief contextual insights are provided of these five Living Labs in the following:

- **The LL in Slovakia.** This Living Lab operates within highly digitalized Slovak farms, already equipped with automated irrigation systems and extensive sensors. It involves both a commercial large-scale farm and an experimental university farm, enabling controlled testing and practical implementation. Farmers are experienced in traditional irrigation but seek data-driven approaches. Challenges include diverse system formats from different providers and limited data sharing due to commercial sensitivities. The timeframe for irrigation research is seasonally constrained, from April to July. Small-scale and family farms are generally less familiar or willing to adopt such digital tools, shaping the scope of the lab.

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- **The LL in France.** Key contextual factors include the low adoption rate of digital technologies in the sector (≈3% of farmers), the complexity of adapting tools designed for cattle to small ruminants, and the competitive landscape among advisory services. Governance structures, including the National Committee of Dairy Sheep (CNBL) and a new National Federation, shape technology adoption and collective decision-making. Socioeconomic factors such as farm size, production levels, and cost considerations influence readiness, while environmental factors like climate change and animal welfare drive innovation needs. Cultural demand for products such as Roquefort cheese also influences investment priorities. The Living Lab operates within these overlapping technological, political, economic, and environmental contexts.
- **The LL in Hungary.** This Living Lab involves 40-70 farms, including demo sites for practical learning and exchange. Adoption is influenced by EU policies, subsidies for digital solutions, and market demand for environmentally sustainable products. Internally, farmer motivation, age, digital literacy, and advisory support shape engagement. Technological readiness is high, but challenges exist in interpreting complex data and integrating information from diverse machinery. Social factors, such as knowledge exchange among farmers and younger generations' engagement, further frame the context of digital agriculture adoption.
- **The LL in Slovenia.** The main contextual factors for the Living Lab include prior experience from earlier projects, established trust among stakeholders, and familiarity with Horizon project processes. Technological readiness has increased over time, with advanced IoT, sensors, and reliable connectivity like LoRaWAN enabling remote monitoring. The COVID-19 pandemic accelerated digital adoption and changed mindsets toward technology. Local conditions, such as vineyard terrain and remote apiary locations, shaped technology choices. Policy influence is minimal, as solutions are mainly private-sector driven. Environmental, social, and economic sustainability considerations guide activities, while existing networks support collaboration and knowledge sharing.
- **The LL in Belgium.** The Living Lab operates within a European context of strict pesticide regulations, driving farmers toward alternative crop protection strategies. Large-scale farms face high financial risks and market volatility, influencing technology adoption. Social factors include declining agricultural labour, variable digital skills, and limited time for learning new technologies. Environmental pressures, including pest resistance and ecological impact, shape decision-making. The ecosystem comprises farmers, service providers, advisors, researchers, and policymakers. Governance, conduciveness, and regulatory frameworks strongly influence adoption, while the environmental footprint of the technologies themselves adds an additional layer of complexity rarely addressed elsewhere.

A total of seven Living Labs operate at ecosystem level, including the Living Labs providing awareness raising of high tech, including Scotland, Serbia and Spain, as well as Living Labs giving direct farmer advice including the two Italian cases in Puglia and Tuscany, as well as the Living Labs in North Macedonia and Germany. Moreover, the two targeting the consumers with marketing, logistics and services, including Poland and Ireland, are also categorised into the digital ecosystem level. More precisely:

- **The LL in Scotland.** In the Living Lab, a virtual farm tour showcases practices and technologies to small-scale farmers, complementing peer-to-peer learning in a demo farm. Farmers learn to use social media, websites, and selling platforms like Facebook, Instagram, Airbnb, and YouTube to support diverse business models. Peer-to-peer exchanges increase technology adoption, inspire new approaches, and expand networks, allowing farmers to adapt digital tools to their contexts, generate extra income, and learn from each other's practices. Learning is informal, flexible, and tailored to each farm's unique needs and business model.
- **The LL in Serbia.** The Living Lab operates within a context shaped by traditional agricultural practices, varying farmer capacities, and limited digital literacy. Regional infrastructure, such as LoRa network coverage, affects technology adoption, particularly in remote areas. Farmers' financial capacity and risk aversion, influenced by limited subsidies and prior experiences, impact uptake. Environmental factors, including soil variability and climate conditions, affect the efficiency and relevance of sensor data. Generational differences also matter, with younger farmers potentially more comfortable with digital tools. Governance structures, including provincial and national support, influence incentives, subsidy allocation, and training opportunities, while social norms and trust in advisors shape farmers' willingness to adopt new technologies.
- **The LL in Spain.** The Living Lab operates in a highly arid region with concentrated small-scale farms, creating both resource constraints and strong competition among local actors. Farmers face high input costs, volatile markets, and strict certification requirements like Global GAP and Agricolor. Producer organisations and

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cooperatives play a key governance role, aggregating small farms to improve traceability, data sharing, and market access. Public administration, advisory services, and tech providers shape readiness and capacity-building. The ecosystem benefits from proximity, fostering competition, co-opetition, and rapid knowledge dissemination, while digitalisation adoption is influenced by farm size, climatic variability, investment capacity, and social-cultural acceptance.

- **The LL in Italy, Puglia.** The Living Lab focuses on large-scale farmers, primarily cultivating high-quality, short-cycle crops such as organic table grapes. Farmers operate within a producer organisation that facilitates coordination, knowledge sharing, and market access. The Living Lab engages multiple stakeholders, including government representatives, technical experts, and service providers, enabling collaboration on shared challenges and innovations. Participation in digital agriculture is growing, with around 20 farmers adopting technologies for fruit and vegetable crops with certifications for organic methods and inputs (e.g. Demeter, ISO, Fairtrade) or for good practices (e.g. EUREP-GAP). This environment fosters collective learning, experimentation, and adoption of advanced digital tools to enhance production quality and market competitiveness.
- **The LL in Italy, Tuscany.** This Living Lab operates in a network centred on the Pecorino cheese factory and its consortium, surrounded by roughly 100 sheep farmers. The area faces challenges like declining farmer numbers, high costs of machinery, low milk prices, and predation by wolves. Farmers vary in age and digital readiness, with younger farmers being more capable of adopting new technologies. Cultural landscapes and tourism add additional dimensions, as farms maintain the territory and contribute to regional identity. External drivers include government incentives, welfare projects, and international markets, which shape farmers' expectations and practices.
- **The LL in North Macedonia.** The Living Lab operates within a context of limited digital literacy, minimal prior exposure to farm management systems, and varying farm sizes in North Macedonia. Farmers range from very small plots to larger estates, and many lack prior experience with digital advisory tools. The socio-technical environment demands a combination of online and in-person support, including field assessments and routine checks, to validate data and build trust. Economic factors, such as flexible subscription models and potential government or association support, also shape adoption, while the diverse agricultural landscape requires a versatile, tailored approach for different crops, farm capacities, and regional conditions.
- **The LL in Germany.** The Living Lab operates within a context of highly heterogeneous farming structures, unequal access to knowledge, and a vocational education system regulated by old curricula that barely acknowledge digital agriculture. External pressures, such as climate change, stricter regulations on inputs, and evolving agricultural policies, shape the relevance of digital tools. Internally, teachers lack time and resources to update their knowledge, while farmers' readiness varies widely due to economic considerations, personal motivation, and the relevance of technologies to different farm types.
- **The LL in Poland.** The Living Lab functions within a dynamic ecosystem of local food markets, technology developers, and diverse stakeholders. In the current pilot, each market hosts around 20 active farmers and 400 registered customers, generating roughly 50 transactions per month per location. The initiative is embedded in the broader objective of fostering digital solutions for sustainable local food systems. The context is shaped by ongoing experimentation, iterative improvements, and collaborative learning, with emphasis on understanding user needs, supporting smallholders, and integrating technology to enhance efficiency, market reach, and organisational resilience.
- **The LL in Ireland.** Key context factors include the platform's non-proprietary, digital nature, which allows inclusive participation and aligns with producers interested in open, cooperative market infrastructure. The localised scale of production and consumption; where delivery and collection occur on the same day, minimises logistics and supports short value chains. Farmers' motivations centre on market diversification and accessing new, reliable routes to market. The system replaces traditional market uncertainty with pre-ordering mechanisms and centralised collection points. The overall context is one of fostering local food economies through low-distance distribution and digital coordination.

Two more Living Labs taking part in the Teams talks have been categorised as operational at a socioenvironmental digitalisation level, with focus on landscapes. Their contextual descriptions are as follows:

- **The LL in Latvia.** Latvia's small-scale beef sector operates within a niche market characterised by price-sensitive consumers and limited culinary traditions around beef. Farmers often manage small or semi-large

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farms, utilising semi-natural grasslands for grasing, supporting biodiversity and landscape maintenance. Digital tool adoption is influenced by age, skills, and willingness, as older farmers may resist learning new technologies or engaging in social media. Cooperative formation faces challenges due to lack of consensus on standards and operational infrastructure. External factors include geopolitical tensions, market demand, and competition from imported beef, while internal drivers include farmers' motivation to sell directly to consumers.

- **The LL in Estonia/Latvia.** The Living Lab operates within intertwined social, environmental, political, technical, and economic contexts. Social factors include farmer peer-to-peer learning, engagement with recreational visitors, and collaboration with local communities. Environmental factors focus on grassland restoration, biodiversity tracking, and ecosystem protection. Technical factors involve drones, satellite imagery, commercial and open-source software, and tailored farmer training. Political and governance factors encompass EU recognition of biodiverse lands, national geographic systems, and government inspections. Economic factors include moderate mapping costs, potential revenue from semi-commercial services, and resource allocation for training and equipment maintenance.

In Table 2, and overview of the categorisation of the Living Labs into which digitalisation level they operate. Obviously, each Living Lab is also in interaction with the other levels of digitalisation.

Table 2 – Living Labs (the 16 taking part in the Teams talks) categorised into main digitalisation levels

#	Country	Business process level	Digital ecosystem level	Socio-environmental level
1	Italy, Tuscany		X	
2	Serbia		X	
3	Italy, Puglia		X	
4	Poland		X	
5	Scotland		X	
6	Ireland		X	
7	Belgium	X		
8	Spain, Almeria		X	
9	Slovenia	X		
10	Slovakia	X		
12	Latvia			X
13	France, Occitan.	X		
17	Germany		X	
18	Estonia/Latvia			X

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#	Country	Business process level	Digital ecosystem level	Socio-environmental level
19	North Maced.		X	
20	Hungary	X		

4.2.2 Living Lab contributions to business process context level

In the CODECS Conceptual framework, the business process level is referred to as a first level of digitalisation. This can have different meaning across the Living Labs, and here the business process contributions per Living Lab is provided:

- **The LL in Slovakia.** The Slovak Living Lab focuses on improving business processes for large-scale farmers by demonstrating the concrete benefits of digital irrigation technologies. Providing hard data on water savings and cost-benefit analyses encourages adoption, as large farmers respond to measurable returns on investment. Small and family farmers, who are generally more conservative and cautious about new technologies, present a challenge. To overcome this, the Living Lab collaborates with farmer networks like the Rural Parliament of Slovakia, using peer-to-peer approaches and experimental farms to showcase practical benefits, gradually building trust and creating case studies that illustrate achievable economic and environmental gains.
- **The LL in France.** The Living Lab enhances business processes by integrating digital technologies into daily farm operations. Individual milk meters, automated feeding, and EID tracking enable precise monitoring of production, health, and feeding efficiency, supporting data-driven decision-making. Advisory services adapt their workflows to provide tailored guidance, while farmers can optimise resource allocation and labour management. Collective governance structures allow coordinated investment and strategic planning. By streamlining operations, improving traceability, and supporting targeted interventions, the Living Lab fosters more efficient, resilient, and adaptive business processes, strengthening the economic viability and competitiveness of small ruminant dairy farms.
- **The LL in Hungary.** This Living Lab improves business processes by providing precise soil and nutrient data, enabling farmers to optimise fertiliser use, reduce waste, and manage input costs. Data-driven decisions lower production risks, enhance efficiency, and allow better labour allocation. Advisors support farmers in interpreting complex datasets, increasing confidence and operational effectiveness. Demo farms and training events foster knowledge exchange, accelerating adoption of digital tools. Integration across the value chain, from farm management to food producers, supports traceability, quality control, and market responsiveness, aligning farm operations with both economic and sustainability objectives.
- **The LL in Slovenia.** At the business process level, the Living Lab contributes by integrating precision technologies into daily farm operations, enhancing efficiency and decision-making. For the winery, it supports organic and sustainable practices by reducing pesticide use and optimising vineyard management. For the beekeeper, it enables remote monitoring of apiaries, lowering travel needs and operational costs. With this Living Lab, resource allocation, workflow efficiency, and productivity improve, while fostering sustainable, environmentally friendly practices. The Living Lab also strengthens collaboration and knowledge exchange between farmers, technology providers, and other stakeholders, embedding digital innovation into core business processes.
- **The LL in Belgium.** The Living Lab demonstrates how digital technologies reshape farm-level processes. High-resolution RGB imagery on drones and data analytics enable precision spraying, optimised resource use, and risk-informed decision-making. Farmers can reduce unnecessary pesticide application, improve efficiency, and better manage crop health. However, adoption requires significant training, data interpretation skills, and sometimes external services, adding operational complexity. The lab highlights interactions across farm workflows, advisory networks, and technology providers, showing how digitalisation affects planning, execution, and management. Insights into these processes inform both practical implementation and policy design,

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illustrating how technology integration at the business process level can enhance efficiency while interacting with environmental, economic, and social sustainability goals.

4.2.3 Living Lab contributions to digital ecosystem context level

The contributions of the Living Labs categorised at the digital ecosystem level, are provided in the following:

- **The LL in Scotland:** Small-scale farmers in the Living Lab seek affordable, practical digital tools suited to their diversified operations—such as social media, small weather stations, digital platforms, and simple livestock-monitoring technologies. Their main motivations are to stay visible, be efficient with time and resources, reach markets, communicate availability, and remain connected with their local farming community. They also want solutions designed for small rather than large farms. A core reason for participating in the Living Lab is the peer-to-peer learning environment, where farmers can share experiences, compare low-cost or free technologies, and learn directly from others facing similar challenges in a rapidly changing digital landscape.
- **The LL in Serbia.** The Living Lab strengthens the regional digital agriculture ecosystem by fostering multi-actor collaboration and knowledge exchange. It connects farmers, advisors, researchers, technology providers, and policymakers, facilitating co-creation and alignment of solutions with local needs. By demonstrating practical applications of sensor networks, mobile apps, and future AI-driven "virtual advisors," the Living Lab enhances awareness, skills, and technology readiness. It also generates data and insights that inform commercial and research development, supporting the scaling of innovations, improving digital literacy, and creating pathways for startups or companies to offer services, contributing to a more integrated and responsive digital agriculture ecosystem.
- **The LL in Spain.** The Living Lab enhances the digital ecosystem by fostering interoperability among sensors, drip irrigation systems, fertiliser controls, and decision-support platforms. It strengthens data-sharing practices through cooperatives, enabling aggregated insights that improve planning, forecasting, and logistics across the value chain. The lab promotes co-creation among farmers, tech providers, advisory services, and public administration, supporting skill development and technology adaptation. By connecting local actors in a competitive, concentrated agricultural area, it encourages innovation and co-opetition. Additionally, it facilitates knowledge dissemination and capacity-building, ensuring that digital tools are accessible, context-specific, and aligned with environmental, economic, and social objectives, improving overall ecosystem efficiency and effectiveness.
- **The LL in Italy, Puglia.** In this Living Lab, the main contributions revolve around facilitating the adoption of digital technologies within large-scale farms. The team acts as a process facilitator and animator, enabling farmers to engage with new systems, such as decision support tools, irrigation management, and digital monitoring. By fostering continuity from previous projects and supporting pioneer farmers, the Living Lab helps optimise farm operations, improve production quality, and reduce labour dependency. Farmers gain structured guidance, market insights, and technical support, ensuring that digitalisation is effectively integrated into field-level activities and broader organisational practices.
- **The LL in Poland.** This Living Lab functions within a dynamic ecosystem of local food markets, technology developers, and diverse stakeholders. In the current pilot, each market hosts around 20 active farmers and 400 registered customers, generating roughly 50 transactions per month per location. The initiative is embedded in the broader objective of fostering digital solutions for sustainable local food systems. The context is shaped by ongoing experimentation, iterative improvements, and collaborative learning, with emphasis on understanding user needs, supporting smallholders, and integrating technology to enhance efficiency, market reach, and organisational resilience.
- **The LL in North Macedonia.** The Living Lab contributes to the digital ecosystem by integrating satellite imagery, soil maps, NDVI data, weather forecasts, and disease models into a centralised web platform. It supports direct communication between farmers and agronomists, enabling exchange of images, videos, and field data for precise decision-making. The system allows farmers to list farm capacity, monitor production, and access advisory services while maintaining human oversight. By combining digital data sources, real-time communication, and flexible subscription-based access, the platform enhances farm management, promotes digital adoption, and strengthens the overall agricultural digital ecosystem in North Macedonia.
- **The LL in Italy, Tuscany.** The Living Lab strengthens the digital ecosystem by connecting farmers, the Pecorino cheese factory, technical advisors, veterinarians, and agronomists through a central app. This

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platform enables real-time sharing of production data, milk quantities, and eventually feed quality, facilitating coordination across the network. By integrating multiple stakeholders, the app enhances traceability, decision-making, and responsiveness, while promoting knowledge exchange. Younger farmers, in particular, can leverage digital tools to optimise farm management. Continuous development, user feedback, and technical support ensure the ecosystem evolves collaboratively, fostering innovation, adoption of new functionalities, and the creation of a resilient, interconnected digital framework for the livestock sector.

- **The LL in Germany.** Although the Living Lab works closely with technologies at farm level, its broader contribution lies in strengthening the knowledge network surrounding digital agriculture. It acts as a hub connecting vocational schools, teachers, students, advisory actors, researchers and technology providers. By mapping barriers, clarifying resource needs, and developing shared understanding of available tools, it enhances information flows within the digital ecosystem. The lab indirectly encourages other educational institutions to engage with digitalisation, compensates for gaps in formal curricula, and supports the diffusion of digital literacy. Its work also highlights systemic obstacles, including unequal access to knowledge reservoirs, and provides a platform for collective learning and experimentation.

4.2.4 Living Lab contributions to socioenvironmental context level

The two Living Lab categorised as contributors to a socioenvironmental digitalisation level are reflected on here:

- **The LL in Latvia.** The Living Lab contributes socially by promoting direct-to-consumer sales, enhancing farmers' engagement with communities, and potentially making agriculture more attractive to younger generations. This may support regional development, retaining population in rural areas and sustaining local infrastructures. Environmentally, it maintains semi-natural grasslands through grasing, preserving biodiversity-rich habitats and cultural landscapes. By encouraging local beef consumption, it reduces reliance on imported meat, lowering transport-related emissions. Social learning within the network strengthens knowledge exchange, while digital tools facilitate communication and marketing. Collectively, the lab fosters both cultural and ecological resilience, integrating social and environmental benefits within a small-scale, sustainable agricultural framework.
- **The LL in Estonia/Latvia.** The Living Lab strengthens socio-environmental systems by enabling precise biodiversity monitoring, grassland management, and restoration of culturally significant landscapes. High-resolution maps allow farmers to track vegetation changes, manage species composition, and align agricultural practices with conservation norms. Social benefits include peer-to-peer knowledge exchange, community engagement, and facilitation of recreational planning without disrupting protected areas. Governance is enhanced by integrating environmental regulations, monitoring by public agencies, and ethical data use. By connecting farmers, researchers, and authorities, the Living Lab fosters informed decision-making, systemic thinking, and collaborative stewardship, promoting ecological resilience, cultural heritage preservation, and social well-being at multiple scales.

4.3 Main challenges and opportunities towards sustainable digitalisation

4.3.1 Sustainable digitalisation as a main objective across Living Labs

In this section, an overview of relevant categorisation of Living Labs according to sustainability perspective is provided. Note that some Living Labs would fit into multiple categories, so this must be seen as examples.

First, many Living Labs contribute to environmental sustainability by focusing on reducing inputs, optimising resource use, protecting biodiversity, and lowering emissions, where digitalisation mainly serves environmental efficiency and stewardship. For instance:

- **The LL in Slovakia.** Digitalisation in rural Slovakia primarily benefits environmental sustainability, particularly through water efficiency, which supports biodiversity and reduces chemical use. Moreover, improved Internet access has enabled remote work, leading to rural repopulation and small-scale home farming, fostering local food production. Digital tools, precision agriculture, and AI have potential to enhance efficiency and environmental stewardship, but their positive impact depends on proper regulation, education, and training for

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farmers, especially smallholders. Social networks and forums support knowledge exchange, while human-centred approaches remain essential.

- **The LL in Slovenia.** This Living Lab promotes sustainability across environmental, economic, and social dimensions. Environmentally, precision technologies like sensors reduce pesticide use, optimise water consumption, and lower CO_2 emissions through reduced travel for the beekeeper. Economically, the lab lowers operational costs, improves resource efficiency, and supports organic certification, which can secure additional funding. Socially, it frees farmers' time, reduces burdens, and fosters knowledge exchange within the local community, strengthening rural resilience. Additionally, it supports ecosystem health, such as bee biodiversity. This Living Lab demonstrates how digital technologies can integrate sustainable practices, providing replicable models for other farms and creating a foundation for long-term systemic change in Slovenian agriculture.
- **The LL in Belgium.** The Living Lab contributes to sustainability by assessing precision agriculture technologies that reduce pesticide use and enhance resource efficiency. Importantly, it highlights the environmental costs of the technology itself, including carbon emissions from AI computation, battery production and disposal, and heavy metal residues, revealing hidden ecological impacts beyond the farm site. Economically, it demonstrates potential cost savings and yield optimisation; socially, it encourages stakeholder collaboration and knowledge sharing. By combining on-farm sustainability with the environmental footprint of digital tools, the lab provides a holistic understanding of sustainable digitalisation in agriculture.
- **The LL in Spain**. The Living Lab promotes sustainability through efficient resource use, particularly water and fertilisers, via precision agriculture and digital decision-support tools. It supports compliance with environmental and social certifications, reinforcing sustainable practices in intensive cropping systems. Digitalisation enables traceability, integrated pest management, and improved crop planning, helping farmers reduce input waste, safeguard human health, and enhance biodiversity. Economic sustainability is equally prioritised: by lowering production costs and improving market alignment, farmers maintain profitability while adopting environmentally responsible practices. In this Living Lab, the lab strengthens long-term viability of farming systems, linking ecological stewardship, social responsibility, and economic resilience in a highly resource-constrained and competitive context.
- **The LL in Estonia/Latvia.** The Living Lab promotes sustainability by combining environmental, social, and economic outcomes. Environmentally, it enables precise monitoring of biodiversity, vegetation, and ecosystem health, supporting conservation and restoration efforts. Socially, it facilitates peer learning, safe recreational use, and community engagement. Economically, farmers can make informed decisions. Digitalisation reduces labour-intensive monitoring, enhances governance compliance, and increases transparency. Through the integration of high-quality data, training, and collaboration with universities and government agencies, the Living Lab creates long-term, systemic benefits for sustainable agricultural practices, landscape protection, and environmental stewardship.

Second, digital tools can simultaneously enhance economic, social and environmental sustainability by means of resource use, strengthen rural society, and enhance profitability, often through training, networks, or collaborative structures. For instance:

- **The LL in Hungary.** This Living Lab enhances sustainability across environmental, social, and economic dimensions. Environmentally, it reduces over-fertilisation, pollution, and soil degradation while lowering carbon emissions. Socially, it empowers farmers with data for confident decision-making, engages younger generations, and strengthens rural communities. Economically, it optimises input use, reduces risks, and supports resilience against volatile input prices. By integrating the broader value chain and responding to consumer demand for sustainable products, it promotes long-term viability and aligns farm practices with both market and ecological sustainability goals.
- **The LL in Italy, Puglia.** Farm-level sustainability in the Living Lab encompasses social, economic, and environmental dimensions. Economically, digitalisation ensures stable, high-quality production, improving market positioning and income potential. Socially, participation in producer organisations, as well as in our Living Lab activities, encourages collaboration, knowledge sharing, and long-term professional development. Environmentally, farmers optimise water use, inputs, and cultivation practices while complying with certifications like organic and Europe GAP, promoting responsible, low-impact farming. Digital tools reinforce traceability and adherence to standards, supporting sustainable practices. These sustainability factors enhance 1) resilience,

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efficiency, and responsible stewardship, 2) positioning farmers to maintain quality, comply with regulations, and 3) positive contribution to environmental and market sustainability.

- **The LL in Slovenia.** The Living Lab promotes environmental, economic, and social sustainability. Sensor technologies reduce water usage by 10–20%, optimise fertiliser application, and limit unnecessary pesticide spraying, improving environmental outcomes. Economically, digital tools can increase average profits and provide scalable cost efficiencies. Socially, it empowers farmers with actionable knowledge, improves decision-making, and fosters community engagement through workshops, demonstrations, and stakeholder networks. By integrating technology with traditional practices and advisors' expertise, the Living Lab supports resilient, informed farming that balances productivity, resource conservation, and local socio-economic well-being.
- **The LL in Latvia.** The Living Lab enhances sustainability by integrating digital solutions that support economic, social, and environmental objectives. Economically, it allows farmers to reach a wider audience cost-effectively, facilitating niche markets for local beef. Socially, it strengthens local networks, cooperatives, and regional development, while fostering skills and digital literacy, particularly among younger farmers. Environmentally, grazing on semi-natural grasslands maintains biodiversity and preserves landscapes. The lab encourages critical evaluation of environmental claims, promoting informed consumer choices. Sustainability gains arise from the combination of short value chains, local production, and efficient digital marketing. The lab exemplifies a holistic approach, linking technological adoption with responsible resource use, social cohesion, and ecological stewardship.

