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An integrated socio-cyber-physical system framework to assess responsible digitalisation in agriculture: A first application with Living Labs in Europe

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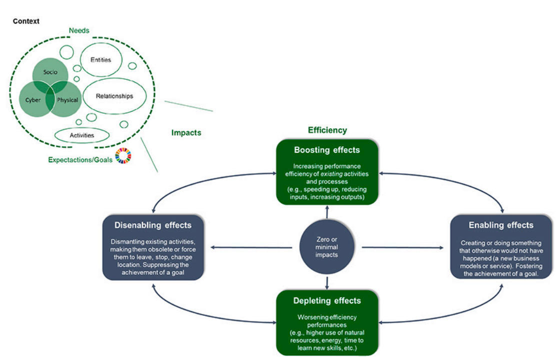
HIGHLIGHTS

- The paper outlines concepts for anticipating the consequences and trade-offs of digitalisation.
- Application of a socio-cyber-physical framework to assess digitalisation impacts in 21 Living Labs.
- Presenting a typology of enabling, disenabling, boosting and depleting impacts of digitalisation.
- This framework and typology enable impact evaluations for responsible digitalisation in agriculture.
- Responsible digitalisation means working in parallel on design, access, and system complexity.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: It is still an open question how to assess the contribution of digitalisation in agriculture to the United Nations' Sustainable Development Goals, and how digitalisation then can be done in a responsible way. A socio-cyber-physical system (SCPS) concept can help this analysis, but little experience exists with its operationalisation and application, and its integration with the Responsible Research and Innovation approach.
OBJECTIVE: To address this gap, this paper has a twofold purpose: a) operationalise the SCPS concept within an integrated assessment framework adaptable to multiple levels of analysis, contexts, and purposes (e.g. ex-ante, ongoing, ex post evaluation) to shed light on impacts of digitalisation in relation to SCPS entities, relationships, and activities; b) apply the designed framework in 21 multi-stakeholder platforms (Living Labs), which were established to explore needs and expectations in specific subjects relevant for European agriculture, forestry and rural areas.
METHODS: Impacts were assessed through interviews (158 respondents), focus groups (378 participants), online surveys (273 respondents), and other secondary data.

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RESULTS AND CONCLUSIONS: The findings indicate that the SCPS framework enables elucidating relationships between digital and broader sustainable development goals and needs, and can sharpen earlier assessments, going beyond a pessimistic or optimistic dichotomy associated to digitalisation by specifying effects and trade-offs in terms of enabling, disenabling, boosting and depleting impacts of digital agriculture. However, the framework being comprehensive and open to emerging socio-cyber-physical interactions, makes that Livings Labs doing participatory impact assessments struggled with the complexity and multiple dimensions of the topic.

SIGNIFICANCE: The paper provides both conceptual and operational knowledge to set up impact evaluations of responsible digitalisation in agriculture and outline concepts that can help anticipating the consequences and trade-offs.

1. Introduction

The transition towards digitalised agriculture and rural areas can have huge socio-economic and environmental impacts (Basso and Antle, 2020; Finger et al., 2019; Galaz et al., 2021; Herrero et al., 2021; Macpherson et al., 2022). Understanding these impacts is becoming increasingly critical as digitalisation is closely connected to the sustainability and ethical trajectories of food, farming, forestry, and rural areas.

There are suggestions that digital agriculture may have beneficial effects on pressing sustainability matters (Kamilaris et al., 2017; Pesce et al., 2019; Schroeder et al., 2021; Wolfert et al., 2017). However, it is not just the technical performances and potential benefits of single digital technologies that are receiving growing attention from funders, technological providers and other actors at the science-policy-society interface (Lioutas et al., 2021; Mulrow et al., 2021; Rose and Chilvers, 2018; Visser et al., 2021).

Concerns about the socio-technical and environmental requirements, direct and side effects of the digital transformation at micro- and macro-level on social inequalities, climate justice, and ethical issues have spurred different approaches to evaluation, some more linear and others more systemic in nature.