Third, sustainability is focused on social innovation and local food systems with digitalisation acting as a social infrastructure to empower small farmers, support local economies, and reshape food networks, with environmental benefits as a secondary effect. For instance:

- **The LL in Scotland.** In the Living Lab, small-scale farmers adopt business models centred on short value chains, selling high-value, locally produced goods directly through farmers' markets, online platforms, and a 24-hour farm shop. These models enhance environmental sustainability by reducing long-distance transport and supporting biodiversity, such as protecting nesting birds and pollinators. Social sustainability is strengthened through strong local networks, collaboration with other farms and businesses, and seasonal agritourism. Peer-to-peer learning, social media, and online storytelling enable farmers to share environmental practices, raise the positive profile of farming, adapt technologies, and respond flexibly to market demands, while combining income streams ensures farm viability and aligns ethical production with consumer expectations.
- **The LL in Poland.** This Living Lab's digital ecosystem is designed to foster collective action among small-scale farmers, moving them from isolated, individual sales to coordinated participation in local food markets via the Appetit platform. It provides farmers with increased exposure, access to customers, and compliance with regulations while retaining existing distribution channels. By connecting producers directly with buyers who value local, seasonal products, the platform supports economic survival, employment, and market opportunities for Poland's majority small farmers. The ecosystem develops iteratively through interaction with farmers to address barriers and identify opportunities. Integrating online and physical markets ensures local food production persists despite urban sprawl, fostering environmental sustainability, social cohesion, and economic resilience while reducing reliance on long-distance food supply chains.
- **The LL in Ireland.** The Living Lab's sustainability impacts fluctuate due to its small scale and the limited size of the towns it serves. Economically, it can support small-scale farmers by giving them an alternative route to market, though fresh-produce sellers must ensure sufficient volume to justify time and transport. Environmentally, coordinated drop-offs reduce waste, but very small deliveries can offset benefits. Socially, while it is not a traditional face-to-face market, it still fosters producer and organiser interaction and offers small farmers fairer market access, helping reduce barriers in local food systems despite seasonal and supply-chain challenges.

Fourth, sustainability improvements come via knowledge diffusion, training, advisory systems, and digital inclusion. For instance:

- **The LL in North Macedonia.** This Living Lab contributes to sustainability across economic, environmental, and social dimensions. Environmentally, precision advisory tools guide farmers on optimal fertiliser and pesticide use, reducing over-application and promoting safer practices. Economically, small and medium farms

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gain access to expert agronomist advice, improving efficiency and crop management while making technological solutions cost-effective. Socially, inclusion in digitalisation empowers farmers who might otherwise be excluded, enhancing knowledge sharing, collaboration, and fairness. By targeting farms with sufficient activity and capacity, the system ensures long-term viability, combining technological support with expert guidance to promote sustainable, informed, and resilient agricultural practices in North Macedonia.

- **The LL in Germany.** The Living Lab supports sustainability mainly through the social dimension, reducing inequality in access to digital knowledge. Environmentally, it teaches how technologies can lower input use, reduce chemical impacts, optimise fertiliser placement, and apply mechanical alternatives where possible. It also familiarises students with tools that address climate-related risks, such as diagnostics, modelling and robotics. Economically, it helps farmers understand cost structures, potential savings, and efficiency gains. By combining these perspectives, the lab strengthens informed pathways toward more resilient and resource-efficient farming practices.

Fifth, sector- and culture-specific sustainability where digitalisation preserves traditional agricultural identities, supports quality-assured products, and enhances sector-specific sustainability (welfare, feed optimisation, dairy value chains). For instance:

- **The LL in France**. This Living Lab promotes sustainability by supporting more precise and efficient herd management, optimising feed distribution, and potentially improving animal welfare. It facilitates data-driven decisions that can reduce resource waste and enhance productivity. While environmental impacts are still under study, the project provides a framework to evaluate potential improvements. Socioeconomic sustainability is addressed through increased farmer autonomy, access to tailored advisory services, and strengthened collective governance, while cultural and market sustainability is supported by preserving small ruminant breeds and high-value dairy products such as Roquefort cheese.
- **The LL in Italy, Tuscany.** Digital solutions support economic sustainability by increasing farm efficiency, optimising milk production, and reducing labour burdens. Socially, they have potential to attract younger farmers, supporting generational renewal and maintaining the rural workforce. Cultural sustainability is reinforced through improved coordination of sheep farming, which preserves landscapes and traditions, and through tourism opportunities such as factory and farm visits. Environmental impacts are limited but future feed analysis features may contribute to better resource management. In this Living Lab, digitalisation strengthens the resilience of the livestock sector, ensuring long-term viability while maintaining the region's cultural and social heritage.

4.3.2 Main challenges across Living Labs

The challenges for sustainable digitalisation across the Living Labs can be categorised into eight broad themes. First, limited digital skills, complex tools, and insufficient training hinder effective use of technologies. Second, high investment costs and uncertain returns constrain adoption, especially where economic capacity is low. Third, fragmented governance, bureaucracy, and misaligned incentives slow implementation. Fourth, infrastructural gaps and interoperability issues undermine performance and reliability. Fifth, social and cultural barriers, including resistance to change, low trust, and generational divides, affect engagement. Sixth, market structures and value-chain pressures limit economic viability. Seventh, environmental and topographical conditions complicate deployment. Eight, sustaining initiatives beyond pilot phases can remains difficult due to resource constraints and limited long-term support. All the Living Labs report on multiple challenges, which makes it inappropriate to cluster them. Instead, the challenges of relevance for each Living Lab are briefly described in the following:

- **The LL in Slovakia.** Public sector involvement in the Slovak Living Lab faces several challenges. Policy frameworks and funding mechanisms are often complex and limited, making it difficult to support widespread adoption of digital irrigation technologies. Small and family farmers are particularly affected, as they lack access to resources, expertise, and guidance. Coordination between ministries, rural parliaments, and other stakeholders can be inconsistent, slowing implementation. Additionally, bureaucratic hurdles and varying regional capacities reduce the effectiveness of subsidies or grants, limiting investment in both hardware and digital solutions, and constraining the potential reach and impact of public sector initiatives.
- **The LL in France**. Challenges in this Living Lab include the high cost of individual milk meters, the low adoption rate, and difficulties adapting technology designed for cattle to smaller-scale sheep farms. Software usability is

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limited, requiring specialised advisory services for effective deployment. Governance and competitive dynamics among advisory services create barriers to uniform adoption. Data ownership and use present further uncertainties. Farmers' diverse digital readiness and limited resources hinder rapid uptake, while environmental and socio-economic outcomes are not yet fully measurable. Collectively, these factors complicate scaling digitalisation and achieving immediate benefits across the sector.

- **The LL in Hungary.** Challenges in this Living Lab include digital literacy gaps, particularly among older farmers, and the complexity of interpreting large datasets. Technological issues such as interoperability across diverse machinery and lack of standardised agricultural data hinder seamless adoption. Social and cultural factors, including resistance to change and varying motivation levels, influence uptake. Dependency on subsidies and external drivers, such as input price fluctuations, can limit consistent engagement. Ensuring user-friendly interfaces, effective training, and clear data ownership agreements are key hurdles to maximising the benefits of digital agriculture.
- **The LL in Slovenia.** Challenges in this Living Lab include adapting technology to diverse local contexts, such as rugged vineyard terrains and remote apiary locations. Farmers need technical and mental support to adopt and use new digital tools effectively. Scaling solutions requires training, capacity building, and peer learning to reach broader rural communities. Ensuring inclusivity is also critical, as benefits depend on who is included or excluded. While policy and governance play a limited role, connectivity and infrastructure considerations must be addressed. Maintaining trust and engagement among stakeholders is essential to sustain collaboration and ensure long-term adoption of digital and sustainable practices.
- **The LL in Belgium.** The main challenges include high financial risks for farmers due to large-scale investments and variable yields. To mitigate the risk of harvest losses from pests or diseases, farmers often overapply pesticides, prioritising yield security over environmental or economic efficiency. Operational complexity and the need for advanced digital skills further hinder adoption of precision technologies. The Living Lab highlights poor communication between public administration and farmers, resulting in guidance that is sometimes irrelevant or impractical, such as recommending unnecessary technology use. Additionally, the environmental costs of digital technologies themselves, including carbon footprint from AI computation, battery production, and heavy metal residues, introduce hidden ecological impacts. Social barriers, including workforce decline and a digital divide, complicate widespread sustainable adoption.
- **The LL in Scotland.** Small-scale farmers often struggle to adopt agri-tech designed for large farms, which is expensive and poorly suited to their context. The Living Lab brings these farmers together to discuss how they adapt existing tools, sometimes not originally intended for their specific farming contexts, to meet their needs. Examples include repurposing livestock sheep scanning technologies for goats. Through peer-to-peer exchange, they explore what works, what doesn't, and how small-scale innovation can emerge from reinterpreting large-scale opportunities. Moreover, formal training often fails to support small rural businesses, including farms, because generic courses are irrelevant and confusing to the farmers. The Living Lab addresses this gap through peer-to-peer learning, centred on the demo farm that acts as a pioneer. Farmers observe technologies in practice, hear about successes and failures, and adapt tools to their contexts. The Living Lab workshops encourage storytelling, questions, and hands-on experiences, enabling farmers to modify technologies for their small-scale operations. Social dynamics, trust, and shared problem-solving make this approach meaningful, fostering learning, innovation, and practical solutions tailored to each farm's unique needs.
- **The LL in Serbia.** Key challenges include limited farmer awareness and digital literacy, financial constraints, and fear of technology adoption. Infrastructure gaps, particularly in rural areas lacking LoRa or GPRS coverage, impede consistent implementation. Proper use of sensors requires technical skill, calibration, and ongoing attention, which may be challenging for some farmers. Generational differences influence willingness to adopt, with older farmers often hesitant. Scaling beyond demo farms requires market research, commercialisation strategies, and alignment with policy frameworks. Social challenges include traditional mindsets, skepticism, and building trust in digital tools. Overcoming these barriers requires training, awareness campaigns, subsidies, and supportive governance.
- **The LL in Spain.** Key challenges include high initial investment costs for digital tools, ongoing operational expenses, and reluctance among some farmers to share data due to privacy concerns. Small-scale farmers may struggle to adopt technologies without cooperative support, limiting scale effects and interoperability. Governance challenges arise in balancing local initiatives with regional or national hubs, often influenced by

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political and institutional priorities. Certification and traceability requirements add administrative burdens, and volatile markets and climatic variability introduce uncertainty. Additionally, technological heterogeneity, differences in greenhouse design, and skill gaps require tailored solutions. Ensuring equitable access, scalability, and sustained farmer engagement remains an ongoing challenge for the Living Lab.

- **The LL in Italy, Puglia.** Despite digital advantages, farmers face contextual challenges that limit their long-term sustainability. Labour shortages, competition from tourism, and uncertainties in agricultural policy create anxiety and constrain planning. Complex regulations and internal rules sometimes complicate the implementation of digital solutions. While technology supports operations, it cannot fully mitigate external pressures such as market fluctuations or workforce availability. Farmers must balance technological adoption with these structural constraints, recognising that digitalisation is supportive but not sufficient to overcome broader systemic and regulatory challenges.
- **The LL in North Macedonia.** The main challenges in the North Macedonian Living Lab include low digital literacy among small and medium farmers and limited familiarity with digital advisory systems. Many farmers require extensive guidance, face-to-face support, and trust-building before adopting new tools. Ensuring user-friendly design is essential, as farmers lack experience with data-driven management. Additional challenges include verifying digital data through field checks, adapting solutions to diverse farm capacities, and establishing viable subscription models in a context where digital agriculture is still emerging.
- **The LL in Italy, Tuscany.** This Living Lab faces several challenges, including declining farmer numbers, high operational costs, low milk prices, and predation by wolves with limited governmental support. The digital solution is still under development, with technical bugs and limited readiness for full-scale use. Older farmers may struggle with technology adoption, and attracting young farmers remains difficult. In addition, coordination across stakeholders, regulatory frameworks, and incentives are not fully optimised, and environmental conflicts arise between wolf protection and livestock sustainability.
- **The LL in Germany.** Key challenges include unequal knowledge distribution, limited economic capacity of smaller farms, and the difficulty of motivating all farmers because only about half show strong interest in digitalisation. The vocational education system poses another barrier: curricula are outdated, digital agriculture is not mandatory, and teachers lack time for upskilling. Broader agricultural policies impose restrictions that require digital solutions but do not necessarily provide adequate support for learning. Additionally, the technological landscape is complex, and many tools are perceived as not well-fitted, too complicated, or poorly communicating their benefits. These factors collectively hinder widespread and equitable uptake.
- **The LL in Poland.** The main challenge for this Living Lab's digital ecosystem is supermarket dominance, favouring imported products over local small-scale farmers. Existing value chains prioritise efficiency and scale, marginalising small producers. Short food chains face logistical complexities, dispersed production, and higher per-unit costs. Farmers must navigate digital literacy gaps, administrative requirements, and competitive attitudes, while overcoming high intermediary margins and survival pressures. Scaling is constrained by complex logistics—packaging, aggregation, and distribution—and urban development threatens farmland. Demonstrating clear financial benefits is essential to motivate adoption. Despite widespread digitisation, building trust, encouraging collaboration, and attracting more farmers and consumers remain socially and technically challenging, limiting turnover and succession in small-scale farming.
- **The LL in Ireland.** This Living Lab faces several interconnected challenges that limit its growth and sustainability. A major issue is the small and fluctuating consumer base, with many shoppers preferring face-to-face markets or reverting to supermarkets. In rural areas, low population density further reduces demand, while free or heavily discounted food from supermarkets and food banks makes price competition nearly impossible. Producers also face dilemmas: some earn more by delivering directly than by using the platform. The market struggles against "Death Star" digital platforms backed by venture capital, which can scale rapidly, operate at a loss, and dominate consumer expectations for convenience and low prices. Limited funding, reliance on volunteer labour, and tensions around digitisation deepen these structural barriers.
- **The LL in Latvia.** Key challenges include limited willingness among farmers to adopt digital tools, and unwillingness to change occupation, for instance, to make a shift from farming/livestock management to production of marketing content or social media communication. The challenge of social media engagement, and the difficulty of integrating these tools into existing workflows without creating extra work, were particularly relevant. Cooperative formation is hindered by disagreement on standards, inadequate slaughterhouse infrastructure, and internal conflicts. Market constraints, such as high beef prices, price-sensitive consumers,

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and niche demand, limit scaling. External factors like geopolitical events and competition from imported meat affect economic viability. Generational differences in skill and motivation further influence adoption, while sustainability claims require critical assessment to avoid misrepresentation.

- **The LL in Estonia/Latvia.** Challenges include sustaining the Living Lab post-project, requiring funding, student involvement, or private sector collaboration. Farmers face technical complexity, especially with open-source software, necessitating tailored training. High-resolution digital data introduces privacy, security, and ethical risks, particularly in sensitive geopolitical contexts. Limited availability of skilled IT personnel and insufficient private-sector engagement constrain scaling. Financial barriers, digital literacy gaps, and complexity of balancing environmental, social, and economic objectives add further difficulty. Conduciveness depends on training, infrastructure, and supportive governance. Coordination with governmental inspections, norms, and regulations requires careful management to ensure compliance without discouraging farmer participation.

4.3.3 Main opportunities across Living Labs

Opportunities for sustainable digitalisation across the Living Labs can be categorised into a total of six. First, digital tools enhance efficiency through real-time monitoring, precision interventions, and improved traceability, strengthening economic and environmental performance. Second, the labs act as learning ecosystems where demonstrations, advisory support, and peer-to-peer exchange build digital skills and confidence. Third, coordinated governance linking policy, research, and collective farmer organisations, supports strategic investment and sector-wide innovation. Fourth, digital platforms and traceability open new market channels, reinforce short value chains, and improve farmers' bargaining power. Fifth, the Living Labs nurture social sustainability by fostering trust, community networks, and rural attractiveness. Sixth, digitalisation enables better environmental stewardship, climate adaptation, and experimentation, providing scalable pathways toward resilient, data-driven agriculture. Because multiple opportunities for each Living Labs, they are not clustered, however, the specific opportunities of relevance to each Living Lab is briefly provided in the following:

- **The LL in Slovakia.** The public sector offers significant opportunities to support digitalisation of the farming. Policy makers can establish grants, subsidies, and investment programs to encourage adoption of digital technologies and innovative irrigation systems, including pumps, valves, and water infrastructure. Organisations like the rural parliament serve as education and transfer centres, organising workshops, focus groups, and conferences to inform small farmers about benefits and best practices. Collaboration with universities and ministries allows alignment of research, policy, and practical implementation, enhancing digitalisation, climate resilience, and sustainable rural development, while creating long-term, systemic support for the agricultural sector.
- **The LL in France**. Opportunities in this Living Lab lie in co-developing tailored software, leveraging individual animal data for herd management, and optimising feeding and welfare. Advisory services can enhance their offerings, fostering farmer autonomy and efficiency. Collective governance and federations enable coordinated investment and strategic decision-making at the sector level. Digitalisation can support market competitiveness, climate-adapted breeding, and sustainable production practices. Early adopters can pilot innovations that inform broader sector uptake, while system-level learning enhances the ability to respond to environmental, economic, and policy changes. The ecosystem approach encourages cross-stakeholder collaboration and long-term innovation.
- **The LL in Hungary.** Opportunities in this Living Lab include optimising input use to reduce costs and environmental impact, increasing operational efficiency, and supporting risk management. Engaging younger farmers via digital tools strengthens workforce renewal and rural retention. The Living Lab fosters knowledge sharing across farms, advisors, and the value chain, enabling innovation diffusion. Data-driven decision-making enhances traceability, market responsiveness, and alignment with sustainable consumption trends. Policy support and subsidies further incentivise adoption. Large-scale uptake could improve soil health, reduce carbon emissions, and promote resilient, economically viable, and environmentally responsible agriculture.
- **The LL in Slovenia.** This Living Lab creates opportunities for enhanced farm efficiency, precision agriculture, and sustainable practices. Farmers gain real-time insights into crops and apiaries, enabling targeted interventions, reducing resource use, and lowering costs. The approach fosters organic certification and supports funding applications. Knowledge sharing and peer learning enhance community capacity and encourage broader adoption of digital tools. It strengthens rural attractiveness, retaining local talent and

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potentially attracting urban residents. The lab also supports ecosystem health, biodiversity, and social sustainability. Scaling the model regionally or nationally could drive systemic change in agriculture, positioning Slovenia as a leader in sustainable, data-driven farming practices.

- **The LL in Belgium.** Opportunities in this Living Lab stem from regulatory drivers pushing farmers toward precision applications and digital tools to meet pesticide reduction targets. Technologies like drones, sensors, and AI can optimise resource use, reduce environmental impact, and maintain yields. Knowledge exchange within the Living Lab fosters co-creation and learning among farmers, service providers, and policymakers. With adequate training, user-friendly devices, and supportive governance, digitalisation can lower operational risks, streamline processes, and integrate sustainability into everyday farm management. This positions sustainable digitalisation as a strategic response to environmental, economic, and social challenges in modern agriculture, offering a pathway to long-term resilience.
- **The LL in Scotland.** Technology supports farmers' social sustainability by reducing isolation, improving mental health, and strengthening family and community ties through digital communication. Peer-to-peer learning is preferred because farmers trust technologies proven locally by people they know, building confidence and ensuring relevance to their specific conditions. This localised sharing fosters community support and practical, context-tested learning.
- **The LL in Serbia.** Opportunities lie in improving farm efficiency, environmental management, and knowledge dissemination. Digital technologies can provide actionable guidance via mobile apps or AI-driven virtual advisors, reducing labour, resource use, and environmental impacts. Stakeholder engagement through Living Lab events strengthens networks, collaboration, and co-creation of solutions tailored to local needs. Scalability allows one sensor node to monitor multiple greenhouses, enhancing cost-effectiveness. Policy support and subsidies could accelerate adoption. Generational shifts toward younger, tech-savvy farmers increase long-term uptake. Data collection and digital integration enable future commercialisation, system optimisation, and insights into regional and national-scale sustainable agriculture practices.
- **The LL in Spain.** The Living Lab provides opportunities to optimise resource use, increase profitability, and enhance sustainability through precision agriculture and digital traceability. Aggregated data enables better decision-making, forecasting, and planning across the value chain. Farmer-centred co-creation promotes adoption of context-appropriate technologies, enhancing operational efficiency. The concentration of farms and proximity to tech providers encourages innovation, competition, and knowledge exchange. Strengthened governance through cooperatives facilitates training, advisory services, and collective bargaining. Opportunities also exist for environmental benefits like water and nutrient savings, improved human health, and biodiversity preservation. Long-term, the Living Lab can demonstrate scalable models for sustainable digitalisation that maintain small-farm viability and resilience in a competitive, resource-limited region.
- **The LL in Italy, Puglia.** Large-scale organic table grape farmers benefit from digital technologies that help maintain high-quality standards, manage irrigation, and ensure traceability for certifications required in premium markets. Digital tools enhance efficiency, allow remote monitoring, and support consistent yields and income stability. Within producer organisations, these technologies foster knowledge sharing and standardisation across farms. For younger farmers, digitalisation offers a pathway to adapt to evolving market demands, improve operational management, and integrate innovations that increase productivity and competitiveness while sustaining organic and certified production practices.
- **The LL in North Macedonia.** This Living Lab demonstrates significant opportunities by engaging stakeholders directly with the RAMAS digital system. Through consecutive demonstrations, farmers and other stakeholders gain familiarity with digital tools, increasing acceptance and understanding of farm management technologies. Observing their reactions allows the team to track progress in digital adoption and tailor solutions to users' needs. This iterative engagement builds trust, improves digital literacy, and strengthens the potential for widespread implementation of effective, user-friendly agricultural technologies in North Macedonia.
- **The LL in Italy, Tuscany.** Opportunities in this Living Lab include attracting young farmers through user-friendly digital tools, improving production efficiency and traceability, and optimising farm management. Expansion of digital features, such as feed quality tracking, could enhance resource use and welfare monitoring. Collaboration among farmers, the cheese factory, technicians, and researchers strengthens the network. Tourism and cultural engagement provide additional economic avenues, while government incentives and subsidies for welfare improvements offer financial support. The lab's digital ecosystem can increase competitiveness in both local and international markets.

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- **The LL in Germany.** The Living Lab can significantly expand digital readiness by offering early exposure to technologies without requiring financial investment. It can motivate schools and teachers to develop new modules, strengthen ties between knowledge providers, and influence broader educational practices. Digital tools also offer opportunities to meet environmental regulations, improve efficiency, and address climate-related farming risks. AI and robotics open additional experimentation possibilities, and the lab's neutral, hands-on setting allows critical testing. With supportive governance and better-conducive policy frameworks, the lab could help integrate digital competencies more systematically across agricultural education.
- **The LL in Poland.** This Living Lab uses digital tools to create local, short value chains, empowering farmers and connecting them directly with consumers. By automating intermediary functions – information, transactions, invoicing – and enabling self-organisation, the platform reduces costs and improves market access. Farmers can efficiently use existing infrastructure, while marketplaces for logistics, financial services, and advisory support enhance economic viability and sustainability. The system saves time, facilitates collective sales, and supports diverse, high-quality ecological and traditional products. Mobile and web access allows easy management of pricing, orders, and invoices. Shared logistics and recyclable packaging cut costs, encourage adoption, and preserve traditional farms, supporting small-scale and urban agriculture while strengthening local food systems and community resilience.
- **The LL in Ireland.** This Living Lab offers opportunities to strengthen bioregional food systems by helping small-scale farmers access markets they might otherwise be excluded from. Its open-source, non-proprietary platform appeals to digitally aware consumers seeking ethical, transparent alternatives to corporate food chains. When funding is available, consumer numbers grow, revealing potential for expansion with adequate support. The model also aligns with emerging policy interests in food security, regional resilience and reduced dependence on globalised supply chains. With appropriate investment, training and basic income supports for food workers, the system could evolve into a stable, community-centred alternative.
- **The LL in Latvia.** Opportunities include expanding direct-to-consumer sales via digital platforms, strengthening local networks, and promoting niche, environmentally conscious beef products. Digital tools can reduce marketing costs, improve visibility, and engage younger farmers, making agriculture more attractive and potentially supporting regional development. Environmental stewardship through grazing maintains biodiversity and semi-natural landscapes. Collaboration within cooperatives, if effectively organised, can enhance consistency in product standards and improve access to markets. Increased awareness and demand for locally sourced beef present economic and social potential, fostering resilient agricultural practices while integrating digital innovation with sustainable farming.
- **The LL in Estonia/Latvia.** Opportunities in this Living Lab include developing semi-commercial mapping services through universities or spin-offs, enhancing automation in agriculture, biodiversity monitoring, and landscape restoration. Digital tools enable informed decision-making, peer-to-peer learning, and safe recreational planning. Integration with national and EU geographic systems strengthens policy alignment, transparency, and evidence-based governance. Farmers gain access to data-driven insights for environmental compliance and optimised land management. Multi-level collaboration between farmers, universities, researchers, and government agencies fosters systemic thinking. Future potential lies in expanding adoption of sustainable digitalisation, improving workflow efficiency, supporting conservation goals, and creating win-win outcomes across ecological, social, and economic domains.

4.4 Main costs and benefits per Living Lab

Costs and benefits with digitalisation in CODECS are explored in both short- and long-term terms, and by focusing on advantages and challenges rather than just financial metrics. In this section, four main categories of costs and benefits are identified based on the responses of the Living Labs. They are related with 1) high-tech efficiency and resource optimisation, 2) digital adoption with high costs and dependency, 3) social, market and community-based digitalisation, and 4) capacity building and governance for long-term readiness.

First, a category can be linking costs and benefits to high-tech efficiency and resource optimisation, with focus on irrigation optimisation, precision inputs, monitoring, biodiversity mapping, as well as strong environmental and economic gains and training and data-interpretation challenges. The Living Labs operating precision technologies,

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sensors, AI, and data analytics drive economic and environmental performance, such as Slovakia, Hungary, Slovenia, Serbia, Spain, and Estonia/Latvia, are relevant here.

- **The LL in Slovakia.** The Slovak Living Lab highlights the economic, social, and environmental benefits of AI-driven irrigation systems. Economically, precise water use reduces costs for water, electricity, and fuel, while improving field yields. Environmentally, it enhances resource efficiency and sustainability. Socially, AI addresses gaps in human expertise caused by a shortage of agronomy specialists, providing real-time data and predictive modelling. However, AI also poses risks: critical human oversight is essential to ensure data accuracy and effective decision-making. Successful implementation requires cross-sectoral expertise combining IT and agricultural knowledge, emphasising the importance of interdisciplinary education for long-term capacity building.
- **The LL in Hungary.** Short-term advantages in this Living Lab include improved input efficiency, reduced environmental impact, optimised labour, and cost savings; enhanced confidence in decision-making. Short-term disadvantages include investment in technology, need for training, and complexity of interpreting data; dependency on advisors. Long-term advantages include increased farm resilience, sustainable resource management, enhanced market competitiveness, engagement of younger farmers, and broader ecosystem benefits including traceability and rural vitality. Long-term disadvantages include continuous maintenance and updates of digital systems, potential technology obsolescence, interoperability issues, and reliance on external support such as subsidies. In this Living Lab, the lab balances economic, environmental, and social gains against initial costs and ongoing operational demands.
- **The LL in Slovenia.** Short-term benefits include reduced operational costs, efficient time management, and improved monitoring of vineyards and apiaries. Farmers gain actionable insights, lower environmental impacts, and enhanced social well-being through reduced workload. Disadvantages may involve learning curves, initial technology adoption costs, and dependence on reliable connectivity. Long-term benefits encompass systemic change, sustainable practices, ecosystem health, enhanced organic production, stronger rural communities, and replication potential for other farms. Potential long-term disadvantages include exclusion of less-connected farmers, risk of technology obsolescence, or over-reliance on digital systems. In this Living Lab, benefits outweigh costs, with both individual farmers and broader society gaining economic, environmental, and social advantages from the Living Lab's sustainable digitalisation approach.
- **The LL in Serbia.** Investment in sensor technology costs around €1,000 per unit, with an average profit increase of €400 per greenhouse per season. Benefits include improved yields, optimised water, fertiliser, and pesticide use, environmental protection, labour savings, and enhanced decision-making through mobile apps or virtual advisors. Short-term advantages are immediate profit gains and reduced input usage; disadvantages include initial investment, required training, and potential technology misuse. Long-term advantages encompass scalability, sustainability, environmental impact reduction, and integration into farm management systems. Governance support and conducive infrastructure, such as subsidies and network coverage, enhance adoption. Disadvantages include infrastructure dependency, ongoing maintenance, and uneven adoption among different farmer groups.
- **The LL in Spain.** Costs in this Living Lab include initial technology investments, maintenance, training, data management, and compliance with certification standards, which can be burdensome for small farms. Administrative and governance coordination adds additional complexity. Benefits comprise resource efficiency (water, fertiliser), improved productivity, traceability, and informed decision-making. Short-term advantages include cost control, market compliance, and skill development, while short-term disadvantages involve learning curves, resistance to data sharing, and potential dependency on cooperatives or tech providers. Long-term advantages are enhanced sustainability, profitability, resilience, and optimised supply chain efficiency through interoperable data-sharing. Long-term disadvantages could include increased reliance on technology, potential exclusion of smaller or less resourced farms, and governance challenges in standardisation, interoperability, and equitable access across the digital ecosystem.
- **The LL in Estonia/Latvia.** Short-term costs include software, training, and mapping services (~€500 per 40–50 hectares). Long-term costs involve maintaining updated maps, infrastructure, and continuous training. Short-term benefits comprise improved operational efficiency, precise biodiversity tracking, and reduced physical risk for inspections. Long-term advantages include enhanced environmental sustainability, informed decision-making for optimising production of goods and services, and integration into EU-level conservation frameworks.

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Disadvantages involve dependency on technical expertise, data privacy risks, and initial financial or cognitive barriers. Conduciveness through training, supportive infrastructure, and governance can mitigate these risks. The Living Lab's digital ecosystem fosters collaboration, evidence-based land management, and compliance, contributing to both environmental and social benefits that potentially outweigh challenges in the long term.

Second, costs and benefits can be linked with digital adoption with high costs and dependency. They have in common that they operate costly devices, are struggling with interoperability issues, are dependent on advisory, and where governance and training determine long-term value. These Living Labs have high upfront investments, reliance on consultants, and unclear economic returns dominate.

Examples are France, Belgium, Italy (Puglia), and Italy (Tuscany):

- **The LL in France.** Short-term costs in this Living Lab include the high purchase price of individual milk meters (≈€1,000–2,000 per sheep), installation, and potential advisory service fees. Farmers face adaptation challenges with software designed for cattle, requiring training and consultancy support. Advantages include improved herd management, targeted feeding, and potential efficiency gains. Long-term benefits involve enhanced animal welfare, optimised production, stronger collective governance, and resilience to climate change. Disadvantages may include uneven adoption and ongoing dependency on advisory services. In this Living Lab, sustainable digitalisation is facilitated by conducive governance, clear stakeholder coordination, and resource allocation, balancing immediate investment against future sector-wide productivity, environmental, and socio-economic gains.
- **The LL in Belgium.** Short-term costs include high investments in drones, sensors, AI tools, and training, as well as potential service fees. Farmers face the risk of crop losses, which often leads them to overapply pesticides to secure yields, reducing the immediate economic benefit of precision technologies. Guidance from public administration can be inconsistent or irrelevant, sometimes promoting unnecessary technology use. Advantages include site-specific pesticide application, better-informed decision-making, and potential yield stabilisation. Disadvantages include environmental impacts from the technology itself, including carbon emissions, battery production, and heavy metal residues, and the learning curve. Long-term, digital adoption can help maintain yields under stricter regulations, optimise resource use, and support sustainable outcomes, provided governance, training, and communication improve.
- **The LL in Italy, Puglia.** Large-scale farmers in the Living Lab face both opportunities and constraints with digital agriculture. Benefits include potential efficiency gains, improved environmental management, and income stability, but these are often unclear or not immediately realised. Challenges arise from limited farmer competencies, reliance on consultants, high investment costs, and uncertain economic returns. Worker availability and weak market bargaining further complicate adoption. While certifications like organic or Europe GAP exist, digital agriculture lacks standardised recognition, limiting its perceived value. Training, knowledge transfer, and demonstration of tangible economic and environmental advantages are essential to help farmers assess short- and long-term costs, benefits, and sustainability impacts.
- **The LL in Italy, Tuscany.** Short-term costs involve technical issues, training, and adaptation time, while benefits include improved efficiency, better production tracking, and enhanced coordination. Long-term advantages encompass sustainable business processes, potential attraction of younger farmers, preserved cultural landscapes, and stronger network resilience. Disadvantages include partial readiness of technology, dependency on external support, and limited immediate environmental impact. While upfront investment and adaptation are needed, the digital ecosystem promises higher productivity, economic sustainability, and social and cultural benefits, creating a robust framework for future innovation and intergenerational continuity in sheep milk production.

Third, costs and benefits can relate with social, market and community-based digitalisation, linked with use of digital tools for marketing, networks, storytelling, local markets, benefits tied to community engagement, and risks tied to workload, digital fatigue, and uneven adoption. These Living Labs typically strengthen digitalisation by means of short supply chains, collective action, marketing, or community resilience. Examples include Scotland, Poland, Ireland, and Latvia:

- **The LL in Scotland.** In this Living Lab short supply chains and low start-up capital entail flexibility, seasonal adaptation, and diversification, supporting resilience. Digital tools, social media, and online sales offer

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opportunities for market reach and storytelling, but bring challenges like digital fatigue, time demands, and pressure to maintain skills and content quality. Farmers must balance online engagement with maintaining their outdoor, nature-focused lifestyles. Long-term sustainability relies on hybrid models combining physical and digital connections, diversified income streams, and peer-to-peer learning to share strategies and manage evolving challenges.

- **The LL in Poland.** The Living Lab identifies costs and benefits across farm, digital ecosystem, and policy scales. Benefits include improved market access, collective action, and digital tools that increase efficiency and inclusivity for farmers and consumers. Demonstration events and platform functionalities help include diverse participants, even elderly or less digitally literate farmers. Costs involve technical investments in logistics, packaging, and infrastructure, as well as time and effort to build trust and adoption. Regulatory gaps and social barriers can limit participation. Long-term benefits depend on inclusion, effective digitalisation, and supportive policy, while short-term costs include training, coordination, and system implementation.
- **The LL in Ireland.** In the short term, this Living Lab offers benefits such as reduced waste through coordinated drop-offs, improved market access for small farmers, and community engagement around regional food. It enables producers to test new routes to market with minimal financial risk. However, short-term disadvantages include small delivery volumes that can negate environmental gains, limited consumer numbers, and dependence on temporary funding or volunteer labour. In the long term, the model could strengthen regional resilience, diversify local food supply and support more sustainable farming. Yet its long-term viability is challenged by powerful corporate platforms, low food prices, rural depopulation, and the need for sustained investment, training and supportive policies to establish a stable, competitive alternative.
- **The LL in Latvia.** Short-term costs include investment of time, learning digital tools, and producing marketing content. Short-term benefits are improved customer communication, broader audience reach, and reduced marketing expenses. Long-term costs involve sustaining engagement, maintaining digital channels, and potential generational gaps in adoption. Long-term benefits include strengthened rural networks, retention of local populations, biodiversity conservation, and stable niche markets. Advantages include low-cost technology integration, environmental contributions via grassland grazing, and social learning. Disadvantages encompass workload duplication, dependence on cooperatives' governance, market limitations, and variability in farmers' willingness. Conduciveness relies on internal motivation and cooperative readiness, while governance is primarily self-regulated, with limited formal regulatory intervention.

Fourth, costs and benefits can be linked with capacity building and governance for long-term readiness. This can further relate with reduced knowledge gaps, provisions of structured decision tools, and strengthen ecosystem readiness rather than focusing on specific technologies. Living Labs in this category contribute primarily with education, decision-support, multi-criteria assessment, and governance structures enabling sustainable digitalisation. Examples include Germany and North Macedonia:

- **The LL in North Macedonia.** This Living Lab helps clarify costs and benefits across farm, ecosystem, and regional levels by using multi-criteria analysis to assess economic, environmental, and social impacts of digital solutions. By comparing technologies across clusters of criteria, it identifies which options deliver the greatest value and where trade-offs occur. This approach supports farmers, advisors, and policymakers in choosing efficient, sustainable tools. At the same time, the Living Lab strengthens readiness and conduciveness by creating a supportive environment that reduces barriers, improves decision-making, and enhances overall system performance.
- **The LL in Germany.** Short-term benefits include improved digital awareness, access to unbiased information, and reduced knowledge inequality. Costs involve teacher time, funding needs, and overcoming reluctance among farmers with established routines. Long-term advantages may include more efficient and precise input use, reduced environmental impact, and strengthened farm resilience through better decision-making. Long-term disadvantages relate to increasing inequality if technologies remain expensive or poorly adapted to diverse farm types. Conduciveness depends on supportive education and agricultural policies, while governance improvements, including updated curricula, training support, and clearer structures, are essential to sustain digital capacity building.

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4.5 Main learning contributions per Living Lab

Comparing the Living Labs, five key learning categories emerge. First, environmental sustainability can be strengthened through precision water management, reduced inputs, and biodiversity monitoring. Second, social learning and community building develop via peer exchange, collaboration, and trust among farmers and stakeholders. Third, effective governance and institutional coordination support interoperability, training, and system-wide integration. Fourth, enhanced digital skills and technological understanding enable informed, context-appropriate adoption. Fifth, economic and market learning highlights how digitalisation improves efficiency, supports short value chains, strengthens competitiveness, and fosters resilient, sustainable business models.

- Most Living Labs cover many of these learning aspects, and hence, not possible to categorise them:
- **The LL in Slovakia.** The Living Lab contributes significantly to water sustainability by generating extensive soil data, which supports detailed water monitoring and management. This data underpins the development of a model designed to optimise water use, enhancing environmental benefits such as improved biodiversity and reduced chemical inputs. Beyond environmental impacts, the lab fosters knowledge exchange and collaboration among farmers, rural communities, and organisations through digital platforms. By integrating digital tools, training, and human-centred approaches, the initiative strengthens precision agriculture, supports smallholders, and promotes inclusive, efficient, and sustainable practices in rural areas.
- **The LL in France**. The French Living Lab demonstrates that sustainable digitalisation in small ruminant dairy farming requires balancing high short-term costs, low adoption, and technology adaptation challenges with long-term productivity, welfare, and resilience gains. Key learning contributions include the value of tailored software, data-driven herd management, optimised feeding, and advisory services supporting farmer autonomy. Collective governance and federations enable coordinated investment and strategic planning. The Living Lab highlights the importance of ecosystem collaboration, context-sensitive solutions, and iterative innovation, showing how digital tools can enhance efficiency, traceability, sustainability, and competitiveness in small-scale sheep dairy systems.
- **The LL in Hungary**. The Hungarian Living Lab provides significant learning contributions by demonstrating how digital agriculture can optimise resource use, improve decision-making, and reduce environmental impacts. Farmers gain practical knowledge on soil nutrient management, input optimisation, and carbon footprint reduction, increasing both economic and environmental awareness. The lab promotes social learning through demo farms, advisory support, and peer exchange, fostering confidence and engagement, particularly among younger farmers. It also illustrates the integration of the broader value chain, linking farm practices to food quality, traceability, and market demands. Additionally, it highlights challenges such as data interpretation, interoperability, and the need for training, offering insights for scalable, sustainable digital farming.
- **The LL in Slovenia.** This Living Lab demonstrates that precision agriculture can enhance farmer health and well-being by reducing workload, travel, and time pressures, while enabling data-driven decisions that improve farm efficiency. Environmental benefits include reduced pesticide use, optimised water consumption, and strengthened biodiversity, supporting healthier ecosystems. Socially, the lab fosters knowledge sharing, collaboration, and trust within rural communities, increasing resilience and retaining local talent. Economically, it supports viable business models through cost reduction, organic certification, and funding opportunities. Key challenges include technology adaptation to local conditions, initial investment and training needs, and ensuring inclusivity so benefits reach all farmers and stakeholders.
- **The LL in Belgium.** The Living Lab provides critical insights into sustainable digitalisation in agriculture. It highlights that while precision technologies can reduce pesticide use and optimise yields, their adoption is constrained by high investment risks, operational complexity, and skill gaps. Uniquely, it reveals that digital tools carry hidden environmental costs, including carbon emissions, battery production, and heavy metal residues. The Living Lab also uncovers governance gaps, showing poor communication between public administration and farmers can lead to irrelevant or impractical guidance. This Living Lab informs practical, social, economic, and environmental dimensions of technology adoption in farming.
- **The LL in Scotland.** In this Living Lab, small-scale farmers face long- and short-term challenges in adopting agricultural technologies, as existing policies mainly favour large farms. Support is needed to help them navigate innovations like AI, manage associated risks, and understand data ownership and transparency. Peer-to-peer learning is preferred, but opportunities for networking are limited. Policy could facilitate these

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interactions by funding knowledge exchange spaces and training, allowing farmers to share experiences, learn from one another, and explore new practices safely. Such support would enhance their capacity to adopt technology effectively while protecting their livelihoods and fostering collaboration within the small-scale farming community.

- **The LL in Serbia.** The Serbian Living Lab contributes to learning by demonstrating practical applications of digital agriculture, enabling farmers to understand and adopt sensor technologies effectively. It builds awareness, digital skills, and sustainable practices through hands-on trials, workshops, and stakeholder interactions. Farmers, advisors, researchers, and policymakers exchange knowledge, addressing local challenges and co-creating solutions. The Living Lab highlights scalable approaches, efficient resource use, and data-driven decision-making. It also fosters understanding of socio-economic, environmental, and technical factors, motivating adoption and informing future technology development and governance strategies in agriculture.
- **The LL in Spain.** The Almería Agri-Ecological Living Lab demonstrates how a farmer-centred, cooperative-based approach can strengthen digital ecosystem development and readiness. Key contributions include fostering interoperability among sensors, irrigation, and decision-support systems, while promoting co-creation between farmers, tech providers, advisory services, and public administration. It highlights how concentrated, small-scale farms can benefit from shared data, improving forecasting, planning, and traceability. The lab also illustrates the importance of governance and organisational structures, such as cooperatives, in enabling adoption and sustainability. This Living Lab provides a replicable model for integrating digital technologies with local context, enhancing operational efficiency, environmental sustainability, and economic resilience.
- **The LL in Italy, Puglia.** In this Living Lab, facilitators support farmers by creating spaces for interaction, observation, and discussion around digital technologies. They organise meetings, demo events, and open days where pioneer farmers demonstrate tools like decision support systems, irrigation management, and monitoring devices. Facilitators ask questions, guide reflection, and highlight opportunities, helping participants understand practical applications and benefits. This hands-on, peer-learning approach shows the importance of continuity, trust, and contextualised guidance in technology adoption. From this, we learn that effective facilitation combines demonstration, dialogue, and ongoing support to encourage informed, sustainable innovation.
- **The LL in North Macedonia.** This Living Lab creates valuable system-wide impacts by improving how farmers work and how institutions monitor agriculture. By providing digital training, advisory support, and traceable field data, farmers gain clearer guidance, adopt better practices, and reduce administrative burdens. At the same time, the platform generates reliable, centralised information – such as input use and crop progress – supporting policymakers, inspectors, and regulatory bodies with accurate, real-time insights. This shift from fragmented, handwritten notes to integrated digital records strengthens transparency, enhances oversight, and promotes more efficient, sustainable agricultural governance across the wider system.
- **The LL in Italy, Tuscany.** The South Tuscany Living Lab highlights how digitalisation can strengthen efficiency, sustainability, and resilience in sheep milk and Pecorino cheese production. Key learnings include the value of user-friendly digital tools for farm management, enabling real-time data sharing, traceability, and optimised coordination between farmers, the cheese factory, and technical advisors. Younger farmers adopt technologies more readily, improving operational efficiency, while older farmers benefit from support and training. The collaborative digital ecosystem fosters continuous improvement through feedback and shared knowledge. Governance, both formal and informal, plays a role in guiding adoption and incentives. Socially, digitalisation may attract young farmers, ensuring generational renewal, and supports cultural and tourism activities, preserving the landscape and regional identity, while economic sustainability remains central.
- **The LL in Germany.** The Living Lab's main learning contribution is giving farmers a first practical, low-risk insight into digital and precision agriculture technologies. It helps them evaluate what tools exist, what skills they require, and whether they fit their specific farm type. By explaining operational complexity, labour needs, economic implications and environmental potential, the lab enables informed, critical decision-making rather than unreflective adoption. It also broadens farmers' understanding of the wider digital ecosystem, highlighting knowledge gaps, realistic benefits, and the conditions needed for technologies to be meaningful and feasible in everyday farming practice.
- **The LL in Poland.** This Living Lab leverages digitalisation to create local, short value chains, empowering small-scale farmers and connecting them directly with consumers. By automating intermediary functions – information, transactions, invoicing – and enabling self-organisation, the platform reduces costs, improves

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market access, and increases efficiency. Existing farm infrastructure and shared logistics are used effectively, while marketplaces for advisory services, financial tools, and recyclable packaging enhance economic viability. The system supports collective sales, diverse ecological and traditional products, and mobile and web management of pricing and orders. Adoption strengthens local food systems, preserves traditional farms, and fosters sustainable, resilient communities.

- **The LL in Ireland.** A key learning from the Living Lab is the challenge of serving small rural communities, where limited population size affects the sustainability of local food systems. Consumer engagement fluctuates, and low order volumes can undermine environmental benefits when producers make small, frequent deliveries. The need to understand rural consumers' expectations is highlighted, including their reliance on global supply chains that offer constant availability, convenience and low prices, which are conditions difficult for small producers to match. The Living Lab also revealed that independent training and education are increasingly unviable without state support, making policy influence essential. Rapid advances in digitalisation and AI further showed how quickly assumptions become outdated, reinforcing the importance of systems thinking and inclusive, environmentally grounded digital strategies.
- **The LL in Latvia.** The Latvia Living Lab offers significant learning opportunities at the socioenvironmental context level by demonstrating how digital tools can support sustainable agriculture while strengthening social networks. Farmers gain insights into managing short value chains, directly engaging with consumers, and effectively communicating environmental and product-related information. The lab fosters understanding of biodiversity conservation through grazing on semi-natural grasslands, highlighting the links between farming practices, habitat preservation, and landscape maintenance. Participants also learn about collaboration, cooperative dynamics, and the importance of aligning standards and practices to achieve collective benefits. Additionally, it illustrates how local production and responsible consumption can reduce environmental impacts, reinforcing the connection between social behaviour, community development, and ecological stewardship.
- **The LL in Estonia/Latvia.** The Living Lab offers comprehensive learning opportunities across digital, ecological, and social domains. Farmers and researchers gain hands-on experience with high-resolution drone and GIS mapping, enhancing skills in remote sensing, data interpretation, and digital land monitoring. Participants learn to track vegetation and biodiversity, manage invasive species, and restore grasslands while balancing agricultural productivity with environmental conservation. Peer-to-peer learning, workshops, and collaborative problem-solving foster knowledge exchange and systemic thinking. The Living Lab also provides insights into governance, EU and national regulations, and sustainable land-use planning. This Living Lab strengthens evidence-based decision-making, supports environmental stewardship, and promotes the integration of socio-environmental and economic considerations.

5 Visioning sustainable digitalisation across Living Labs

In this Chapter, the second research question is addressed: What are the context specific sustainability outcomes of relevance to each Living Lab? The overall comparisons of the Living Labs is provided about their visioning of economic, social and environmental sustainability outcomes are hence presented for the fourteen Living Labs who contributed to this activity, included the Slovakia, Hungary, Belgium, Slovenia, Czech Republic, Serbia, Spain, Scotland, Germany, North Macedonia, Ireland, Poland, Estonia/Latvia, and Latvia Living Labs.

5.1 Overall comparison of the relative priorities sustainable digitalisation outcomes

The relative priorities of the contextual sustainability outcomes identified in each Living Lab are provided in this Chapter. Before addressing each Living Lab separately, an overall overview at a general level including the main categories of economic, social and environmental sustainability outcomes, including all LL are provided in Figure 4 below. The Figure illustrates substantial variation in how digitalisation is interpreted across Europe, with some

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countries emphasising environmental outcomes, while others are prioritising economic or social outcomes. Economic sustainability outcomes are prioritised most strongly among the Living Labs operating in Belgium (64%), Poland (61%), Latvia (59%), Germany (54%), Serbia (54%), and North Macedonia (54%). The Living Lab in Slovenia assigns a priority of 48%, while the Living Lab in the Czech Republic reports 44%. Living Labs operating in Spain and Hungary both report 33%. The Living Lab in Scotland reports a priority of 28%, followed by the Living Lab in Slovakia at 27% and the Living Lab in Ireland at 20%. The Living Lab operating in Estonia/Latvia assigns the lowest priority to economic sustainability outcomes at 10%. Overall, the distribution shows a cluster of six Living Labs at or above 50%, two in the low-to-mid 40% range, two at one-third (33%), and three below 30%.

For social sustainability outcomes, the Living Lab operating in Scotland reports the highest relative priority at 46%, followed by the Living Lab in Ireland at 40%. Five Living Labs report one-third or above: those operating in Scotland (46%), Ireland (40%), Spain (33%), Hungary (33%), and Estonia/Latvia (33%). Living Labs in Germany and North Macedonia each report 30%, while the Living Lab in Poland reports 27% and the Living Lab in Latvia 25%. Lower priorities are reported by Living Labs operating in Slovenia (17%), Serbia (16%), Slovakia (12%), and both Belgium and the Czech Republic (11%).

Regarding environmental sustainability outcomes, the Living Lab operating in Slovakia assigns the highest relative priority at 61%, followed by the Living Lab in Estonia/Latvia at 57% and the Living Lab in the Czech Republic at 44%. The Living Lab in Ireland reports 40%, while the Living Lab in Slovenia reports 35%. Living Labs operating in Spain and Hungary each report 33%, and the Living Lab in Serbia reports 30%. Living Labs in Belgium and Scotland both report 26%. The Living Labs operating in Germany, North Macedonia, and Latvia each report 16%, while the Living Lab in Poland reports the lowest priority at 12%. Overall, eight Living Labs report environmental priorities of 30% or higher.

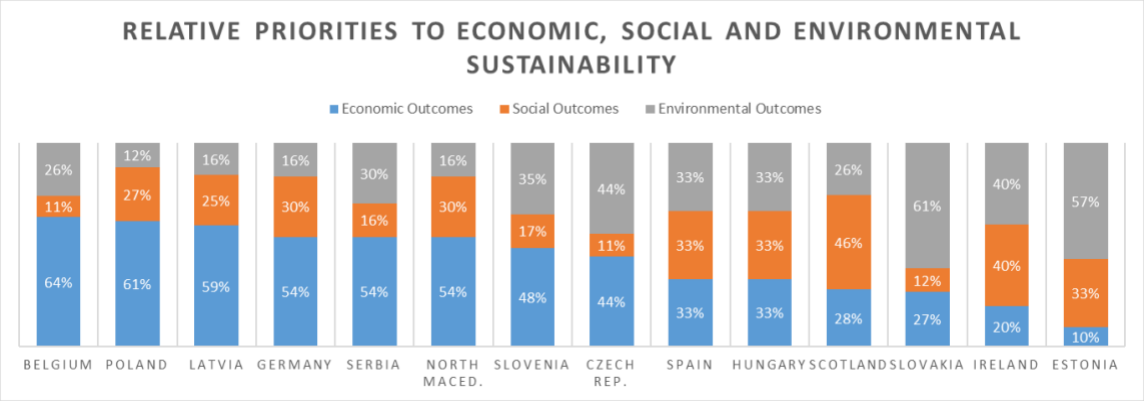

Figure 4 – The relative priority scores of economic, social and environmental sustainability outcomes – comparison across the Living Labs

This overall main overview of the relative priorities of the main sustainability outcome categories across the Living Labs taking part gives and interesting idea about how they differ, however, this does not inform on what specific economic, social and environmental sustainability outcomes are of relevance in each Living Labs and which would be more relevant. Therefore, the next is to understand what this overall overview implies at contextual level in each Living Lab. Not only are the specified economic, social and environmental sustainability outcomes of relevant different across the Living Labs, but also the relative relevance of them.

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5.2 Sustainability outcomes per Living Lab, including value-trees and priority scores

In this section, the value-trees as well as the priority scores are presented visually for each Living Lab. There is a link between the two, as the priority score visualisation only includes the sustainability outcome of the exclusive value-tree for the particular Living Lab.