Some authors propose linear, theory-driven approaches that observe impacts as the result of a logical chain going from digital technologies (inputs) to outputs and outcomes (Bieser and Hilty, 2020; Bieser and Hilty, 2018a, 2018b; Mergel et al., 2019; Rojo-Gimeno et al., 2019). Pre-established sustainability missions, goal frameworks or benchmark indicators can actively guide evaluations towards assessing desired societal expectations, like those agreed in the United Nation's Sustainable Development Goals (SDGs) (Herrero et al., 2020; Macpherson et al., 2022). Still, top-down frameworks and pre-defined quantitative metrics can also jeopardise reflexivity and narrow down the understanding of the interrelations (trade-offs or synergies) between digitalisation and its impacts on stakeholders needs and sustainability dimensions, which remain still poorly explored and documented so far (Del Río Castro et al., 2021; Klerkx et al., 2019; Klerkx and Rose, 2020).

Therefore, to address shortcomings of linear evaluation approaches, a better understanding of the systemic impacts of digitalisation can help to strengthen the transformational nature of technological development towards sustainable development (Herrero et al., 2020; Macpherson et al., 2022; Smith et al., 2021). Different frameworks already exist to design system-oriented approaches to assess digital agricultural innovations (Malerba, 2002, 2004; Schnebelin et al., 2021). For instance, Kernecker et al. (2021) frame the trajectory of smart farming as a dynamic, circular process determined by the interactions among actors, their roles, constellations, and activities. Similarly, Smith et al. (2021) include the role of the situational context and donor-funded interventions in shaping the interactions among orgware, software, and hardware components of digital innovations in agriculture.

While the choice among linear, system-oriented, and other approaches might depend on different evaluation purposes and ultimate use of the findings (e.g., accountability, formative, summative, steering), the design and implementation of system-oriented assessments of digitalisation in agriculture is receiving growing attention for the potential to address ethical questions and accommodate multiple dimensions of the responsible research and innovation (RRI) approach (Eastwood et al., 2021; Fleming et al., 2021; Klerkx and Rose, 2020; van Mierlo et al., 2020), namely reflexivity, responsiveness, inclusion and anticipation (Steinke et al., 2022; Stilgoe et al., 2013; van der Burg et al., 2019). RRI inspired evaluations aim to gain in-depth insights on the direct and indirect implications, trade-offs, or externalities of digitalisation (Hackfort, 2021; Klerkx and Rose, 2020; Scholz et al., 2018) and steer its development towards socio-ethical and environmental desirability (Lioutas et al., 2021; Stilgoe et al., 2013).

For this purpose, recently Rijswijk et al. (2021) outlined the concept of a socio-cyber-physical system (SCPS) to study the impacts emerging from the mutual interactions between social- (e.g. people, business, institutions), cyber- (e.g. data infrastructure, digital technologies and skills, other digital requirements), and physical-entities (e.g. machinery, natural resources) at different possible levels of analysis (e.g. farms, sectors, supply chains).

The literature around SCPS continues to expand in different socio-economic fields (Ciliberti et al., 2022; Dressler, 2018; Wang et al., 2019; Yilma et al., 2021; Zeng et al., 2020). However, little experience exists with its operationalisation and application, and its integration with the RRI approach, especially in a diverse range of participatory settings dealing with closely related sustainability issues in agriculture, forestry, and rural development.

To address this gap, this paper has a twofold purpose: a) operationalise the SCPS concept within an integrated assessment framework adaptable to multiple levels of analysis, contexts, and purposes (e.g. ex-ante, ongoing, ex post evaluation); b) apply the designed framework in real-life multi-stakeholders platforms to deepen the understanding of the impacts of digitalisation, while learning about the benefits and challenges to assess system-level impacts in line with the RRI approach and UN's SDGs.