Visioning towards economic sustainability outcomes. The Living Labs based in Belgium, Poland, Latvia, Germany, Serbia, and North Macedonia, have in common that they give strong prioritisation of economic sustainability outcomes, typically exceeding 50% of total priority scores. Across these Living Labs, digitalisation is primarily interpreted as a means to enhance competitiveness, efficiency, and financial resilience of agri-food systems. The dominant criteria within their value-trees include reducing operational costs, increasing revenues, improving productivity, expanding access to markets, finance and insurance, and developing or optimising business models. While environmental and social outcomes are present, they tend to function as secondary or enabling criteria rather than primary objectives. Environmental priorities are often narrowly defined and linked to efficiency gains (e.g. energy or water use reduction), rather than broader ecosystem transformation. Similarly, social criteria, such as labour conditions, community interaction, or digital skills, are typically framed in instrumental terms, supporting workforce efficiency or business performance.

Differences within this category relate mainly to the structure of economic priorities. For example, the Living Labs in Belgium and Germany emphasise business model innovation and cost efficiency, while Poland and Latvia place stronger weight on market access and revenue growth. Serbia and North Macedonia additionally highlight risk mitigation and productivity as responses to structural vulnerabilities in their food systems. In the following, the outcomes in each Living Lab are explained in more detail.

The LL in Belgium. In the Belgian LL, the distribution of outcomes is strongly dominated by economic outcomes (64%), followed by environmental outcomes (26%) and social outcomes (10%). This profile highlights a food system primarily oriented toward economic performance and efficiency, with ecological and social aspects receiving comparatively smaller shares. Within the economic outcomes (64%), the largest contribution comes from reducing costs (34%), followed by developing new business models (17%), agricultural production increases (9%), and improved access to insurance systems (4%). These outcomes indicate a strong focus on competitiveness, innovation, and efficiency, with financial risk management also present. The environmental outcomes (26%) are spread across soil quality improvement (11%), reductions in GHG emissions (6%), energy use efficiency (6%), and water quality enhancement (3%). This reflects a complementary but secondary emphasis on sustainability, particularly in soil and climate-related areas. The social outcomes (10%) consist of contributions to human health and labour conditions (7%) and external support to business management (3%). These results point to a modest but relevant recognition of workforce well-being and institutional strengthening.

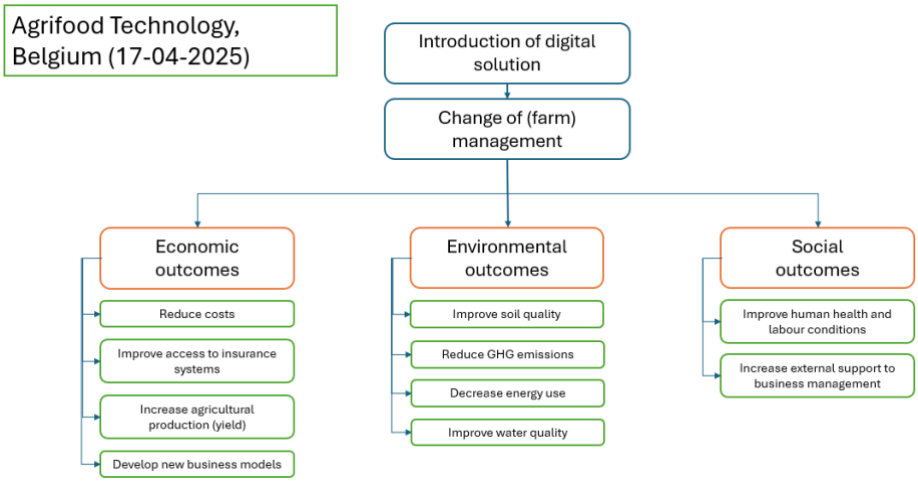

Figure 5 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in the Belgian Living Lab

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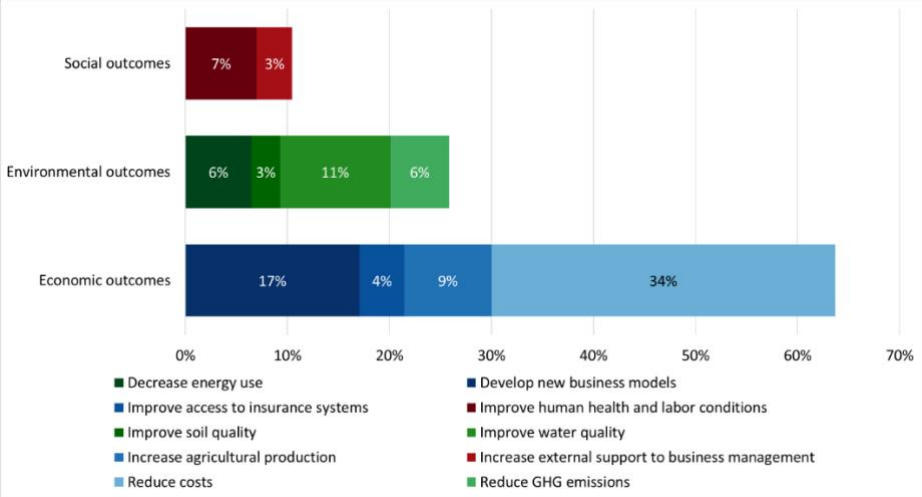

Figure 6 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Belgium

The LL in Serbia. In the Serbian LL, the distribution of outcomes is dominated by economic outcomes (54%), followed by environmental outcomes (30%) and social outcomes (16%). This indicates a food system where economic priorities are central, supported by substantial ecological contributions and more modest social outcomes. Within the economic outcomes (54%), the largest contributions come from reducing costs (19%) and agricultural production (19%), followed by developing new business models (9%) and improved access to markets, finance and insurance (7%). These outcomes highlight a strong emphasis on efficiency, productivity, and financial integration as key levers of food system development. The environmental outcomes (30%) are distributed across biodiversity enhancement (12%), energy use reduction (10%), and smaller shares from water use reduction (2%) and soil quality improvement (6%). This reflects a complementary ecological agenda focused on biodiversity and resource efficiency. The social outcomes (16%) include human health and labour conditions (6%), community interaction (5%), digital skills and literacy (4%), and external support to business management (2%). While comparatively smaller, these outcomes signal ongoing efforts to strengthen human and social dimensions of the food system.

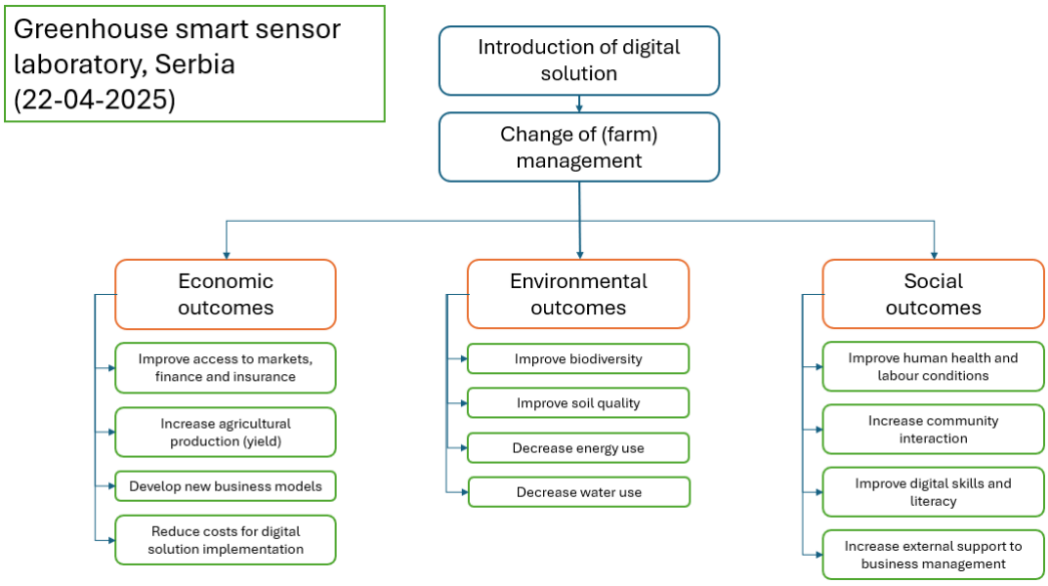

Figure 7 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in the Serbian Living Lab

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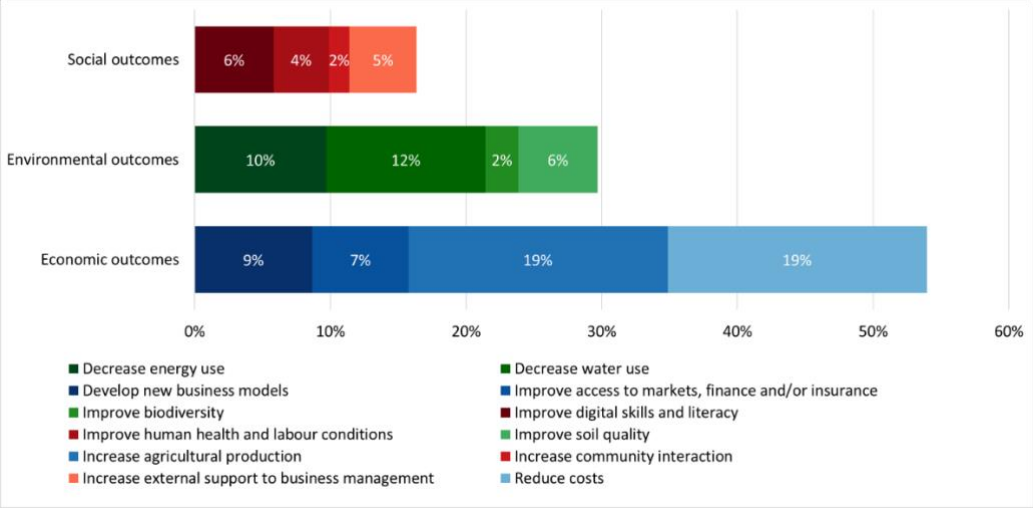

Figure 8 – The relative priority scores of economic, social and environmental sustainability outcomes in Serbian LL

The LL in Germany. For the Living Lab in Germany, the distribution of outcomes is dominated by economic outcomes (54%), followed by social outcomes (29%) and environmental outcomes (16%). This profile reflects a food system where competitiveness, productivity, and market efficiency are emphasised, while social and environmental priorities play important but secondary roles. Within the economic outcomes (54%), the largest share comes from developing or optimising business models (24%), followed by increased access to markets (14%), cost reductions (11%), and agricultural production (5%). These results highlight a strong orientation toward innovation, efficiency, and integration into markets as central drivers of food system performance. The social outcomes (29%) are distributed between improvements in human health and labour conditions (22%) and community interaction (7%). This indicates a significant focus on workforce well-being and health, alongside strengthening community-level connections. The environmental outcomes (16%) comprise contributions from water quality improvement (11%) and crop health (5%). While relatively smaller in proportion, these outcomes underline an effort to embed ecological resilience and resource management into food system development.

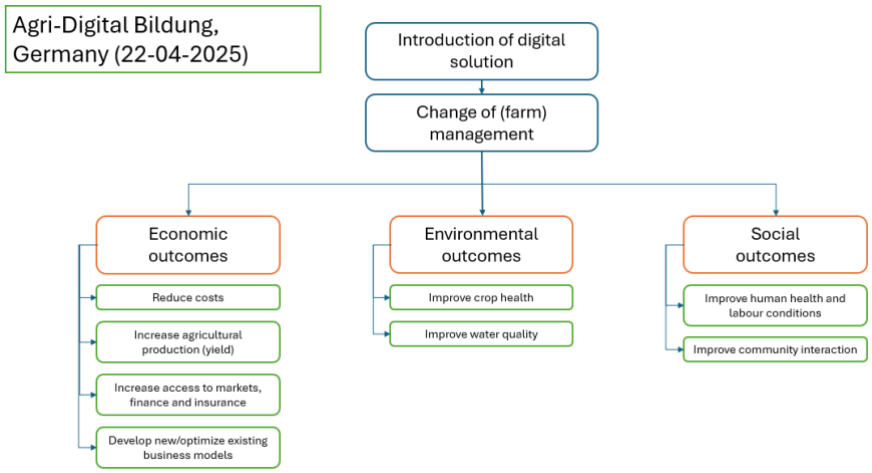

Figure 9 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this German Living Lab

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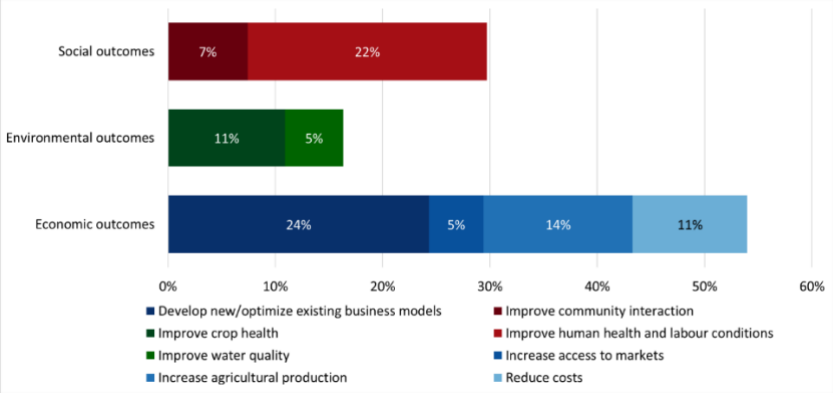

Figure 10 – The relative priority scores of economic, social and environmental sustainability outcomes in the German LL

The LL in North Macedonia. In the North Macedonian Living Lab, the distribution of outcomes is dominated by economic outcomes (53%), followed by social outcomes (30%) and environmental outcomes (17%). This indicates a strong emphasis on economic performance and resilience, with social and environmental outcomes playing smaller, though significant, roles. Within the economic outcomes (53%), the largest share comes from reducing operational costs (23%), followed by access to markets, finance and insurance (7%), agricultural production (12%), and mitigating production risks (11%). These outcomes point to a food system strategy strongly oriented toward efficiency gains, productivity, and risk management. The social outcomes (30%) are evenly distributed across digital skills and literacy (10%), human health and labour conditions (10%), and external support to business management (10%). This reflects an emphasis on capacity-building, workforce well-being, and institutional support as complementary levers to economic transformation. The environmental outcomes (17%) are made up of decreasing water use (6%), improving biodiversity (3%), improving soil quality (5%), and reducing waste (3%). While smaller in share, these outcomes indicate an orientation toward resource stewardship and ecological improvement within the food system.

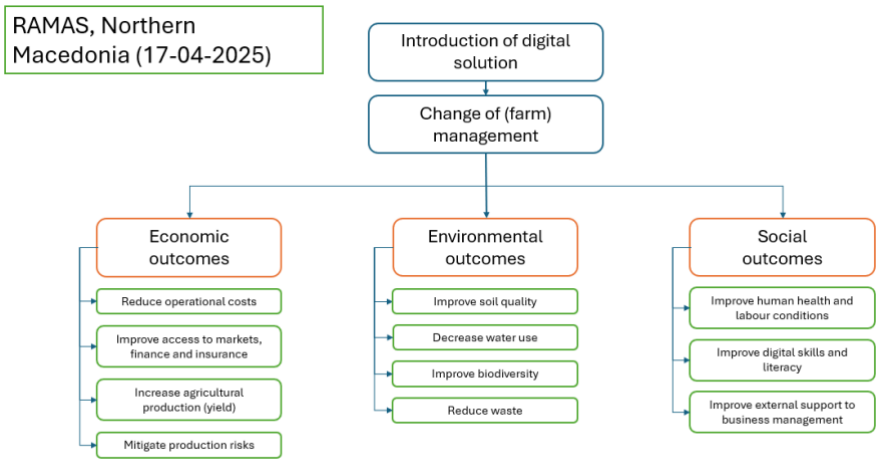

Figure 11 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this North Macedonian Living Lab

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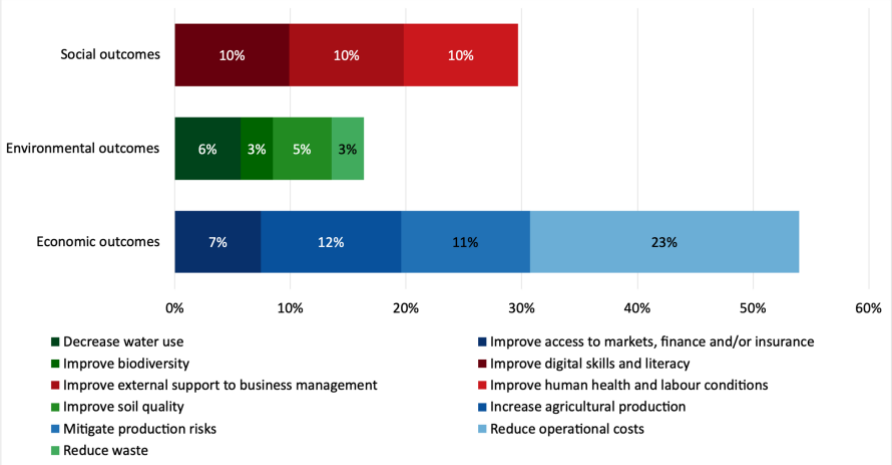

Figure 12 – The relative priority scores of economic, social and environmental sustainability outcomes in the North Macedonian LL

The LL in Poland. In the Living Lab in Poland, the distribution of outcomes highlights a strong predominance of economic outcomes (61%), followed by social outcomes (27%) and environmental outcomes (12%). This configuration reflects the prevailing orientation of food system interventions toward economic resilience, with comparatively lower attention to ecological functions and socio-cultural dynamics. Within the environmental domain (12%), the most relevant contributions are linked to improving soil quality (2%), reducing waste (3%), and mitigating greenhouse gas (GHG) emissions (4%). Smaller shares are dedicated to decreasing energy use, water use, and enhancing biodiversity (1% each). These outcomes indicate incremental rather than systemic ecological gains, suggesting that environmental externalities of food production remain under-addressed. In the social dimension (27%), the outcomes are more balanced. The highest shares derive from rural revitalisation (10%) and community interaction (10%), with smaller contributions from external business support (6%) and improvements to health and labour conditions (2%). This points to an emphasis on strengthening rural communities and enhancing the socio-institutional fabric that underpins food system sustainability. The economic outcomes (61%) dominate, with the largest proportion coming from improved access to markets, finance, and insurance (27%). This is followed by reductions in costs and income increases (19%), development of new business models (10%), and decreased financial risks (6%). Such a configuration reflects a market-oriented trajectory in Poland's food systems, emphasising competitiveness and financial stability as primary levers of change.

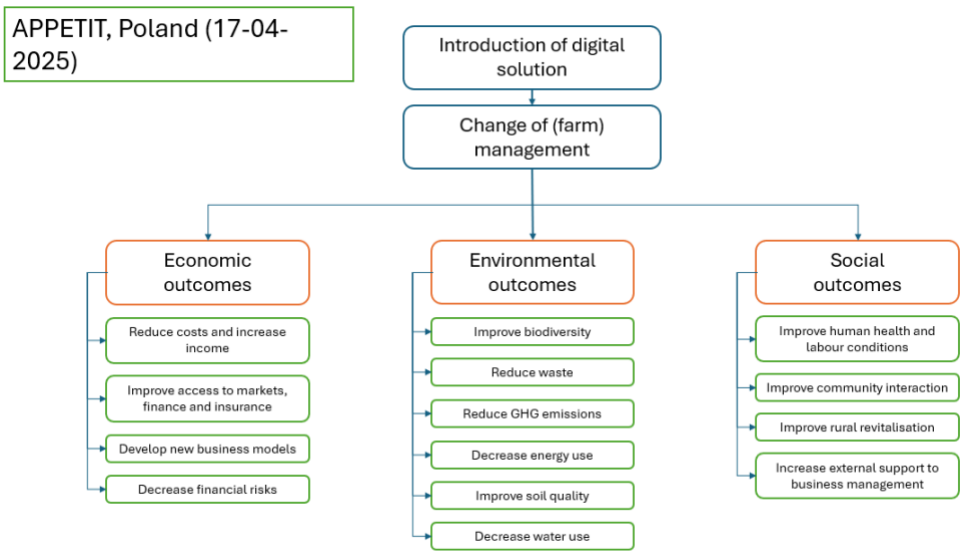

Figure 13 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Polish Living Lab

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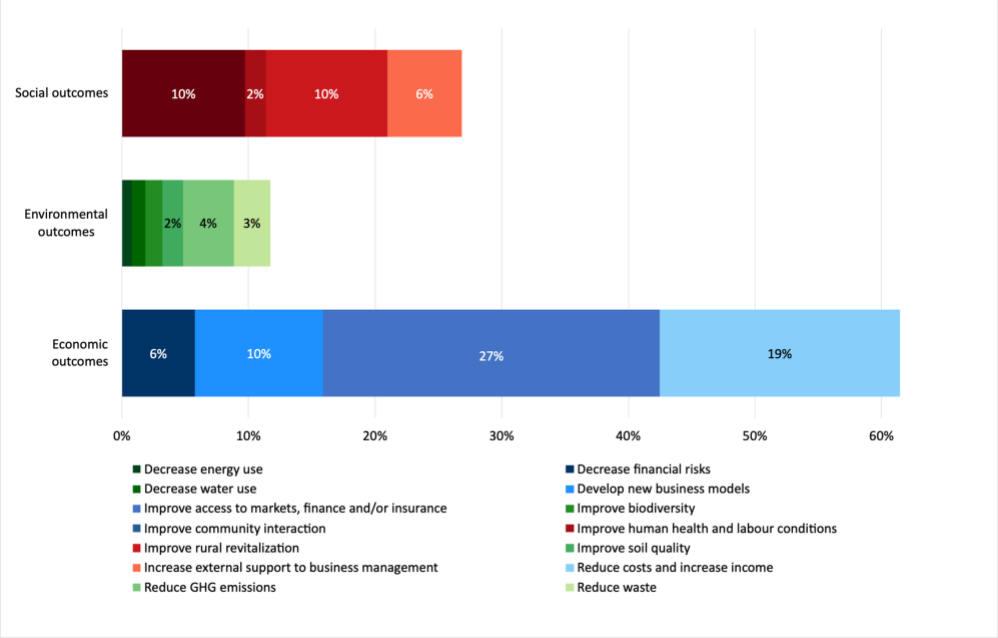

Figure 14 – The relative priority scores of economic, social and environmental sustainability outcomes in the Polish LL

Visioning towards environmental sustainability outcomes. The Living Labs in Slovakia, Estonia/Latvia, and Ireland have in common that they give high priorities to ecological sustainability outcomes. In these cases, digitalisation is conceptualised primarily as a tool for addressing environmental pressures such as climate change, biodiversity loss, soil degradation, and water scarcity. The dominant criteria in their value-trees relate to decreasing water use, improving soil quality, enhancing biodiversity, increasing animal welfare, and reducing greenhouse gas emissions. These Living Labs differ in the scope of their environmental focus. The LL in Slovakia displays a broad ecological portfolio, with strong emphasis on water and soil management alongside biodiversity and climate adaptation. The Estonia/Latvian LL has developed a value-tree which is more concentrated with biodiversity and animal welfare emerging as defining criteria, reflecting a strong ecological and ethical framing of sustainability. Ireland represents a more targeted environmental strategy, where climate mitigation, specifically GHG emission reduction, accounts for the entirety of its environmental priority.

Economic outcomes in this group are present but clearly subordinate, often limited to efficiency improvements or niche business innovation. Social outcomes, however, get higher priorities, particularly in Estonia/Latvia and Ireland, where community interaction and health outcomes are strongly represented. In this way, environmental sustainability in these contexts is closely linked to social legitimacy and public good provision. In the following, the outcomes in each Living Lab are explained in more detail.

The LL in Slovakia. In the LL in Slovakia, the distribution of outcomes is dominated by environmental outcomes (61%), followed by economic outcomes (27%) and social outcomes (12%). This profile indicates a strong prioritisation of ecological sustainability within the food system, while economic and social outcomes play supportive but secondary roles. Within the environmental outcomes (61%), the largest shares are linked to decreasing water use (27%) and improving soil quality (14%), with further contributions from biodiversity enhancement (7%), climate change adaptation and resilience (5%), and reductions in waste and greenhouse gas emissions (4% each). This demonstrates a broad ecological focus spanning water management, soil health, biodiversity, and climate adaptation. The economic outcomes (27%) are distributed across cost reductions (6%), new business model development (6%), improved access to finance (2%), and efficiency gains through productivity (13%). These outcomes reflect an orientation toward financial stability and efficiency improvements, though at a scale significantly smaller than ecological outcomes. The social outcomes (12%) are comparatively modest, comprising human health and labour conditions (6%), community interaction (3%), digital skills and literacy (2%), and other small contributions (1%). This suggests that while social factors are recognised, they remain less central than ecological priorities.

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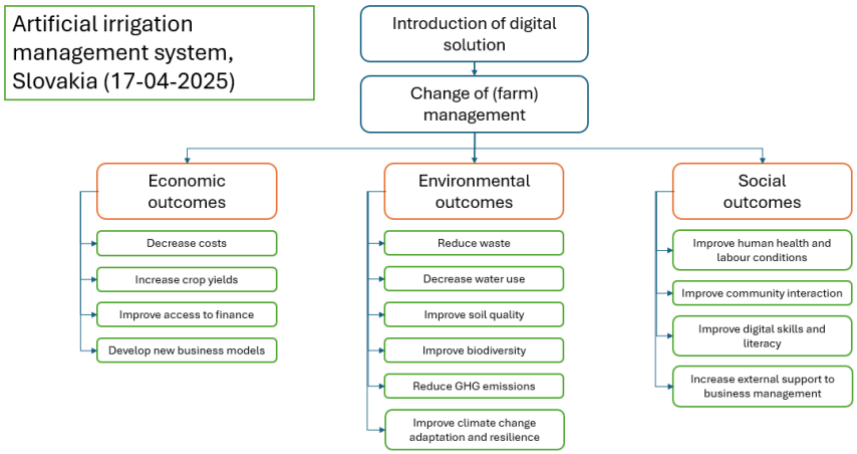

Figure 15 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Slovakian Living Lab

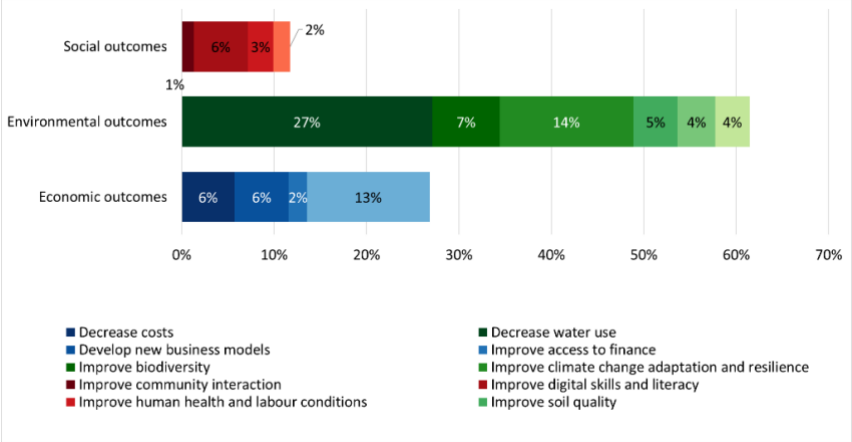

Figure 16 – The relative priority scores of economic, social and environmental sustainability outcomes in Slovakian LL

The LL in Estonia/Latvia. The LL in Estonia/Latvia, the outcome distribution is led by environmental outcomes (57%), followed by social outcomes (34%) and economic outcomes (10%). This indicates a food system orientation strongly centred on ecological sustainability, with social outcomes also significant and economic aspects playing a comparatively minor role. Within the environmental outcomes (57%), the largest contributions come from increasing biodiversity (28%) and animal welfare (18%), followed by decreasing water use (11%). These outcomes highlight a strong emphasis on ecological resilience, animal health, and sustainable resource management. The social outcomes (34%) are equally distributed between improvements in human health and labour conditions (17%) and community interaction (17%). This underscores the importance of strengthening well-being and social cohesion as part of food system transformation. The economic outcomes (10%) are relatively small, comprising contributions from developing new business models (6%), access to markets, finance and insurance (3%), and reducing labour costs (1%). These results suggest that economic restructuring is present but clearly secondary compared to ecological and social priorities.

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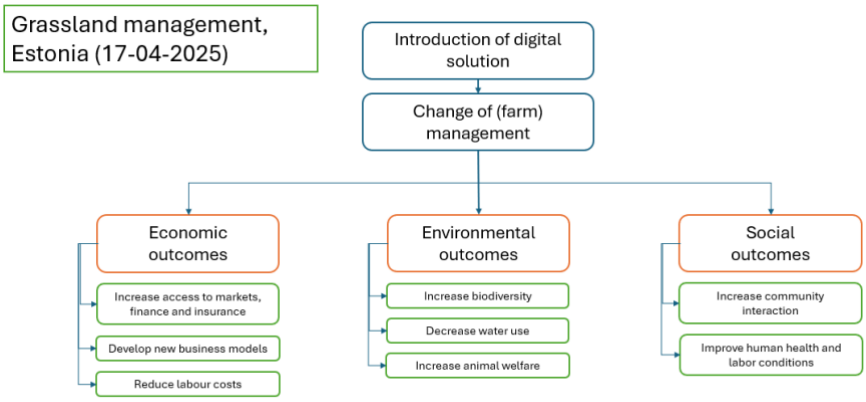

Figure 17 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Estonian/Latvian Living Lab

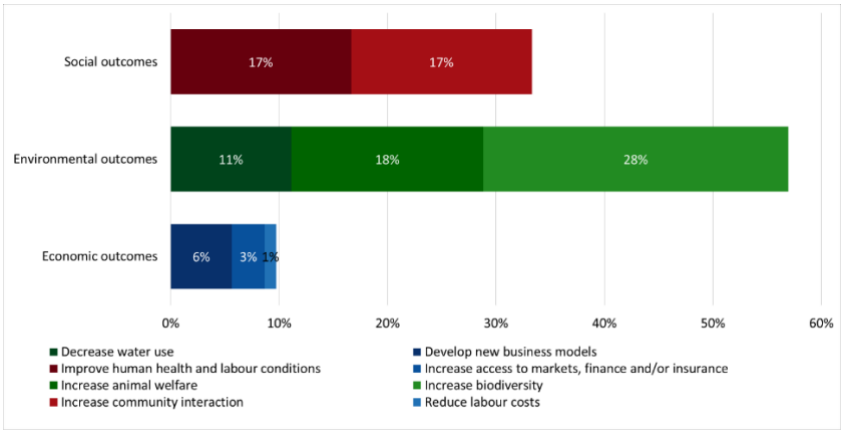

Figure 18 – The relative priority scores of economic, social and environmental sustainability outcomes in the Estonian/Latvian LL

Visioning towards social sustainability outcomes. The Living Labs in Scotland and Ireland are highly socially oriented, favouring in particular the social sustainability outcomes related with community resilience, human well-being, and capacity development. The LL in Scotland stands out as the most social oriented Living Lab, while Ireland also exhibits strong social co-prioritisation alongside environmental goals. The dominant criteria within this category include community interaction, human health and labour conditions, digital skills and literacy, and external support to business management. Digitalisation is therefore framed less as a productivity tool and more as a mechanism for strengthening social capital, inclusiveness, and institutional capacity within food systems.

Differences within this category relate to the balance between social and other dimensions. The LL in Scotland maintains a relatively even distribution across social, economic, and environmental outcomes, suggesting an integrative but people-centred transition pathway. The LL in Ireland, by contrast, combines strong social outcomes with a highly focused environmental agenda, particularly climate mitigation. In the following, the outcomes in each Living Lab are explained in more detail.

The LL in Ireland. For the LL in Ireland, the distribution of outcomes is dominated by environmental outcomes (40%), followed by social outcomes (40%) and economic outcomes (20%). This indicates a relatively balanced orientation of the food system across ecological, social, and economic dimensions, though with a clear emphasis on environmental mitigation. Within the environmental domain (40%), the outcome is entirely concentrated on reducing greenhouse gas emissions. This reflects a targeted priority on climate mitigation, which is a critical challenge in

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Ireland's agri-food sector. The social outcomes (40%) are spread across community interaction (20%), improvements in human health and labour conditions (12%), and external support to business management (8%). These outcomes highlight the role of social cohesion, institutional support, and health in shaping food system resilience. The economic outcomes (20%) are more narrowly distributed, comprising the development of new business models (9%), increased access to finance and markets (8%), and reductions in costs (3%). These reflect an orientation toward innovation and financial integration, though with limited emphasis on broad efficiency gains.

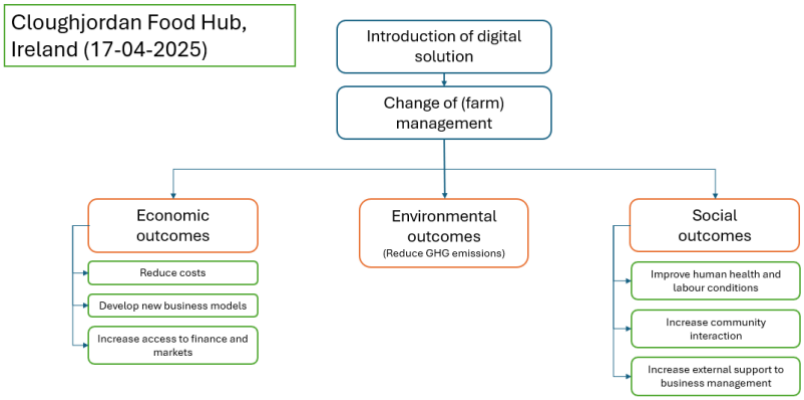

Figure 19 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Irish Living Lab

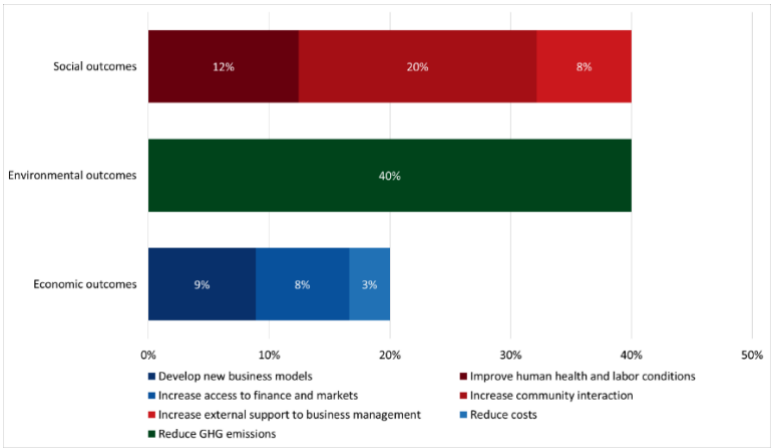

Figure 20 – The relative priority scores of economic, social and environmental sustainability outcomes in the Irish LL

The LL in Scotland. For the LL in Scotland, the distribution of outcomes shows a relatively balanced profile across dimensions, with social outcomes (47%) holding the largest share, followed by economic outcomes (29%) and environmental outcomes (25%). This configuration points to a food system trajectory where social resilience is emphasised, though economic and ecological priorities remain significant. Within the environmental domain (25%), the dominant outcome is decreasing energy use (14%), complemented by reductions in water use (3%), improvements in soil quality (2%), and reductions in GHG emissions (6%). These outcomes collectively suggest incremental gains in resource efficiency and mitigation of climate externalities, with energy conservation emerging as a particularly relevant focus for Scottish food systems. The social dimension (47%) is led by community interaction (19%) and human health and labour conditions (14%), followed by digital skills and literacy (10%) and external support to business management (4%). This reflects an emphasis on strengthening social capital and human capacity as core levers of resilience, reinforcing Scotland's orientation toward inclusive, skills-based and health-conscious food systems. The economic outcomes (29%) are driven by the development and optimisation of new

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business models (13%) and improvements in animal health (12%), with a smaller share directed to decreasing operational costs (4%). This indicates that the economic dimension in Scotland is more focused on innovation and productivity than on immediate cost savings, aligning with a transition-oriented perspective in food system economics.

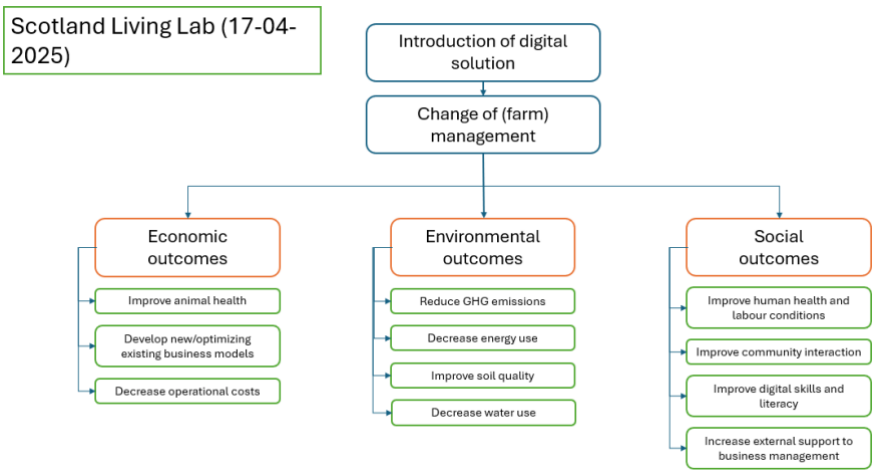

Figure 21 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Scottish Living Lab

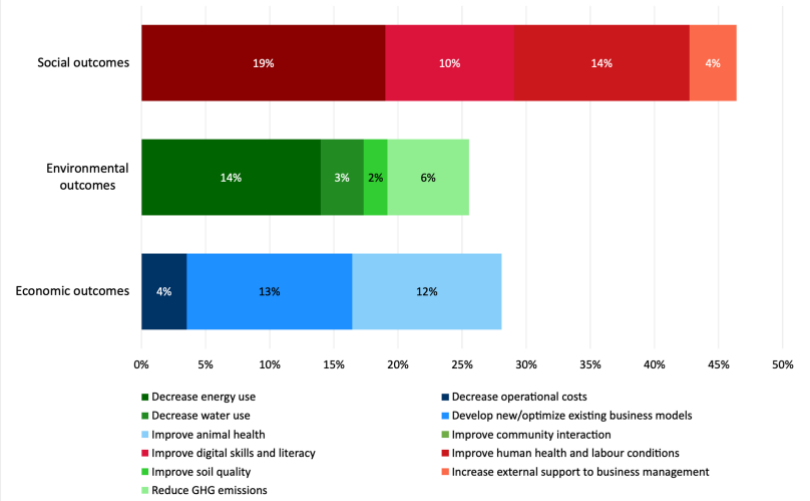

Figure 22 – The relative priority scores of economic, social and environmental sustainability outcomes in the Scottish LL

Visioning towards balancing economic, social and environmental sustainability outcomes. The Living Labs in Spain, Hungary, Slovenia, and Czech Republic provide a highly balanced priority across economic, social, and environmental outcomes. The LLs in Spain and Hungary are the clearest examples of full balance, while the LLs in Slovenia and the Czech Republic show strong economic–environmental alignment with more modest social contributions. In these Living Labs, value-trees are more diversified, with no single criterion dominating the sustainability narrative. Economic criteria include market access, productivity, and risk management; environmental criteria span soil quality, biodiversity, climate resilience, and resource efficiency; and social criteria focus on health, skills, and rural revitalisation. This indicates that digitalisation is understood as a multi-functional enabler capable of delivering simultaneous gains across sustainability dimensions.

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Differences within this group relate to emphasis rather than exclusion. The LLs in Spain and Hungary explicitly integrate social outcomes into their sustainability logic, whereas the LLs in Slovenia and the Czech Republic give greater weight to economic performance and environmental stewardship. In the following, the outcomes in each Living Lab are explained in more detail.

The LL in Slovenia. For the LL in Slovenia, the distribution of outcomes is dominated by economic outcomes (49%), followed by environmental outcomes (35%) and social outcomes (16%). This outcome profile indicates a food system strongly oriented toward economic performance, supported by significant ecological interventions and more limited social contributions. Within the economic outcomes (49%), the largest share derives from revenues (16%), followed by new business models (12%), access to markets and finance (9%), agricultural production (7%), financial risk reduction (5%), and other smaller contributions. This reflects a strong focus on competitiveness, financial stability, and innovation. The environmental outcomes (35%) are distributed across crop health improvement (11%), biodiversity enhancement (8%), climate change adaptation and resilience (8%), soil quality (3%), waste reduction (3%), and energy efficiency (4%), with an additional 6% from other environmental measures. These outcomes emphasise ecological resilience and resource efficiency as complementary pillars of the food system. The social outcomes (16%) include contributions from human health and labour conditions (7%), community interaction (3%), digital skills and literacy (3%), and external support to business management and collaboration (3%). While smaller in scale, these outcomes highlight the importance of institutional capacity, social cohesion, and workforce well-being.

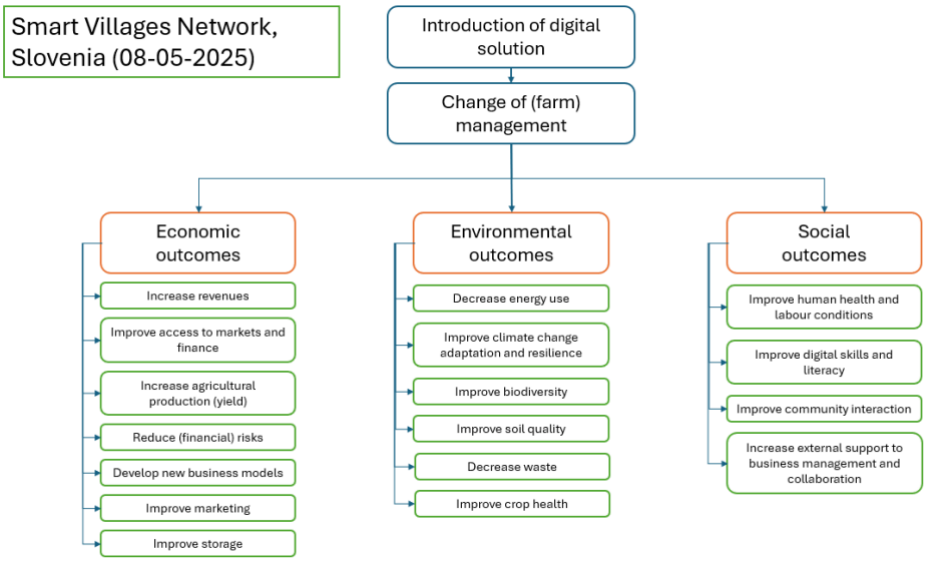

Figure 23 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Living Lab in Slovenia

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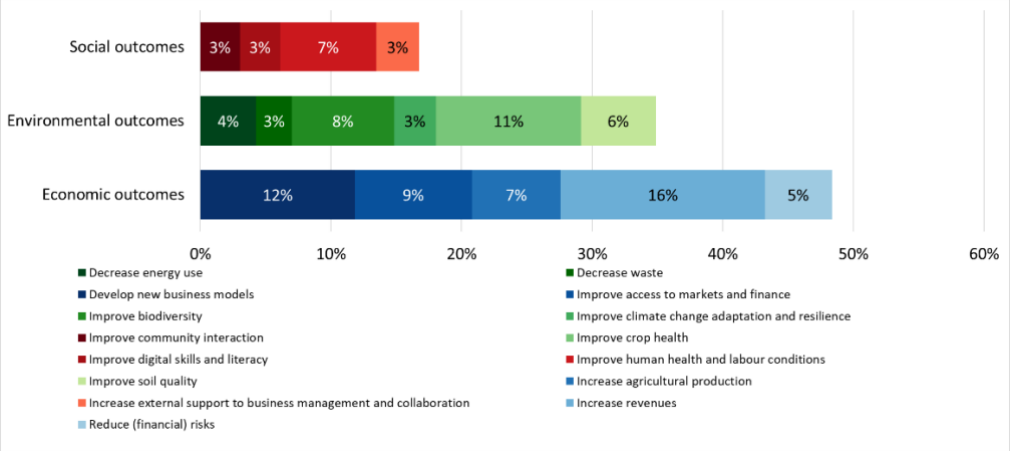

Figure 24 – The relative priority scores of economic, social and environmental sustainability outcomes in the Living Lab in Slovenia

The LL in Spain. For the LL in Spain, the distribution of outcomes is relatively balanced, with economic outcomes (34%), environmental outcomes (34%), and social outcomes (30%) each playing substantial roles. This suggests a food system profile that integrates market, ecological, and social priorities in a relatively even way. Within the economic outcomes (34%), the largest share comes from improving access to markets, finance and insurance (22%), followed by revenue increases (8%) and labour productivity (4%). These results indicate a strong orientation toward market access and financial integration, with complementary efforts to enhance productivity and income. The environmental outcomes (34%) are distributed across climate change adaptation and resilience (10%), soil quality (12%), waste reduction (4%), GHG emission reduction (4%), and water use efficiency (4%). This reflects a multi-dimensional approach to ecological sustainability, spanning climate resilience, soil stewardship, and resource efficiency. The social outcomes (30%) are led by human health and labour conditions (13%) and digital skills and literacy (10%), followed by community interaction (3%) and rural revitalisation (4%). These outcomes highlight a significant focus on social well-being and capacity-building, supported by community-level interventions.

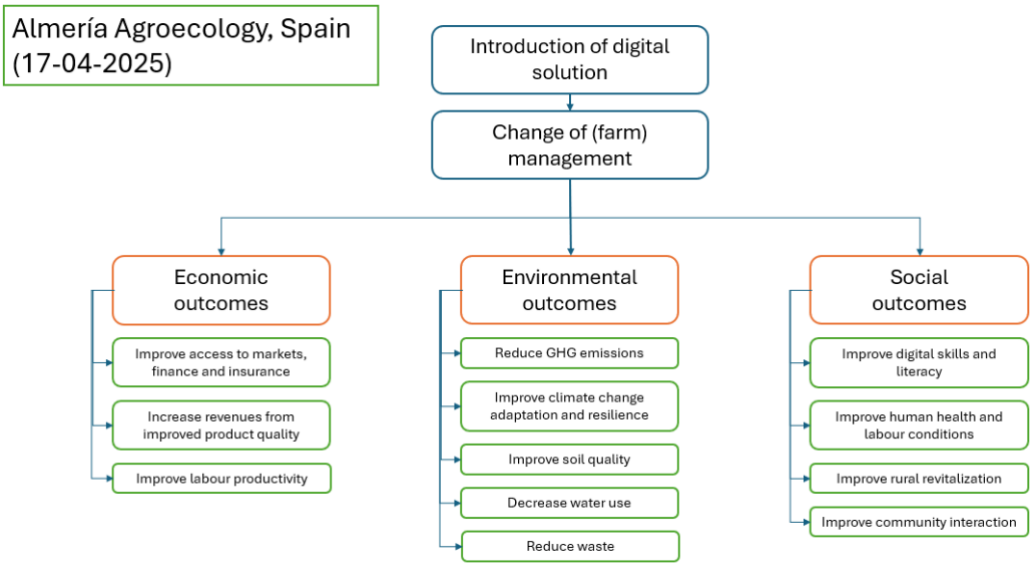

Figure 25 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Spanish Living Lab

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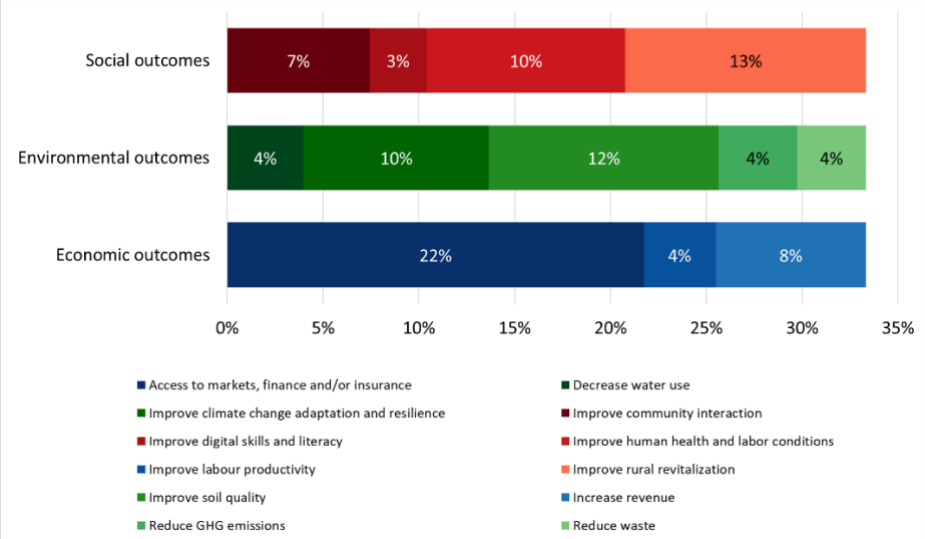

Figure 26 – The relative priority scores of economic, social and environmental sustainability outcomes in this Spanish LL

The LL in Hungary. For the LL in Hungary, the outcome distribution is the same for social outcomes (33%), environmental outcomes (33%) and economic outcomes (33%), indicating a balanced orientation across the three dimensions of the food system. Within the social outcomes (33%), the largest share comes from improvements in digital skills and literacy (16%), followed by human health and labour conditions (8%), rural revitalisation (4%), and external support to business management (5%). These outcomes highlight a strong emphasis on human capacity development and institutional strengthening within the food system. The environmental outcomes (33%) are distributed across biodiversity improvement (8%), soil quality (17%), and GHG emission reductions (8%). This reflects a focus on ecological functions of agriculture, particularly soil management and biodiversity as key levers for sustainability. The economic outcomes (33%) are made up of improved access to markets, finance and insurance (12%), agricultural production (4%), risk mitigation (8%), and other forms of productivity enhancement (9%). Together these outcomes underscore a drive toward market integration and resilience against production and price volatility.

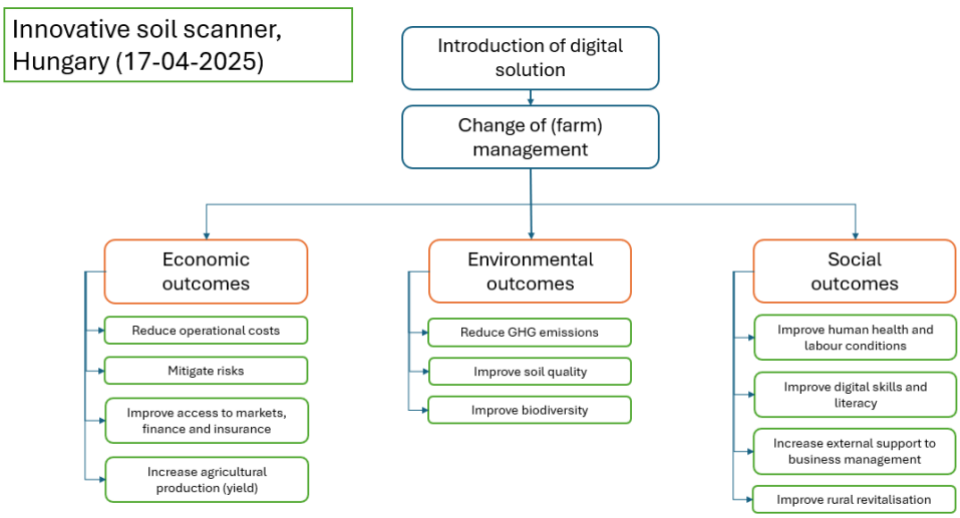

Figure 27 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Hungarian Living Lab

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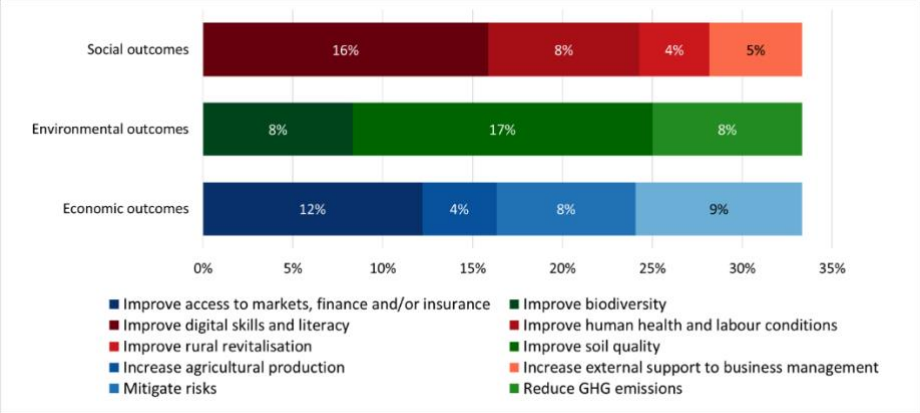

Figure 28 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Hungary

The LL in Latvia. The LL in Latvia, the distribution of outcomes is dominated by economic outcomes (59%), followed by environmental outcomes (16%) and social outcomes (24%). This highlights a food system configuration where market expansion and revenue growth are prioritised, with more modest attention to ecological sustainability and social well-being. Within the economic outcomes (59%), the largest share is attributed to increasing revenues (35%), complemented by improved access to new markets (17%) and the development of new business models (8%). These outcomes underscore a strong orientation toward competitiveness, growth, and structural transformation of the agri-food sector. The environmental outcomes (16%) are represented solely by ecological improvements, signalling a narrower but significant commitment to integrating sustainability considerations into the food system. The social outcomes (24%) are split evenly between human health and labour conditions (12%) and community interaction (12%). These outcomes point to a parallel recognition of the importance of well-being and social cohesion in supporting systemic resilience.