To this end, 21 Living Labs (Gamache et al., 2020; Marone et al., 2020) were mobilised[1] across Europe to assess digitalisation impacts in relation to specific focal questions. The questions inquired the past and present consequences of the integration of cyber-elements in socio-physical systems, on relevant subjects for European agriculture, forestry, and rural areas (e.g., weed control, farm diversification, firefighting, direct selling). Although our findings are based on a broader dataset, in view of the special issue this article is part of, we zoom in on the LLs dealing more closely with digital agriculture.

By providing a framework and applying it empirically, the paper provides a knowledge base and a methodological experience aimed to reconcile and integrate multiple ethical principles, evaluation objectives and concepts in various participatory settings and situations.

The 21 LL assessments add further theoretical and operational

[1] Living Labs were established and funded as part of the Horizon-2020 research project DESIRA2020.eu.

insights in the field of participatory impact evaluation and responsible digitalisation in agriculture. In more detail, they contribute to including behavioural and social elements in cyber-physical systems analyses (Verdouw et al., 2021), encompassing the physical and environmental aspects in participatory evaluations of digitalisation (Mulrow et al., 2021), overcoming researchers' own agency (Stilgoe et al., 2013), dealing with power imbalances in stakeholder inclusion (van Mierlo et al., 2020), ensuring a balanced diversity of actors and views along the participatory evaluation process (Fleming et al., 2021), and building societal awareness and capacity to anticipate unexpected effects (Lange et al., 2020; Pohl and Finkbeiner, 2017; Rolandi et al., 2021).

Finally, this paper provides insights on the multifaceted impacts of digitalisation, by refining on what (e.g., needs, individual entities, relationships, activities, SDGs) and how (e.g., enabling vs disenabling, boosting vs depleting effects). By being responsive to the surrounding context and centred on stakeholder needs, we discuss how our framework and findings can be useful to prepare ex-post, ongoing, or forward-looking impact assessments of digitalisation. Coherently, these latter also take into account multiple factors (Klerkx et al., 2019; Rijswijk et al., 2021), such as the attributes embodied in digital technologies (e.g., connectivity, flexibility, security), access conditions (e.g., opportunity cost for learning, running, repairing digital technologies) and the duality between digitalisation and other system dynamics (e.g., COVID-19 pandemics, logistics infrastructure, market power).

2. Theoretical background

Digitalisation is based on the general-purpose process of digitisation started already with the advent of computer science around the 1950s, i.e. the technical conversion of analogue information into digital form (Autio, 2017; Rijswijk et al., 2021). Through digitisation, data can be generated from everyday life, peoples, interactions, business activities or physical objects: a process better known as datafication (Mejias and Couldry, 2019; van Dijck, 2014).

However, digitalisation or digital transformation goes beyond digitisation and datafication (Nochta et al., 2019). For many years, governmental and academic actors have adopted technology-centred definitions of digitalisation, which ultimately confined it only to the technical design and incorporation of data-driven technologies like ICT, blockchain, and big data analytics into the farming sector, though this approach has yielded criticism lately (Bacco et al., 2019; Basso and Antle, 2020; Eastwood et al., 2021; Finger et al., 2019; Lioutas et al., 2021; United Nations, 2017).

To fully grasp the socio-ethical nuances and deeper implications, digitalisation should more broadly be considered as a process whereby a broader spectrum of digital elements are gradually used by, and impacting on socio-physical systems (Bronson, 2019; Rijswijk et al., 2021; Vial, 2019). This broader understanding opens digitalisation towards other dimensions and attributes, ranging from digital technologies to data infrastructure, connectivity, digital strategies, digital tasks/skills and so forth (Prause et al., 2021; Rose et al., 2021; Sparrow and Howard, 2021).