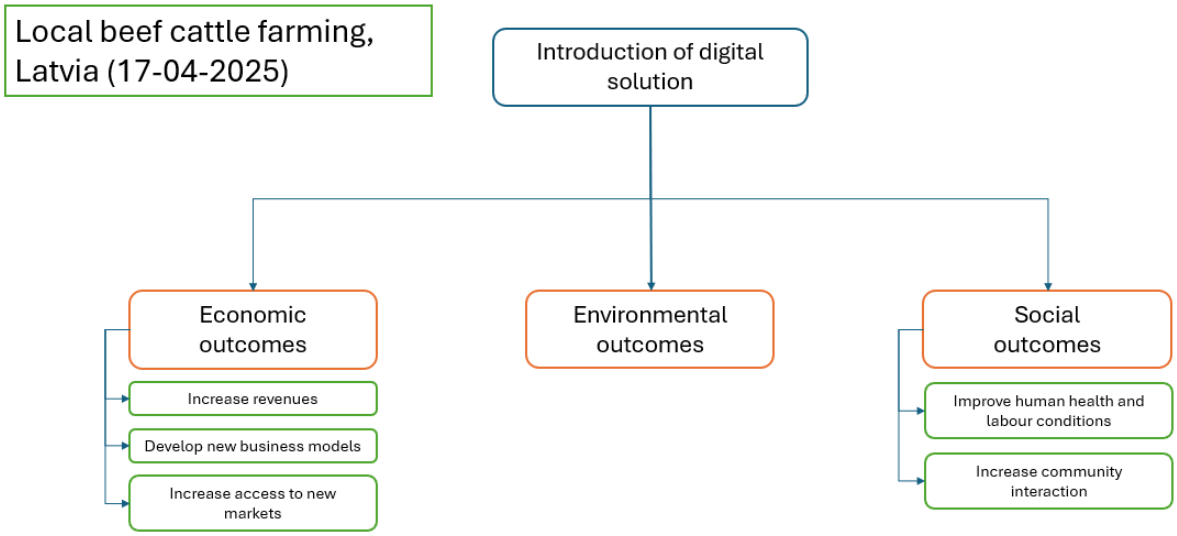

Figure 29 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Latvian Living Lab

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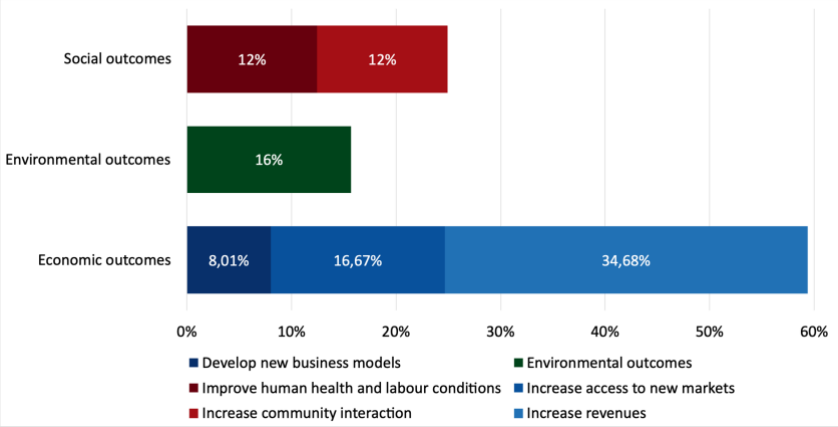

Figure 30 – The relative priority scores of economic, social and environmental sustainability outcomes in the LL in Latvia

The LL in Czech Republic. In the Czech Republic LL, the distribution of outcomes shows equal emphasis on environmental outcomes (45%), and economic outcomes (45%), and a comparatively smaller share for social outcomes (11%). This indicates that both ecological sustainability and economic performance are central priorities in the food system, with social dimensions playing a more limited role. Within the environmental outcomes (44%), the largest contributions come from improving soil quality (14%) and decreasing water use (13%), followed by tree health (9%), biodiversity enhancement (5%), and reducing greenhouse gas emissions (3%). This distribution suggests a strong focus on resource management and ecosystem services, highlighting the role of land and water stewardship in food system resilience. The economic outcomes (45%) are distributed across access to markets, finance and insurance (13%), labour productivity improvements (13%), external support to business management (13%), and mitigating price volatility risks (6%). These outcomes reflect a balanced economic orientation, equally weighting market integration, productivity, and institutional/business support. The social outcomes (11%) are shared between human health and labour conditions (6%) and external support to business management (6%). These relatively modest contributions indicate that social dimensions, while present, are less strongly emphasised than economic or ecological priorities.

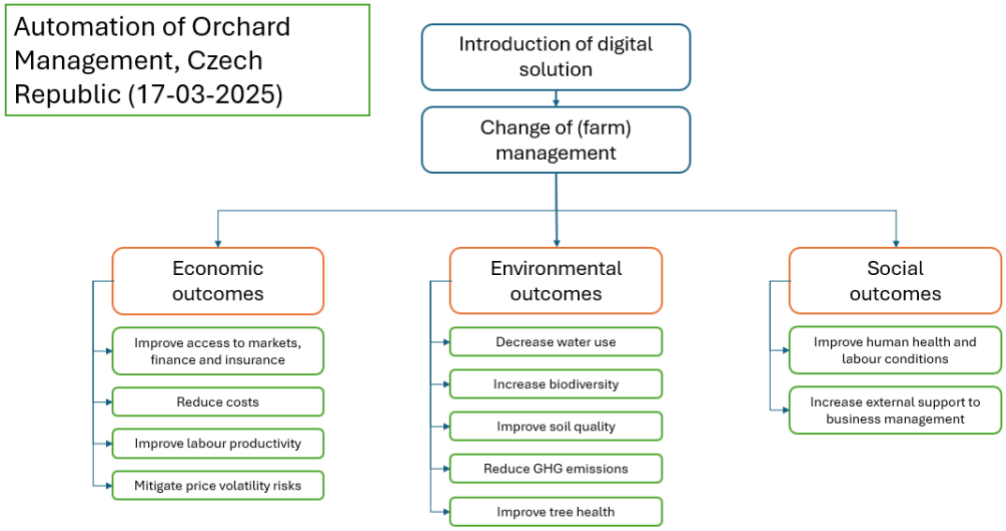

Figure 31 – The value-tree with core sustainability outcomes based on insights from relevant stakeholders in this Czech Republic Living Lab

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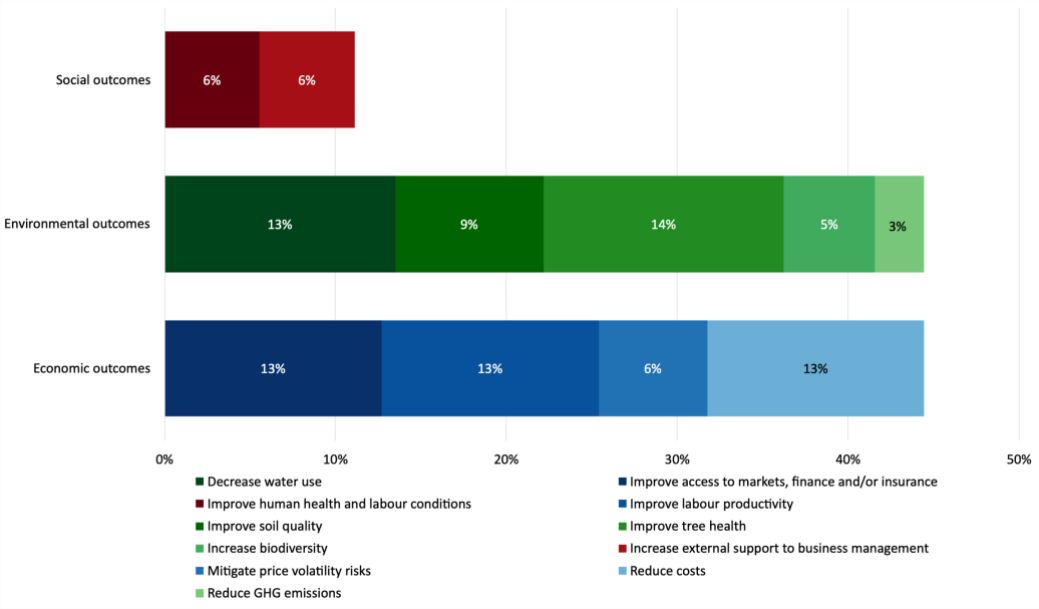

Figure 32 – The relative priority scores of economic, social and environmental sustainability outcomes in the Czech Republic LL

5.3 Summary of the participatory theory building outcomes

In this Chapter, the Living Labs in Slovakia, Hungary, Belgium, Slovenia, the Czech Republic, Serbia, Spain, Scotland, Germany, North Macedonia, Ireland, Poland, Estonia, and Latvia have contributed to participatory theory building revealing how digitalisation has been interpreted and prioritised within each Living Lab. The outcomes of sustainability priorities across these fourteen Living Labs illustrate high diversity in how sustainable digitalisation is framed across economic, social, and environmental sustainability dimensions within agri-food systems.

Although all the Living Labs captured economic, social, and environmental sustainability dimensions, the relative priority assigned to each dimension differed substantially, reflecting the contextual differences across the Living Lab.

First, economic sustainability was strongly priorities by a group of Living Labs, including the LLs in Belgium, Poland, Latvia, Germany, Serbia, and North Macedonia. In these cases, economic outcomes accounted for more than half of total priorities, reaching as high as 64% in the LL in Belgium. Sustainable digitalisation can in this group be understood as a means to enhance competitiveness, reduce operational costs, improve productivity, and strengthen market integration. Social and environmental outcomes were not absent but tended to play a supporting role, often framed in instrumental terms that reinforce economic performance rather than as standalone objectives.

Second, the Living Labs that prioritised environmental sustainability the most, included the LLs in Slovakia, Estonia, and the Czech Republic. The LL in Slovakia stood out with environmental outcomes accounting for 61% of total priorities, reflecting a broad ecological agenda focused on water management, soil quality, biodiversity, and climate resilience. The LL in Estonia similarly demonstrated a strong environmental orientation (57%), complemented by substantial social priorities, while economic outcomes are clearly secondary. For the LL in Czech Republic, the environmental and economic outcomes were almost equally prioritised, indicating a dual focus on ecological and economic performances, with social outcomes playing a more limited role.

Third, social sustainability outcomes appeared most strongly in the LLs in Scotland and Ireland. Scotland was the most socially oriented Living Lab, with 46% of priorities devoted to social outcomes related to community interaction, human health, labour conditions, and digital skills. Economic and environmental outcomes remained important but showed to be within a people-centred transition pathway. Ireland provided a distinctive outcome, in which social and

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environmental outcomes were equally prioritised at 40%, combining strong community-oriented goals with a highly focused climate mitigation agenda, while economic outcomes received comparatively less attention.

Fourth, a group of Living Labs demonstrated a balanced sustainability orientation, most notably the LLs in Spain and Hungary, where economic, social, and environmental outcomes each accounted for roughly one-third of total priorities. This balance suggests an integrated understanding of digitalisation as a multifunctional enabler capable of delivering simultaneous gains across sustainability dimensions. Notably, Slovenia and the Czech Republic would also fit within this group, although with a stronger emphasis on economic and environmental outcomes than on social dimensions.

The outcomes illustrate that sustainable digitalisation as a driver of food system transformation operate differently across the Living Labs. There is hence no single pathway to sustainable digitalisation. Instead, digital technologies are mobilised in diverse ways, reflecting differing development trajectories and sustainability challenges. These differences underscore the importance of context-sensitive approaches to policy design and Living Lab implementation. An overview is provided in Table 3.

Table 3 – Summary table of outcomes of the participatory theory building across 14 Living Labs in CODECS engaged in developing a value-tree with relevant context factors including economic, social and environmental sustainability outcomes of digitalisation, and in assigning weights to reflect on relative relevance to the different sustainability outcomes in their specific context (highest priority scores marked in red)

Living Lab	Economic sustainability	Social sustainability	Environmental sustainability
LL in Belgium	Competitiveness, efficiency, business models **(64%)**	Labour conditions, support structures **(11%)**	Soil, climate, energy & water efficiency **(26%)**
LL in Poland	Market access, revenue growth, financial stability **(61%)**	Rural revitalisation, community interaction **(27%)**	Soil quality, waste & GHG reduction **(12%)**
LL in Latvia	Revenue growth, market expansion **(59%)**	Health, labour conditions, community cohesion **(25%)**	Ecological improvements **(16%)**
LL in Germany	Business model optimisation, market integration **(54%)**	Health, labour conditions, community interaction **(30%)**	Water quality, crop health **(16%)**
LL in Serbia	Cost reduction, productivity, market integration **(54%)**	Health, community interaction, digital skills **(16%)**	Biodiversity, energy & soil efficiency **(30%)**
LL in North Macedonia	Cost reduction, productivity, risk mitigation **(54%)**	Digital skills, health, institutional support **(30%)**	Water use, soil quality, biodiversity **(16%)**
LL in Slovenia	Competitiveness, innovation, financial stability **(48%)**	Health, skills, collaboration **(17%)**	Crop health, biodiversity, climate resilience **(35%)**
LL in Czech Republic	Market access, productivity, business support **(44%)**	Health and labour conditions **(11%)**	Soil quality, water use, biodiversity **(44%)**

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Living Lab	Economic sustainability	Social sustainability	Environmental sustainability
LL in Spain	Market access, income growth, productivity **(33%)**	Health, digital skills, rural revitalisation **(33%)**	Soil quality, climate adaptation, efficiency **(33%)**
LL in Hungary	Market access, risk mitigation, productivity **(33%)**	Digital skills, health, institutional support **(33%)**	Soil quality, biodiversity, GHG reduction **(33%)**
LL in Scotland	Business innovation, productivity **(28%)**	Community interaction, health, digital skills **(46%)**	Energy efficiency, GHG & water reduction **(26%)**
LL in Ireland	Innovation, market access **(20%)**	Community interaction, health, business support **(40%)**	GHG emission reduction **(40%)**
LL in Slovakia	Efficiency gains, productivity **(27%)**	Health, community interaction, skills **(12%)**	Water use, soil quality, biodiversity **(61%)**
LL in Estonia/ Latvia	Limited business innovation focus **(10%)**	Health and community cohesion **(33%)**	Biodiversity, animal welfare, water efficiency **(57%)**

6 Conceptual analyses of sustainable digitalisation at multiple levels

6.1 Overview

This Chapter addresses the third research question: What level specific concepts are of relevance to the CODECS Conceptual framework? Digitalisation reshapes not only technologies but also processes, actor roles, decision-making, and governance, requiring a socio-technical perspective. At the business process level, key concepts include socio-technical processes, collective decision-making, role reconfiguration, learning loops, work organisation, process transparency, inclusion/exclusion dynamics, and dependency/control. Analyses such as DEMO's, socio-technical process modelling, and assessments of economic, social, and environmental costs and benefits provide insights into how digital tools integrate into daily farm operations, influence actor interactions, and support sustainable practices (see overview of methods applied in CODECS across WPs in Appendix 1). At the digital ecosystem level, concepts such as socio-ecological systems, digital ecosystems, resource systems, governance, AKIS, knowledge networks, and interoperability guide the understanding of actor interactions, resource flows, and system integration. Mapping these ecosystems highlights enablers and barriers for digitalisation adoption. At the socioenvironmental level, CODECS applies participatory approaches, including VARI and Multicriteria Assessment (MCA) via the Sustainability Assessment Tool (SAT), to evaluate integrated sustainability scenarios across economic, social, and environmental dimensions. This is elaborated on in the following.

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6.2 Conceptual analyses at business process level

6.2.1 Selected business process level concepts and their relevance in CODECS

Digitalisation in agriculture transforms not only technological infrastructures but also the underlying business processes through which farming activities are planned, executed, and coordinated. Understanding these transformations requires a socio-technical perspective that recognises processes as combinations of technologies, actors, routines, and rules. Living Lab approaches provide a practical lens to observe how digital tools, ranging from sensors and decision support systems to farm management software and drones, are embedded in daily farm operations and advisory workflows, reshaping how work is organised and decisions are made. Key changes include the evolution of decision-making from individual, experience-based judgement to collective, data-informed processes, and the reconfiguration of actor roles, where farmers, advisors, and technology providers develop new dependencies and collaborations. LL activities also highlight the importance of iterative learning, feedback loops, and adaptive experimentation, which embed continuous improvement within operational routines. Additionally, digitalisation influences work organisation, wellbeing, and social inclusion, as automated or remote systems can reduce labour intensity but may also create barriers for certain groups. Transparency, traceability, and control emerge as critical factors, with process visibility fostering accountability while reliance on external platforms raises questions of autonomy and governance. Collectively, these insights demonstrate how sustainable digitalisation depends on aligning technological innovations with social practices, learning mechanisms, and equitable participation.

Relevant concepts for business process contexts, including meaning, appearance in Living Labs in CODECS, type of techno-social change observed and relevance for sustainable digitalisation are provided in Table 4.

Table 4 – Concepts with relevance for business process contexts, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation

Business process concepts	Meaning in conceptual terms	How it appears in Living Lab practice (4.2.2)	Type of techno-social change observed	Relevance for sustainable digitalisation
Socio-technical processes	Business processes are composed of technologies, actors, routines, and rules	Digital tools (sensors, DSS, FMIS, drones) are embedded in daily farm routines and advisory workflows	Technologies reshape how work is organised, not only how tasks are performed	Shows that sustainability depends on aligning technical tools with social practices
Decision-making processes	Decisions are collective, information-driven and context-dependent	Data-driven irrigation, feeding, spraying, and monitoring require interpretation by farmers and advisors	Shift from individual, experience-based decisions to shared, data-supported judgement	Improves efficiency while redistributing knowledge and responsibility
Role reconfiguration	Technological change alters actor roles within processes	Farmers act as data managers; advisors as translators; tech providers as ongoing process actors	New dependencies and collaborations emerge at farm level	Highlights power relations, inclusivity, and long-term autonomy

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Business process concepts	Meaning in conceptual terms	How it appears in Living Lab practice (4.2.2)	Type of techno-social change observed	Relevance for sustainable digitalisation
Learning loops and adaptation	Processes evolve through feedback and experimentation	Demo farms, pilots, and iterative use of tools embed learning in operations	Learning-by-doing becomes part of the production process	Essential for long-term adoption and resilience
Work organisation and wellbeing	Processes affect labour, stress, and time use	Automation and remote monitoring reduce workload and uncertainty	Improved work-life balance and reduced stress	Social sustainability becomes a direct outcome of digitalisation
Process transparency and traceability	Digital processes generate auditable information flows	Monitoring, certification compliance, and traceability integrated into routines	Increased visibility of practices within and beyond the farm	Supports accountability and market trust
Inclusion and exclusion dynamics	Process design shapes who can participate	Small farms, older farmers, or low-skill users face barriers	Unequal capacity to benefit from digitalisation	Identifies risks of unsustainable, uneven transitions
Dependency and control	Control over processes depends on access to data and expertise	Reliance on external advisors, platforms, or service providers	Risk of loss of autonomy despite efficiency gains	Raises governance and long-term sustainability concerns

6.3 Conceptual analyses at digital ecosystem level

6.3.1 Selected digital ecosystem level concepts and their relevance in CODECS

The transition toward sustainable digitalisation in agriculture necessitates a comprehensive understanding of the socio-technical and ecological dimensions that shape farming systems. Living Labs provide an interactive, participatory framework to investigate these dimensions by engaging multiple stakeholders, including farmers, advisors, technology providers, and policymakers. Central to this approach is the recognition of socio-ecological systems, wherein agricultural practices emerge from complex interactions among actors, resources, and governance structures. Living Labs operationalise this perspective by mapping key actors, resource units, resource systems, and governance mechanisms, thereby identifying systemic interdependencies and co-creating context-specific solutions. Complementing this, the concept of digital ecosystems emphasises the networks of actors, infrastructures, and data flows that enable digital agriculture. Through systematic mapping of Digital Ecosystem needs and available services, Living Labs identify gaps in digital access, interoperability, and integration, guiding the design of effective digital infrastructures. Furthermore, understanding governmental systems, resource allocation, and Agricultural Knowledge and Innovation Systems (AKIS) allows Living Labs to align technological interventions with regulatory frameworks, optimise resource use, and strengthen actor coordination. Finally, fostering knowledge networks, digital literacy, and interoperability supports informed decision-making, peer-to-peer learning, and scalable adoption of digital tools.

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Relevant concepts to digital ecosystem context, including meaning, appearance in Living Labs in CODECS, type of techno-social change observed and relevance for sustainable digitalisation, are provided in Table 5.

Table 5 – Concepts with relevance to digital ecosystem context, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation

Concepts	Meaning in conceptual terms (WP3)	How it appears in Living Labs (4.2.3)	Type of techno-social change observed	Relevance for sustainable digitalisation
Socio-ecological systems	Ecosystem of actors, resources, and governance interacting around farm-level activities	Farmers, cooperatives, and technology providers collaborate to optimise irrigation, fertilisation, and operational planning while incorporating environmental objectives	Co-creation, adoption of context-specific digital tools	Ensures that digitalisation respects ecological constraints and enhances sustainable farm management
Digital ecosystems	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	Farmers utilise cost-effective tools and engage in peer-to-peer learning, supported by centralised platforms that integrate data and advisory services	Integration of tools, platforms, and human actors; enhanced connectivity	Strengthens local digital infrastructure, adoption, and resilience of agricultural systems
Governmental systems	Comprises formal and informal interactions, rules, and self-governance mechanisms, focusing on decision-making processes and their implementation, reform, and reinforcement	Coordination with public authorities occurs alongside active involvement of policymakers in co-creation processes	Multi-actor engagement; alignment of innovation with policy	Promotes regulatory alignment, governance support, and adoption of sustainable digital tools
Resource systems	Outline the management and organisational conditions of these resource units, including social, economic, technological, knowledge/information, and environmental aspects	Adoption of decision-support systems and digital irrigation management tools enhances farm operations and resource efficiency; local food market platforms facilitate connections between	Optimisation of resource use via digital tools	Enhances efficiency, reduces labour dependency, and supports resource-efficient farming

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Concepts	Meaning in conceptual terms (WP3)	How it appears in Living Labs (4.2.3)	Type of techno-social change observed	Relevance for sustainable digitalisation
		producers and consumers		
Agricultural Knowledge and Innovation Systems (AKIS)	Combined organisation and knowledge flows between persons, organisations and institutions who use and produce knowledge for agriculture and interrelated fields	Multi-actor collaboration and knowledge exchange strengthen innovation and learning within agricultural networks; hubs connect educational institutions, advisory services, and research actors	Co-creation, knowledge transfer, and adoption of innovations	Facilitates the adoption of practice-relevant innovations, acquirement of skills and out-scaling of innovations
Knowledge networks and digital literacy	Skills, trust, and communication enabling use of digital tools	Knowledge flows are enhanced through structured engagement among schools, students, advisors, and peer-to-peer learning among farmers	Capacity-building, skill enhancement, digital literacy growth	Supports long-term adoption and effective use of digital technologies; addresses knowledge gaps
Interoperability and data integration	Ability of systems to share, process, and combine data effectively improving the flow of information across multiple systems	Interoperable sensors, irrigation systems, and decision-support tools enable integrated management; digital applications link multiple stakeholders through shared production data. fostering collaboration across the value chain	System integration, improved decision-making, cross-actor coordination	Enables efficient data-driven management, coordination, and innovation across the digital ecosystem with focus on optimising resource use and supporting sustainable practices

6.4 Conceptual analyses at socioenvironmental level

6.4.1 Selected socioenvironmental level concepts and their relevance in CODECS

The following table synthesises key techno-social concepts emerging from the analysis of Living Lab practices (Section 4.2.4), illustrating how farm digitalisation extends beyond technical efficiency to shape broader social, ecological, and institutional dynamics. Rather than viewing digital technologies as isolated tools, this conceptual framework highlights how their use contributes to transformations in farming systems as socio-technical and socio-

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ecological systems. Each concept is presented alongside its conceptual meaning, its concrete manifestation in Living Lab practice, the type of techno-social change observed, and its relevance for sustainable digitalisation. This structure enables a systematic link between theory and practice, showing how digital tools influence farmers' adaptive capacities, environmental decision-making, social relationships, governance arrangements, and territorial dynamics. By doing so, the table captures both intended and emergent effects of digitalisation at multiple levels, from on-farm practices to community and governance structures. Overall, this framework supports a more holistic understanding of sustainable digitalisation, emphasising resilience, stewardship, social legitimacy, and collective learning as essential dimensions alongside economic and technological performance.

Relevant concepts to socioenvironmental contexts, including meaning, appearance in Living Labs in CODECS, type of techno-social change observed and relevance for sustainable digitalisation, are provided in Table 6.

Table 6 – Concepts with relevance to socioenvironmental contexts, including meaning, appearance in Living Labs (LL) in CODECS, type of techno-social change observed and relevance for sustainable digitalisation

Concept	Meaning in conceptual terms	How it appears in Living Lab practice text (4.2.4)	Type of techno-social change observed	Relevance for sustainable digitalisation
Socio-ecological resilience	Digitalisation supports adaptive capacity of coupled social and ecological systems	Biodiversity monitoring, adaptive grasing, landscape management	Farming systems better absorb environmental and social change	Connects digitalisation to long-term system resilience
Environmental stewardship	Digital tools enable responsible management of natural resources	Grassland monitoring, species tracking, conservation planning	Environmental decisions become evidence-based and proactive	Aligns digitalisation with environmental sustainability goals
Cultural landscape preservation	Digitalisation supports maintenance of heritage landscapes and practices	Semi-natural grasslands, culturally significant grasing systems	Conservation becomes integrated with productive use	Protects cultural values alongside ecological ones
Social embeddedness and community	Digitalisation reshapes relationships between farmers and society	Direct-to-consumer sales, local engagement	Stronger connections between farming and communities	Enhances social legitimacy of digital agriculture
Governance and accountability	Digital systems interact with rules, ethics, and public oversight	Monitoring supports regulation and ethical data use	Governance shifts toward data-supported accountability	Ensures digitalisation aligns with public values
Territorial cohesion and rural vitality	Digitalisation supports rural development and attractiveness	Local markets, youth engagement, regional identity	Digital tools counter rural marginalisation	Supports balanced territorial development

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Concept	Meaning in conceptual terms	How it appears in Living Lab practice text (4.2.4)	Type of techno-social change observed	Relevance for sustainable digitalisation
Collective learning and systemic awareness	Actors jointly interpret data and system interactions	Peer exchange, shared interpretation of environmental data	Systems thinking becomes shared social practice	Enables integrated socio-environmental sustainability

7 Policy implications and main advice

In this Chapter, the fourth research question is addressed: How can the CODECS Conceptual framework contribute to more responsible policy making? In CODECS a policy analysis was conducted providing a comprehensive overview of the policy environment shaping digitalisation in agriculture across Europe, drawing on a review of EU-funded projects, interviews with policymakers, and national and EU-level policy developments (Hurtado *et al.,* 2025). In line with this deliverable and the CODECS conceptual framework for sustainable digitalisation (Soma *et al.,* 2024a;2024b;2025), as well as the outcomes of the Living Lab analyses conducted in this deliverable, a comprehensive overview of the policy environment shaping digitalisation in agriculture across Europe has been provided[1] (Hurtado *et al.,* 2025). At a general level, CODECS advises that digitalisation should not be understood as an end in itself. Instead, sustainable digitalisation must be seen as a socio-technical process which simultaneously deliver economic viability, environmental sustainability, and social legitimacy. Against this background, a series of policy recommendations in CODECS (*ibid.*), summarised as follows.

First, over the last decade, policy recommendations have tended to focus on similar issues, with low adaptation to change. In CODECS, it has been shown that policy recommendations pertaining to digitalisation in agriculture or rural areas have shown to 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 (*ibid.*). Hence, over the past 10 years the core recommendations have not adapted to the changes observed as a consequence of transformation, indicating an implementation gap, rather than a knowledge gap. Now with transformations of the global policy environment, issues of cyber security, privacy, on the one hand, and interoperability and data sharing, on the other hand, may have higher priorities. Moreover, the role of AKIS linked with contextual factors are of high relevance, taking account of internal drivers of motivation, opportunities and capabilities, as well as the external drivers.

Second, research indicates coordination gaps across ministries and programmes. However, coordinating efforts is essential across all policy layers to ensure alignment and continuity of digitalisation efforts. Sustainable digital transformation requires good governance, strong institutional capacity and a systematic approach to harness the potential of the digital transformation for addressing various challenges. A proactive policy vision and context-specific policies are necessary to harness the transformative potential of digital technologies. Many digital technologies can have positive impacts, but uptake requires coordinated action to steer investments, supported by robust EU-level

[1] The analysis of policy environments for digitalisation in Europe (Hurtado *et al.,* 2025) draws on the views of a diverse array of European, national, and regional stakeholders from the agriculture and digitalisation sectors. It establishes a baseline for understanding how European and national policies shape the digital transformation of agriculture and rural areas. Drawing on a review of policy recommendations from past projects, current European Union (EU) and national policy initiatives regarding digitalisation in agriculture and rural areas, and 101 interviews with policymakers and experts across 15 EU Member States and three candidate countries, the report identifies progress made, challenges ahead, and the systemic conditions that will determine the future trajectory of digitalisation in agriculture. This analysis was complemented by an examination of the AKIS system.

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regulation on data and cybersecurity. Furthermore, a multi-level approach is needed (guidance and funding at EU level, enabling frameworks at national level, and granular programme design at regional and local level).

Third, from a policy perspective, digitalisation in agriculture should be conceived as a multi-level process that is shaped by multiple, interconnected and frequently context-sensitive factors. No single level can deliver results in isolation. Success also depends on a coherent and synergistic approach across different domains. The digital transformation of agriculture is a gradual process. System solutions are needed to address structural challenges, such as fragmented governance, limited interoperability, uneven digital skills, and inadequate connectivity. This can ensure that technological innovation and adoption is embedded within broader institutional, social, and economic frameworks.

Fourth, it is important to recognise that there is no single trajectory toward agricultural digitalisation. Distinct pathways arise from the interaction between several contextual factors, such as governance, geography, economic conditions, connectivity, human capital and demographics, farm size structure. Indeed, 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, and access to finance. Moreover, the motivation, opportunities and capacities at farm, regional and national levels to identify, acquire and integrate new knowledge and technologies are also critically important.

Fifth, informed decision making is fundamental to ensure that policy interventions are fit for purpose. 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. Building a strong evidential basis for decision making is needed for more targeted support (incl. financial), better evaluation, and timely course correction.

Sixth, accelerating technology uptake also requires enhancing digital skills, meaning that a lack of skills and fragmented advisory services are critical bottlenecks that require attention. Improving digital literacy among farmers and advisors is a key challenge. More engaging and accessible learning models, such as demonstration farms, peer-to-peer learning, can address this. AKIS actors, including advisory services, public agriculture administrations, and education institutions must continually upskill to stay current with technological advances and adapt their services to the dynamics of the digital transformation. Current advisory systems often lack the requisite digital expertise and are not prepared to meet new demands. This leads to discrepancies in how AKIS and intermediary actors are conceived by policy makers and other actors, potentially leading to inefficient public policies, highlighting the need for debate about how to anchor AKIS policy discussions in the realities of farmers' practices, networks, and resources.

Seventh, securing the future of agricultural digitalisation requires integrating different forms of skills and support. Integrating digital skills into vocational training, agricultural curricula, and lifelong learning programs is crucial. However, other skills, such as for business and management, are equally important to ensure that farmers can assess the costs and benefits of technologies and integrate digital technologies effectively and sustainably. Beyond education, incentives for land transfer, improved access to finance and infrastructure, and targeted advisory support can foster a digitally competent and resilient new generation.

Eight, policies should be farmer centred. Policies that promote the digital transition should be perceived by farmers as supportive, intending at closing the digital gap between small farms and large farms. Trusted advisory support from public administrations, clear rules on data use, and digital services that reduce paperwork and save time are also advisable to ensure that farmers experience concrete gains, rather than additional financial or administrative burdens. Likewise, prioritising support for appropriate technologies that fit the operational realities of different farm types and skill levels is necessary. Strengthening collaboration between farmers and technology developers is key to ensuring that tools aligned with actual needs.

Although the Common Agricultural Policy (CAP) is a key lever, it should not be regarded a silver bullet (*ibid.*). The CAP has put digitalisation on the policy agenda and requires Member States to include a digital strategy in their National Strategic Plans. Digitalisation is integrated through eco-schemes, investments, and knowledge sharing or advisory services. However, the CAP is also seen as a source of increased bureaucracy, existing indicators may not

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be well suited to capture digital progress and there is no robust baseline against which to assess change and levels of expenditure on digitalisation.

8 Concluding remarks

Based on the empirical analyses applying the CODECS Conceptual framework across the CODECS Living Labs in this Deliverable, it has been illustrated in different ways that digitalisation in agriculture is inherently multi-level and context-specific, requiring tailored approaches across farm, ecosystem, and socio-environmental levels. At the farm level, policies should support data-driven decision-making, learning, and equitable access to technologies. At the ecosystem level, effective governance, AKIS coordination, interoperability, and skill development are crucial to enable innovation uptake. At the socio-environmental level, policies must integrate environmental stewardship, social inclusion, and rural development. Recognising local conditions, capacities, and priorities is key: one-size-fits-all solutions are insufficient, and sustainable digitalisation requires flexible, multi-level strategies aligned with regional, cultural, and ecological contexts. This learning is expected to be relevant to future policy making.

The outcomes of the participatory theory building by means of Teams talks and value-tree analysis conducted by each Living Lab to identify most priorities visioning about sustainability outcomes, can be distinguished into four main sustainability outcomes categories.

First, strong economic orientation, where the environmental and social aspects were instrumental, was observed among the countries Belgium, Germany, Poland, Latvia, Serbia, and North Macedonia. Note that the Living Labs in Italy (Tuscana) and France who participated only in the Teams talks, would most probably fit into this category as well. These Living Labs prioritise economic sustainability, framing digitalisation primarily as a means to improve efficiency, competitiveness, productivity, and market access. The Teams talks outcomes reinforce this orientation, namely that farmers gain hands-on experience with digital tools, cost–benefit evaluation, risk mitigation, short value chains, and scalable business models (e.g. Poland, Serbia, Germany). Environmental and social aspects exist but are mainly instrumental. Environmental benefits are often linked to efficiency gains (reduced inputs, optimised resource use), rather than transformative ecological change. Social learning focuses on skills acquisition, advisory support, and institutional coordination that enable economic performance.

Comparing the two participatory theory building activities, the outcomes are highly comparable. Notably, the outcomes of the Teams talks inform that the Belgium's Living Lab explicitly reveals hidden environmental costs of digitalisation (carbon footprint, batteries, heavy metals), which are not explicit in the value-tree analyses where outcomes indicate an efficiency-driven environmental framing. Moreover, governance gaps and farmer–administration misalignment in Belgium and Germany indicate that digitalisation is not necessarily straightforward in enhancing resilience.

Second, high emphasis on environmental context factors, combined with strong knowledge and governance, was provided by the Living Labs in Slovakia, Estonia/Latvia, and Ireland (environmental dimension). These Living Labs conceptualise digitalisation as a tool to address climate change, biodiversity loss, soil degradation, and water scarcity. Teams talk outcomes strongly support this vision that precision water management (Slovakia), biodiversity and habitat monitoring (Estonia/Latvia), and emissions reduction (Ireland) are paired with advanced data collection, modelling, and evidence-based decision-making. They share the understanding that social learning is prominent, especially through peer exchange, trust-building, and community engagement, reinforcing environmental legitimacy. Governance and regulatory learning (e.g. EU and national frameworks in Estonia/Latvia) further anchor ecological goals institutionally.

Although the two participatory theory building outcomes are overall equivalent, in the Teams talk Ireland's expose tensions between environmental ambition and rural market realities of low demand volumes, inefficient logistics, and consumer expectations. This complicates environmental gains, challenging visioning that ecological priorities naturally align with viable local food systems.

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Third, strong orientations towards social dimensions of capacity, inclusion and peer-to-peer learning were emphasised by the Living Labs in Scotland, and Ireland (social dimension). Note that the Living Lab in Italy (Puglia) who participated only in the Teams talks, could fit into this category, because of the focus on wellbeing of the (large scale) farmers. These Living Labs prioritise social sustainability, focusing on community resilience, human well-being, digital literacy, and institutional capacity. The Teams talks strongly align with the visioning in terms of advising for peer-to-peer learning, trust-building, facilitation, and inclusive support mechanisms are central, particularly for small-scale farmers. Digitalisation is understood, not as a productivity driver, but as a social infrastructure that is supporting collaboration, informed decision-making, and protection of livelihoods. Policy learning is also critical, as shown by Scotland's emphasis on structural inequities in technology access.

Comparing the two participatory theory building approaches, the visioning is clearly social goals as central, however, the Teams talks reveals that limited structural support and policy bias toward large farms are enabling conditions which hamper the socially oriented visioning.

Fourth, a highly emphasised approach for economic, social and environmental integration, was put forward by Spain, Hungary, Slovenia, and the Czech Republic. For them, digitalisation is understood as a multifunctional enabler, which was confirmed through the Teams talks in terms of resource optimisation and carbon awareness (Hungary), farmer well-being and biodiversity gains (Slovenia), cooperative governance and interoperability (Spain), and diversified sustainability strategies. Moreover, social, economic, and environmental learning reinforce each other through demo farms, cooperatives, advisory services, and shared digital ecosystems.

While these Living Labs displayed strong alignment between visioning and the Teams talks, it appeared that Slovenia and the Czech Republic lean more toward economic–environmental priorities, while social outcomes were more strongly embedded in the views of Spain or Hungary.

Hence, sustainable digitalisation requires coordinated policies across agriculture, digital, education, and innovation domains. Future policy efforts should prioritise inclusive access, collective solutions, transparent data governance, and strengthened AKIS, ensuring digitalisation supports farmers' resilience, sustainability goals, and long-term trust in the digital transition.

Building on the CODECS analysis of European policy environments (Hurtado *et al.,* 2025) and the Living Lab findings, this policy review confirms that digitalisation in agriculture should be understood as a socio-technical transformation rather than a technological objective in itself. Sustainable digitalisation depends on its ability to simultaneously deliver economic viability, environmental sustainability, and social legitimacy, which requires coherent and context-sensitive policy approaches. Despite growing policy attention, recommendations on agricultural digitalisation have remained largely stable over the past decade, pointing to an implementation gap rather than a lack of knowledge. While connectivity, data governance, skills, regulatory frameworks, technologies, and social aspects remain central, emerging challenges related to cybersecurity, privacy, interoperability, and data sharing demand stronger prioritisation. The effectiveness of digitalisation is also closely linked to the functioning of AKIS and to internal and external contextual drivers shaping adoption. Persistent coordination gaps across ministries, programmes, and governance levels continue to constrain progress. Digital transformation requires strong governance, institutional capacity, and aligned action across EU, national, regional, and local levels, supported by robust regulatory frameworks and coordinated investment strategies. As a gradual and systemic process, digitalisation must be embedded within broader institutional, social, and economic structures to address challenges such as fragmented governance, uneven digital skills, limited interoperability, and inadequate connectivity.

No single pathway exists to agricultural digitalisation (Hurtado *et al.,* 2025). Outcomes are shaped by governance quality, geographic conditions, farm structures, human capital, market dynamics, and access to finance, as well as by farmers' motivation, opportunities, and capabilities. Effective policymaking is hindered by limited farm-level data and inadequate indicators, underscoring the need for a stronger evidence base. Accelerating sustainable digitalisation requires sustained investment in digital, advisory, business, and management skills, farmer-centred policies that reduce digital divides and administrative burdens, and close collaboration between farmers and technology developers. While the CAP plays a key enabling role, it is not sufficient on its own and must be complemented by improved indicators, reduced complexity, and clearer baselines for assessing digital progress.

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APPENDIX 1. CODECS' ASSESSMENT METHODOLOGIES CARRIED OUT ACROSS WPs, AT DIFFERENT LEVELS

A.1.1. Introduction

This Appendix 1 provides an overview of the analytical approaches applied in the CODECS project across multiple contexts, and multiple levels, including the business process, digital ecosystem, and socio-environmental levels. Given the diversity of Living Labs and their focal action situations, a broad set of qualitative and quantitative methods was employed to capture context-specific dynamics of farm digitalisation. The analyses address technological, economic, environmental, social, and governance dimensions, generating complementary evidence to support theory building, sustainability assessment, and the development of policy- and practice-relevant insights.

A.1.2. Relevant analyses conducted at business process context level in CODECS

Most analyses in CODECS took place at business process level, including the DEMO farm analyses, farm socio-technical process modelling of contextual factors analysis, farmer perceptions of costs and benefits with digitalisation, environmental costs and benefits, economic costs and benefits and social costs and benefits. They are briefly described in the following.

DEMO farm analyses. In the CODECS project, Demonstration activities (Demos) constitute a structured methodological approach to showcase and evaluate digital technologies in agriculture within Living Labs (Contreras and Guichaoua, 2023). Demo Farms serve as the primary physical or virtual spaces where farmers, advisors, researchers, technology providers, and other stakeholders interact with innovative technologies in real-world contexts. The methodological approach combines practical exposure, peer-to-peer learning, and empirical assessment. On-farm Demos enable participants to observe technologies applied under operational conditions, engage directly with demonstration farmers or advisors, and reflect on their potential adaptation to their own practices. These events are complemented by Virtual Demos, which leverage digital platforms to reach geographically dispersed participants, fostering knowledge exchange and feedback collection while reducing travel and logistical constraints. CODECS Demos are systematically structured around objectives such as introducing technologies, gathering stakeholder perceptions, and assessing social, economic, and environmental costs and benefits through a standardised Demo assessment grid. Additionally, international cross-visits expand the peer-to-peer learning dimension by facilitating cross-border knowledge exchange between Living Labs. All Demo activities contribute to evaluating digital ecosystems, farmers' readiness for technology adoption, and sustainability performance, while generating data to inform practice abstracts, interactive storybooks, and policy-relevant insights.

Farm socio-technical process modelling. Socio-technical Process Modelling (STPM) focuses on capturing and representing the transformation of farm-level processes in response to digitalisation (Giagnocavo *et. al.,* 2024). It uses principles of business process modelling (Aguilar-Savén, 2004) and requirements engineering (Loniewski *et al.,* 2010; Horkoff *et al.,* 2019), creating structured abstractions of processes to identify actors, resources, tasks, and interactions before and after technology adoption. The methodology is designed to be participatory and iterative, involving Living Lab stakeholders, and employs standard graphical notations: UML class diagrams (Object Management Group, 2017), for outlining process structure with actors, resources and relationships; iStar goal diagrams (Yu *et al.,* 2011), highlighting actors' objectives and strategic relationships; and BPMN diagrams (Object Management Group, 2010), depicting the process flow and dependencies. The creation of process models follows a structured procedure: data collection via workshops, focus groups, and interviews; reporting using standardised templates; validation and refinement by task leaders; diagram formalisation; and stakeholder agreement. Data collection is tailored to three states of digitalisation – Zero Digital, Digitalising, and Digitalised – ensuring context-sensitive capture of processes. Training sessions prepare Living Lab coordinators for the data collection activity, and feedback loops help refine both the reports produced bu the Living Labs and the resulting diagrams. This method provides detailed qualitative insights into how digital technologies reconfigure farm operations, actor roles, and resource use, and supports downstream analyses, including cost–benefit evaluation. STPM bridges socio-technical analysis and ecosystem mapping, translating abstract system interactions into actionable representations for Living Labs.

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Farmer perceptions of costs and benefits with digitalisation. To analyse stakeholder perceptions of the costs and benefits of farm digitalisation, CODECS adopted an inductive, qualitative research approach based on focus group discussions (Gobrecht *et al.,* 2024). Data were collected through 18 focus group meetings organised by Living Labs across Europe between October 2023 and January 2024. Each focus group included a diverse mix of stakeholders, primarily farmers, policymakers, and farm advisors, alongside other relevant experts such as researchers and technology providers. Groups typically consisted of six to ten participants and were moderated by trained Living Lab leaders. The discussions followed a semi-structured guide comprising 8–12 questions designed to elicit perceptions of the economic, social, and environmental costs and benefits of specific digitalisation technologies, as well as current and future challenges linked to increasing digitalisation in agriculture. Sessions lasted between 45 and 90 minutes and were conducted in a confidential and open environment. Following each focus group, moderators produced summary reports and transcripts, which were translated into English where necessary. These materials were analysed using thematic content analysis. Three researchers independently coded the data, identifying key words and phrases and grouping them into inductively derived themes aligned with the research questions. Cross-checking and joint discussions ensured consistency and robustness, resulting in a comprehensive synthesis of stakeholder perceptions across different European contexts.

Environmental costs and benefits. The environmental impacts of farm digitalisation in CODECS are assessed using Life Cycle Assessment (LCA), a standardised and widely recognised methodology (ISO 14040/44) for quantifying environmental impacts across the full life cycle of products and services. LCA is applied at the agricultural process and/or farm level to compare environmental performance before and after the adoption of digital agriculture technologies (DATs). CODECS employs a comparative LCA approach, assessing a reference scenario representing conventional farming practices against a digitalised scenario in which specific DATs are implemented (Gobrecht *et al.,* 2024).. This enables identification of environmental changes attributable to digitalisation, including efficiency gains, resource use reductions, and potential trade-offs. The analysis also supports hotspot identification, highlighting process stages with the highest environmental impacts. The LCA follows four main phases: (1) goal and scope definition, tailored to each Living Lab use case; (2) life cycle inventory (LCI), combining farm-level quantitative data, Living Lab documentation, interviews with farmers, and secondary data from literature and databases; (3) life cycle impact assessment, covering multiple environmental indicators; and (4) interpretation of results. To ensure feasibility and data quality, data collection protocols are customised per use case, distinguishing mandatory and optional data. Pilot LCAs in selected Living Labs are used to refine the methodology before wider deployment across CODECS.

Economic costs and benefits. The economic impact assessment in CODECS aims to identify and estimate the economic costs and benefits associated with the adoption of digital technologies in farming (Gobrecht *et al.,* 2024). The analysis focuses primarily at the farm level, where adoption decisions are made, and applies an ex-post cost–benefit framework comparing situations before and after digitalisation. Depending on the Living Lab use case, the assessment may also target specific farm processes. The methodology follows a multi-step, data-driven approach tailored to each Living Lab according to its level of digitalisation and data availability. First, a basic qualitative analysis is conducted using a concise questionnaire to identify transition and operational costs and expected benefits, particularly in Living Labs with limited quantitative data. Second, where data permit, whole-farm or partial budget analysis is applied to compare costs, revenues, productivity indicators, and net income before and after adoption. Third, Net Present Value (NPV) analysis is used for selected cases to evaluate investment profitability over time, with optional sensitivity and scenario analysis to account for uncertainty. In advanced cases, stochastic budgeting or stochastic NPV may be employed to assess economic risk. Data are collected through structured farm interviews, accountancy records, and Living Lab documentation, using tools developed jointly with the environmental assessment. The results support farmers, advisors, and policymakers by revealing economic trade-offs, barriers, and incentives for farm digitalisation.

Social costs and benefits. The social/human-centred assessment in CODECS aims to analyse the intangible costs and benefits of farm digitalisation on farmers and other people engaged in farming activities at the farm level (Gobrecht *et al.,* 2024). Unlike economic or environmental analyses, this approach focuses on qualitative, human-centred changes linked to farmers' well-being, work practices, skills, social relations, and organisation of production systems, acknowledging the strong influence of contextual, cultural, and socio-economic factors. The methodology follows a qualitative, exploratory research design. It begins with a multidisciplinary workshop involving T4.5 researchers, held in March 2023, to identify and structure potential human-centred costs and benefits of

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digitalisation. This process resulted in a conceptual framework organised around three key human components: (i) people on farms (farmers, workers, family members), (ii) work and tasks, and (iii) organisation of the production system. These components were further operationalised into indicator families, including health and well-being, skills and knowledge, quality of work, time, and communities and networks. Based on this framework, semi-structured interviews were conducted with farmers from CODECS Living Labs at different stages of digitalisation (digitalised and digitalising). Interviews explored experiences, expectations, perceived changes, concerns, and opportunities related to digital technology use. Data were analysed using qualitative content analysis, with phrases as units of analysis, supported by MAXQDA and NVivo software. This approach enables a systematic and contextualised understanding of social and human transformations induced by farm digitalisation.

Technology Assessment Tool (TAT). The Technology Assessment Tool (TAT) developed in CODECS is designed to support decision-making on farm digitalisation at the business process level, the most granular level of system transition within the project (Šimek *et al.,* 2024). At this level, assessment focuses on information flows, technology characteristics, farm readiness, economic performance, and practical usability within Living Lab contexts. The primary purpose of the TAT is to provide a structured, transparent, and user-oriented evaluation of digital technologies used or considered by farmers, enabling alignment between technological performance and farmers' context-specific needs. The tool assesses a portfolio of approximately 80–100 digital technologies, identified and validated by the 20 CODECS Living Labs. Technologies are evaluated using a multicriteria analysis, which structures assessment criteria from general dimensions to specific indicators. Expert-defined impact scores are assigned to each technology, while needs scores (weights) reflect user priorities and contextual relevance. The combination of impact and needs scores produces a ranked shortlist of technologies tailored to individual users. The TAT supports analyses of technology practicality, data handling capacity (including interoperability), data quality, and usability. It builds on and improves existing assessment approaches, ensuring adaptability, transparency, and future extensibility. The final online tool will be accessible to farmers, advisors, researchers, and policymakers, with potential for wider application beyond CODECS, supporting inclusive, sustainable, and informed digitalisation at farm level.

A.1.3. Relevant analyses conducted at digital ecosystem context level in CODECS

In this section, two methodological approaches that have been conducted at digital ecosystem level are introduced, including mapping of the socio-ecological context, and Agricultural Knowledge and Innovation System (AKIS) Analysis.

Mapping the socio-ecological context. The socio-ecological context of each Living Lab is mapped using a four-step participatory methodology designed to co-create understanding of the digital ecosystem (DE) in which the Living Lab operates (Giagnocavo *et. al.,* 2024). The first step involves stakeholders identifying current and required resources, capabilities, collaborations, and innovations (RCCIs) relevant to a clearly defined Focal Action Situation (FAS). Step two maps these RCCIs onto the four subsystems of Ostrom's Social-Ecological Systems Framework (SESF): actors, resource units, resource systems, and governance. This analysis determines how these subsystems enable, constrain, or foster digitalisation and the adoption of RCCIs. Steps three and four, to be carried out later, focus on identifying conducive and readiness characteristics of the DE and validating indicators through consultations, focus groups, and stakeholder interviews. Data were collected during Living Lab workshops (October 2023–March 2024), guided by structured questions addressing the four SESF subsystems. Stakeholders reflected on which actors, resources, and governance mechanisms supported or hindered digitalisation and how ecosystem characteristics shaped the Living Lab's ability to solve its FAS. Preliminary qualitative analyses synthesise the workshops' findings to provide a contextual understanding of the DE, highlighting interdependencies, enabling conditions, and potential barriers to technology adoption. This mapping provides an essential foundation for subsequent analyses, including the socio-technical process modelling and cost–benefit evaluations, by situating digitalisation within the broader ecological, social, and governance contexts.

Agricultural Knowledge and Innovation System (AKIS) Analysis. The AKIS analysis focuses on understanding the structure, coordination, and governance mechanisms of actors in and around the Living Lab that influence the FAS (Giagnocavo *et. al.,* 2024). The process of digitalisation affects, and it is affected by, knowledge flows, e.g., through the emergence of new actors (Klerkx *et al.*, 2019) or through a shift in knowledge relationships (Ingram and Maye, 2020). Digital innovations can enable or disrupt knowledge networks, allowing new actors to enter and

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changing preexisting roles (Ingram and Maye, 2020) The methodology for the analysis of AKIS combines qualitative coding cycles with theoretical grounding in AKIS literature. During the first coding cycle, responses from participatory workshops were used to identify salient ideas, classify actor types, and assess their roles. This stage captured the diversity of actors, including farmers, advisors, service providers, and institutional stakeholders, as well as the types of coordination mechanisms they employ. In the second coding cycle, the analysis was refined by aligning the emergent categories with the AKIS framework, allowing systematic comparison across Living Labs. Governance mechanisms were classified according to relevant norms, rules, and coordination arrangements affecting the Living Lab's knowledge flows affecting the adoption of digital solutions. This dual-cycle approach enables a structured understanding of both the social and institutional dimensions that shape digitalisation in agriculture. The analysis highlights actor networks, influence relations, and coordination mechanisms, offering insight into ecosystem conduciveness and the effectiveness of AKIS in supporting sustainable digital transitions. Digitalisation brings new actors, new roles, and new rules of interaction that affect how private and public actors interact, posing a challenge in terms of how data, information, and knowledge are shared and used. The use of analytical methods that can shed light on complex governance arrangements can support the monitoring and assessment of knowledge sharing. By connecting actor characteristics with governance structures, the AKIS analysis provides critical input for designing interventions and supporting the Living Labs' technology adoption strategies.

A.1.4. Relevant analyses conducted at socioenvironmental context level in CODECS

Besides the VARI study introduced in this Deliverable, Multicriteria analyses (MCA) is a method applied in CODECS at the socioenvironmental level. They are briefly explained in the following.

Multicriteria analyses (MCA). The Multicriteria Assessment Tool (MAT), also referred to as the Sustainability Assessment Tool (SAT), applies a Multicriteria Analysis (MCA) approach to evaluate digitalisation at the digital ecosystem level, moving beyond individual technologies to assess integrated sustainability scenarios (Šimek *et al.,* 2024). In CODECS, digital ecosystems are understood as socio-technical and socio-environmental systems that combine digital tools, organisational structures, social relations, and environmental processes. The MAT therefore captures interactions and trade-offs across economic, social, and environmental dimensions of sustainability. The methodological approach focuses on the comparison of alternative scenarios (e.g. conventional practices, partially digitalised systems, or advanced digital decision-support configurations) that represent different pathways of digital ecosystem development. Each scenario is evaluated against a structured set of criteria derived from the CODECS conceptual framework and Living Lab evidence. These criteria are operationalised through indicators covering social (e.g. access, skills, equity), economic (e.g. costs, productivity, livelihoods), and environmental (e.g. resource use, ecological impacts) perspectives. The MCA combines the Analytic Hierarchy Process (AHP) to weight criteria based on stakeholder priorities with the TOPSIS method to rank scenarios according to their relative closeness to an ideal sustainability outcome. Expert-based impact scores are combined with stakeholder-defined weights, allowing context-sensitive and transparent evaluation. By analysing scenarios at the socio-environmental level, the MAT supports strategic decision-making on sustainable digitalisation pathways within agricultural digital ecosystems.

Value-Analysis of Relative Importance (VARI). As explained above (section 2.2), the VARI was used for the participatory theory building analyses and can be used at all the three levels, including the socio-environmental contest level. Hence, the approach combines theory building with Multicriteria Analysis (MCA) by assigning weights following the Analytic Hierarchy Process (AHP). The method involves four main steps. First, researchers constructed a preliminary value tree based on a literature review, structuring economic, social, and environmental outcomes of digitalisation at farm process level. Second, this value tree was discussed and adapted in participatory stakeholder workshops held in 14 Living Labs, enabling the creation of context-specific value trees that reflect local priorities and conditions. Third, the relative importance of the identified outcomes was assessed using a Value Analysis of Relative Importance (VARI) survey. Fourth, the Living Lab representatives conducted pairwise comparisons of outcomes, assigning weights to indicate their relative relevance. The resulting weightings, summing to 100%, reveal which sustainability outcomes of digitalisation matter most in each Living Lab context at the specific level they are mostly associated with.

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APPENDIX 2. POLICY BRIEF: CONCEPTUAL BASIS OF SUSTAINABLE DIGITALISATION

November 2024

Abstract. The digitalisation of our societies is transforming our world. As a result, people's routines and ways of life are redefined through economic, environmental, social and governance domains. To some extent, it is unclear who will benefit from changes caused by digitalisation, and how, especially in the long term. In CODECS, we aim at shedding light on how socio-economic benefits will be distributed and redistributed and identifying ways of ensuring social, environmental, and economic sustainability with digitalisation. The CODECS conceptual framework operates in an ever-changing contextual situation in the agricultural sector in Europe. External drivers (e.g., social, technical, environmental, and political drivers) and internal drivers (e.g., capabilities, motivations and opportunities) influence entities, relationships and activities in different ways across different contexts. CODECS responds to this by applying a 'system thinking' approach to digitalisation levels. Three interconnected digitalisation levels are core to the CODECS conceptual framework: 1) Business processes, 2) Digital ecosystems, and 3) Socio-ecological systems. By distinguishing between different levels of digitalisation, the CODECS conceptual framework enables the necessary understanding of how to ensure acceleration of sustainable digitalisation through policymaking to influence change, by for instance, focusing on boosting the abilities of those involved and ensuring resources are sustained, accessible and fairly distributed.

Introduction

The world is in transition due to the digital transformation of our societies, and agriculture is no exception. Digital technologies make it possible to automate processes, which have resulted in opportunities that were unthinkable some years back. These advancements are made possible due to the representation of the physical world through numbers. For example, large datasets can be obtained by using sensors. The use of sensors in precision agriculture provides opportunities to gain large amounts of information on the spatial and temporal variation in crops, soil, weeds, diseases, etc. A wide range of sensors exist that can be used for different purposes, including satellite data for precision agriculture, crop data for improved harvests, soil data for water optimisation, livestock data for improved animal health, and disease and weed detection in crops for improved yields.

Digitisation is "the technical conversion of analogue information into digital form", or in other words "a process of representing the physical world through numbers". Digitisation has led to the third industrial revolution, which results from computers providing opportunities to the automated processes, leading to increased effectiveness in the use of inputs and enhanced profitability of outputs. This has been followed by the fourth industrial revolution, 'digitalisation'. With digitalisation, people's routines and way of life are redefined according to the digital transformation of new economic, environmental, social and governance domains. The process of digital transformation is referred to as digitalisation.

Whereas digitisation opens ways to digital transformation by reorganising physical, social, and digital relationships in positive ways, it is unclear what possible long-term negative consequences this will have on the environment and societal inequalities. The analyses to date are often simplistic and analysing only linear relationships. Such analyses suffer from not including factors that may be explanatory for sustainability. In a systems approach, multiple relations, interdependencies, and feedback loops are included, and more real findings with factors influencing sustainability can be identified. Systems thinking offers ideas on how to investigate influences across and between factors and does not simply look at linear evaluation approaches.

The main aim of CODECS is to achieve sustainable digitalisation. This policy brief presents a CODECS conceptual framework that addresses the main interrelationships in a system with three levels are taken into account in observing digital transformation. This is to improve the understanding of the potential costs and benefits of digitalisation and to create a solid basis for decision-making that can enhance transformation towards sustainable digitalisation. Motivated by the risks associated with digitalisation, including an increase in societal inequalities,

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CODECS supports the following definition: **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.**

The CODECS conceptual Framework

The CODECS conceptual framework operates in an ever-changing contextual situation, impacted by external drivers, such as social, technical, environmental, and political drivers, as well as internal drivers, such as capabilities, motivations and opportunities. The contextual factors include entities, relationships, and activities. The framework is exploratory and gives an overview of how to systematically link digital technologies in transitions to sustainable digitalisation through a lens fit to a context with complexities, multiple dimensions, feedback loops, and rebound effects (see Figure PB1).

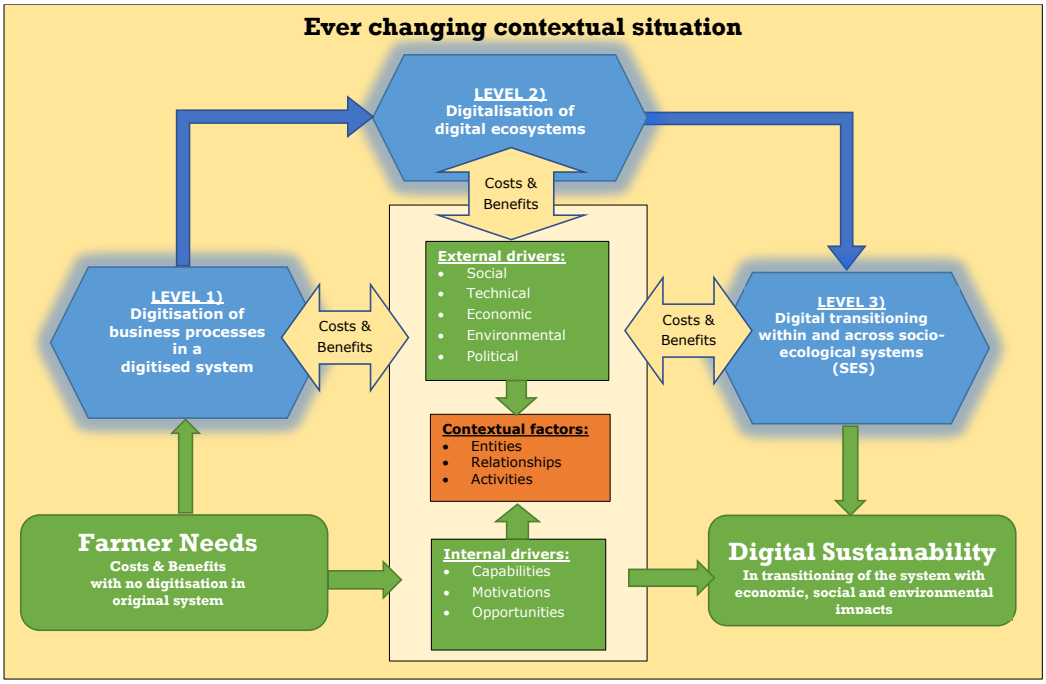

Figure PB1 – The CODECS conceptual framework

The CODECS conceptual framework begins with the farm enterprise- or farmers' needs and their digitalisation transition through the business processes, digital ecosystem and Social Ecological System (SES) levels. At each level, the digitalisation impacts cover a larger scope in terms of more involved numbers of people, larger geographical area, more changes of behaviours and increase in use of technologies. With this increase in outreach and scope of digitalisation, the impacts on the economic, environmental, social and governance domains will increase. In addition, the context is changing. This illustrates that estimated costs and benefits of sustainability impacts at a certain step, period and context, can be changing over time, and differ across areas. The advancement of the transition period must be understood, to identify the actual costs and benefits of digitalisation. This insight can assist taking actions that ensures transitioning towards sustainable digitalisation. In short:

LEVEL 1. At a digitised business level, a transition from a basic level with no digitisation (referred to as a socio-physical system level), has taken place. At a digitised business level (referred to as a socio-physical system level), which is concentrated around the farm activities, a transition from a basic level with no digitisation takes place. At this level, the external drivers interact with the farm socio-physical system, resulting in different costs and benefits across different business process contexts.

LEVEL 2. At a digital ecosystem level (also referred to as socio-cyber-physical system level), a transition has taken place advancing the business process level to more multifarious and stronger societal impacts of digitalisation.

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At this level, more people, businesses, geographical coverage, activities, and interactions are involved than at the digitised business level. With these advancements in digitalisation, change is impacted by contextual external and internal factors, which interact with digitalisation processes. The environmental, economic, and social costs and benefits will vary across contexts, timeframes, and across different levels.

LEVEL 3. At a Socio-Ecological Systems (SES) level, a wide reach of potential influences of digitalisation are accounted for, including complex natural ecosystems, societal inequalities, and governance of our societies. The transformation has hence advanced. The SES level is also referred to as a transitioned socio-cyber-physical system level. At the SES level, interaction and outcomes appear within and across ecosystems, natural resources, governance and actor interactions.

Level 1: The business processes

CODECS begins with farmers' needs to analyse transitioning towards different levels of digitalisation. Thus, technologies for development of digitisation meet the needs of farmers and advance the basic level with no digitisation to a business processes level. Costs and benefits of the farm related processes can be analysed before and after digitisation, i.e. after the introduction of technologies. The business process level is where digital technologies deploy their effects, and it is at this level that, to date, the outputs and impacts of digitisation most frequently have been measured and analysed. Key elements of the business processes include:

- **Actors:** Human/animal components of the process.
- **Artifacts:** Physical components of the processes.
- **Activities:** Individual tasks or steps that make up a process.
- **Events:** Triggers or occurrences that initiate or conclude activities.
- **Gateways:** Decision points or branching paths in the process flow.
- **Flows:** Movement of information, materials, pollutions, or resources between activities or from/to the environment.
- **Resources:** Resources required to carry on the process.

Analyses of the changes introduced by digital technologies are typically based on the analyses of a) the system as-is, i.e. the business processes before the introduction of the technology; and b) the system to-be, i.e. after the introduction of the technology (Figure PB2).

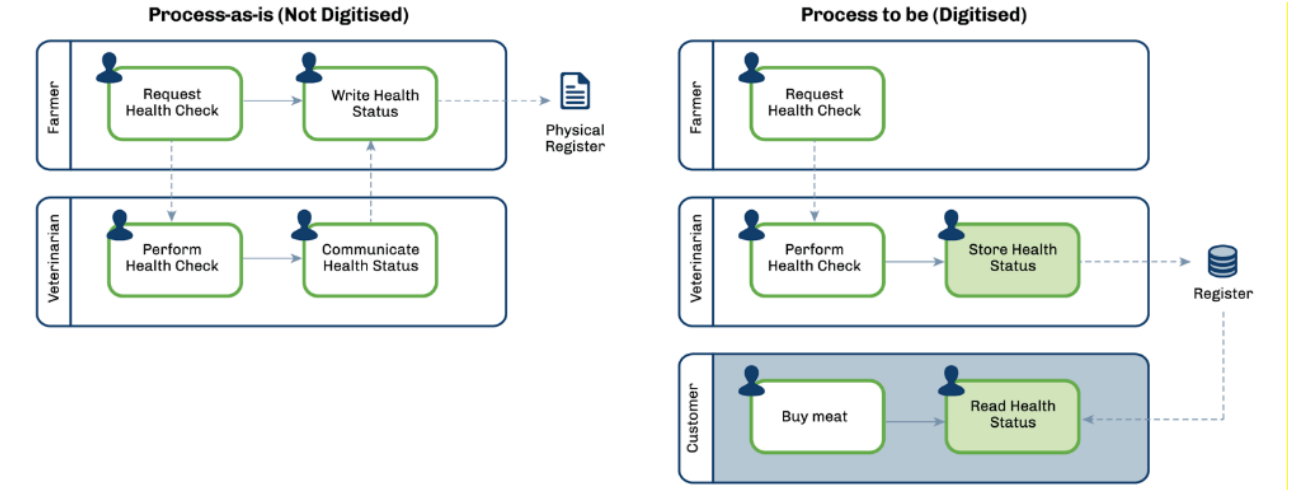

Figure PB2 – Business processes before and after organisation at farm level is digitised

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The business process development depends on *readiness processes, defined by capabilities, motivations and opportunities at the farm level.* Optimal user readiness for digital technology is located at the overlap of capability, opportunity, and motivation (COM-components)[2].

Level 2: The digital ecosystem

At the second transitioning level in the CODECS conceptual framework, digital ecosystems are defined as **dynamic systems where digital, socio-economic, organisational, knowledge, and physical components converge to support the production, storage, communication, and utilisation of digital technologies and data.** A digital ecosystem supports the digitalisation of processes at the farm level by means of costs and benefits of connectivity infrastructures, organisational resources, human resources, knowledge, data, and platforms. With digitalisation, the reach of impacts of digital ecosystems extends networks of people, knowledge (e.g. the Agricultural Knowledge and Innovation System (AKIS)), users of technologies, and changing behaviours. The impacts depend on the system readiness factors in the specific digital ecosystem. The digital ecosystem is judged "conducive" if it is successfully providing the benefits of these services. The core external drivers characterising digital ecosystems are summarised in Table PB1.

Digital ecosystems are ecosystems where digital technologies mediate and affect the relationships among entities to perform a vast array of functionalities. Notably, a digital ecosystem has also been explained as a social system which needs to deal with heterogeneity and greater variations of actors' abilities and resources to participate in a network. The digital ecosystem entails interconnected and intra-dependant digital platforms, created at key institutional levels (international, national and local/community) augmented by technical (ICT) and social networking processes. In the context of knowledge transfer and learning, a digital ecosystem can provide knowledge creation, recreation, diffusion, absorption, and exchanges that support the dynamics of social innovation.

Table PB1 – External drivers characterising digital ecosystems

External drivers	Characteristics linked to the ecosystems
Social/ cultural	Trust, cooperation, communication, conflict resolution
Technical/ technological	Connectivity, interoperability, intensity of data flows
Economic/ financial	Transaction costs, power distribution, trust
Environmental	Ecosystem integrity, diversity, connectivity
Political	Communality of values and interests, institutional cohesion

Level 3: The Socio-Ecological System (SES)

At the third level, the Ostrom framework of socio-ecological systems (SES) is integrated in the CODECS conceptual framework. The transitioning from the digital ecosystems (a socio-cyber-physical system) level to the SES level (a transitioned socio-cyber-physical system) is encountering an ever-larger reach of costs and benefits. At this level, analyses of costs and benefits of digital technologies and interactions between human activity-based processes and natural resources are assessed at a more advanced level of digitalisation. The reach of digitalisation can be observed throughout the whole of Ostrom´s SES approach, covering the sustainability of natural resources and environmental ecosystems, as well as the governance, actors and capability dimensions.

[2] McCampbell, M., Adewopo, J., Klerkx, L., Leeuwis, C. (2023). Are farmers ready to use phone-based digital tools for agronomic advice? Ex-ante user readiness assessment using the case of Rwandan banana farmers. The Journal of Agricultural Education and Extension, 29(1), 29-51.

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The Ostrom SES framework consists of different subsystems with variations within these subsystems (Figure PB3). The subsystems are categorised as resource systems, resource units, governance systems, and actors, who interact in so-called Focal Action Situations (FAS's). Outcomes depend on these system interactions, including feedback loops. This system thinking can help to understand how the different factors impact real-world situations, including legal, economic, technological, political, social, and psychological components. The SES can examine situations where people interact with rules and norms repeatedly, guiding their decisions and actions.

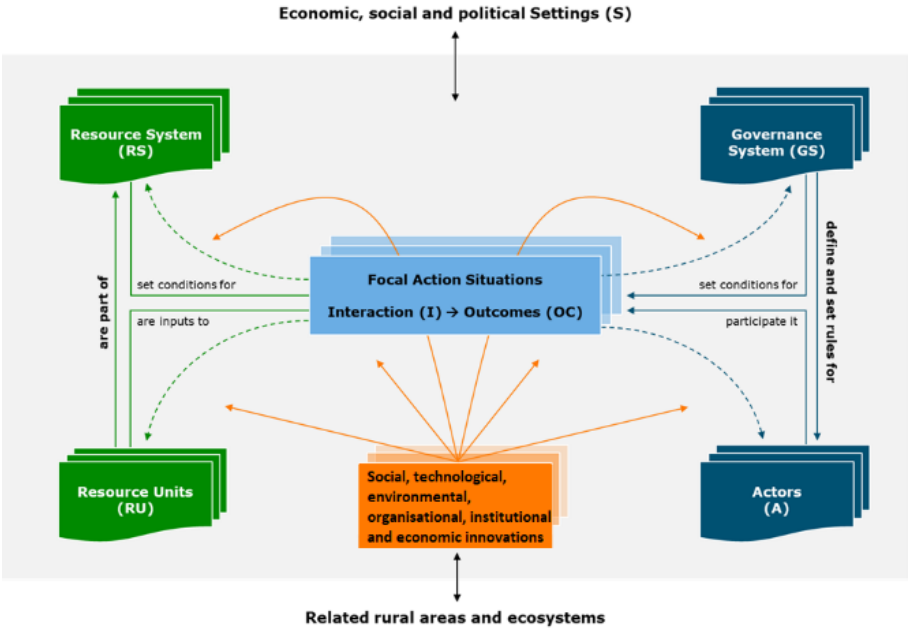

Figure PB3 – The Ostrom socio-ecological system (SES). Outcomes depend on interactions of resource and governance system, units and actors

Policy implications

This policy brief focuses on supporting sustainable digitalisation. Given the limited knowledge available about the actual reduction of negative social and environmental effects of digitalisation, CODECS presents in this policy brief a conceptual framework to account for the complexities involved in using a system thinking approach to facilitate the understanding of short- and long-term costs and benefits with digitalisation. CODECS uses systems thinking when addressing the costs and benefits of digitalisation, covering economic, environmental, and social costs and benefits. CODECS intends to assist in making a significant contribution to establish a basis for development, implementation, and evaluation of sustainability- and data-related policies at regional, national and EU levels. Moreover, CODECS has the ambitions to provide support to related objectives, including Green Deal ambitions, the new CAP, and the fair data sharing and exchanges through Common European Data Spaces, among others, as in the 2030 Digital Compass.

Digitalisation is a consequence of ever-improving smartness in the use of huge amounts of relatively cheap data to effectively support farmer's activities, with Artificial Intelligence (AI) expected to change opportunities drastically in the near future, with human behaviours and system interactions resulting in costs and benefits that can be unexpected. With the CODECS conceptual framework, we specify the transitioning across different levels of digitalisation. When digitalisation reaches levels beyond the primary intentions of adopting new technologies e.g., at the business level, people within the society adapt their behaviours in various ways, and in turn, environmental conditions and ecosystem cycles are eventually impacted by the changing human behaviours. Core societal impacts, including social inequalities and negative environmental impacts, e.g. climate change hazards, water scarcity, and biodiversity loss, will become issues of urgency if the European policy strategies are not acting and taking the necessary measures in time.

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The CODECS framework suggests that digitalisation requires specific strategies that articulate the intervention at the three levels and tailor it to their specificity.

At the level of business processes, measures such as support to investments, agri-environmental schemes, and training programs should improve farmers' capabilities, their quality of life, and their production of public goods. This level requires a deep understanding of the diversity of farmers' readiness concerning the context where they live, to their structural characteristics, and to their transformative potential of digital solutions. Costs and benefits at this level should consider the return on public investment in digital technologies, as well as the spillover effects in terms of learning and innovation.

The digital ecosystem provides the resources necessary to activate the potential of digital technologies at the farm level. At this level, connectivity infrastructures, data-sharing schemes, platforms, advisory services, research and innovation policies should be considered. Also, policies addressing the existing AKIS should consider how digitalisation affects the relations between advisory services, research, technology providers, training and education.

The socio-ecological system (SES) is the level where social, economic, and environmental sustainability is assessed in a broader context. Addressing digitalisation at this level entails considering how the governance influences patterns of natural resources and the overall societal norms to allow consistency of using digital technologies and adopting sustainable management of resource systems. Policy tools at this level - for example, land use, water policies, biodiversity strategies, but also technology-related policies such as data and AI regulation - should take into account the role digitalised agricultural practices can play in the sustainable management of these resources, as well as the risk of introducing non-appropriate technologies.

To accelerate sustainable digitalisation through policymaking, it is crucial to focus on boosting the abilities of those involved and ensuring resources are sustained, accessible and fairly distributed.

When setting priorities, it is key to identify which actors could enhance the system's performance with policymaking and recognise how governance system changes can aid resource creation and capability improvement. CODECS suggests that innovation policies should seek a balance between technical, institutional, and technological advancements. Digital readiness requires that users are comfortable with the technology, have access to necessary hardware and software, and possess the skills and knowledge to use them effectively. Acknowledging digital readiness as a major drive to extend transitions towards sustainable digitalisation across Europe is vital and plays a pivotal role in adapting to higher digitalisation levels.

With the CODECS conceptual framework, a system's understanding of potential costs and benefits will improve substantially. A clearer understanding of the socio-cyber physical system level (i.e., in the CODECS conceptual framework) in future policy implementation will likely enhance sustainable digitalisation. In CODECS, scientific insights will be derived about costs and benefits across a total of 20 Living Labs distributed across Europe. In addition, CODECS will focus on selected topics in-depth on a larger scale such as increased inequalities and digital divide, inclusion of women in digitisation, and biodiversity. CODECS desires to trigger the transition towards the Sustainable Development Goals (SDGs) by enhancing social, environmental and economic benefits at all levels and reducing costs. To contribute to more insights into social, economic and environmental costs and benefits of digitalisation, relevant research questions remain, such as:

- Do the existing digitalisation trends in agriculture correspond to the sustainable digitalisation criteria?
- How should the costs and benefits of sustainable digitalisation of agriculture in the near and far future be measured and distributed?
- How should the different dimensions of sustainability when promoting the digitalisation of agriculture be conciliated?

Authors Policy Brief: KATRINE SOMA (WR), GIANLUCA BRUNORI (UNIPI), CYNTHIA GIAGNOCAVO (UAL), ANDREA KNIERIM (UHOH), DANIELE VERGAMINI (UNIPI), ROSA MARIA HEREDIA HORTIGÜELA (UAL), ALESSIO FERRARI (CNR), CHIARA MANNARI (CNR), MANLIO BACCO (CNR), TROND SELNES (WR), ELISA CIRAVEGNA (WR), LIVIA ORTOLANI, (UNIPI), ALEXIA GOBRECHT (INREA), VERONIQUE BELLON-MAUREL (INREA), CONSTANTINE ILIOPOULOS (AGRERI), REINOUT GODAERT (ILVO), MARK RYAN (WR). Contact: Email: Katrine.soma@wur.nl

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