In the specific case of digital agriculture, the analysis of the potential impacts of digitalisation depends also on how agriculture is understood among various paradigms. Digitalisation for specialised agriculture would be different from digitalisation for a multifunctional agriculture, as the first is presumably concerned on improving the productivist performances (e.g. efficiency gains, higher productivity, lower environmental impacts) and the latter looks at the tensions and synergies between productivist and non-productivist functions (Klerkx and Rose, 2020; Renting et al., 2009; Schnebelin et al., 2021; Wilson, 2001, 2007).

Concepts like agricultural multifunctionality offer suitable lenses to recognise the wider role of agrarian life for rural areas and regional development (van der Ploeg et al., 2000). At the same time, multifunctional agriculture can drive evaluations to tackle the implications of the digital transformation in a wider range of agricultural and non-agricultural entities, relationships, and activities. In this spirit, the assessment of digital agriculture can concern the consequences on the farming dimension (e.g., precision or smart farming), but also on the stewardship of the countryside, and/or the provision of public and private goods and services (Huylenbroeck and Durand, 2003).

As agriculture goes beyond the production of food and fibres (Wilson, 2007), evaluations supporting responsible digitalisation in agriculture can move the non-productivist dimension of agriculture or on-farm diversification activities out of the margins and right to the centre of RRI-proofed evaluations of digital agriculture.

This broader perspective is well justified if one observes the dynamics stimulated by the COVID-19 pandemic in the digitalisation of on-farm diversification activities, like a short-term increase of local food and farm direct sale (Mastronardi et al., 2021; Nemes et al., 2021). Digitalisation in multifunctional agriculture should address concerns about the sustainability of production activities like farming, but also about the innovation trajectories of digitally mediated on-farm diversification services like agritourism, educational and social inclusion activities, food processing and direct selling, contractual work, biodiversity restoration, and so on.

As much as the digital transition can occur at farm level, the outcomes of digital agriculture can be assessed in relation to micro-, meso- and macro-levels of analysis (Klerkx et al., 2019; Super et al., 2021), such as individual farms or activities, to scale up to agricultural knowledge and innovation systems (Rijswijk et al., 2019), value chains or regional economies (Rijswijk et al., 2021). If a farm, value chain, or community is selected as specific system under analysis (micro-level), other meso- or macro-level assessments can be used to validate, contradict, complement, contextualise, or extrapolate the findings from lower to higher scale of analyses, or vice versa.

For instance, some macro-level appraisals of the digital transformation have looked so far into the delivery of European agricultural and rural policies (Ehlers et al., 2021; European Court of Auditors, 2020); knowledge transfer and advisory networks (Fielke et al., 2020; Ingram and Maye, 2020); trade, markets and agri-food transactions from farm to fork (Donaldson, 2021); and the provision of public goods and services at farm, community, landscape or other levels (Garske et al., 2021; Moran et al., 2021; O'Rourke et al., 2020).

In sharing these insights, we aim to bring three conceptual clarification that are essential for integrating the SCPS concept with the RRI approach when framing digital agriculture and its impacts. These imply that assessment frameworks supporting responsible digitalisation can enhance reflexivity and stakeholder inclusion when they are:

- Aware of the multiple dimensions of digitalisation (not only the incorporation of new technologies, but also adaptations and socio-technical requirements, like infrastructures, energy, skills, space, relationships, and so forth).
- Suitable to study digitalisation at different level of analysis (micro-, meso-, or macro-).
- Open to engage with farming and extra-farming actors and critically explore the implications of digitalisation on the multiple productivist and non-productivist functions performed by agricultural systems, as well as their interactions, tensions and synergies.

3. Methodology

3.1. An integrated framework operationalising socio-cyber-physical system concepts

In this paper, we propose and refine an analytical framework through its instantiation and application across 21 DESIRA Living Labs, thus contributing to make its adoption more robust and applicable in other assessments of digital impacts. DESIRA is a Horizon 2020 project that aims to assess the social and economic impact of digitalisation on agriculture, forestry and rural areas (see also https://www.desira2020.

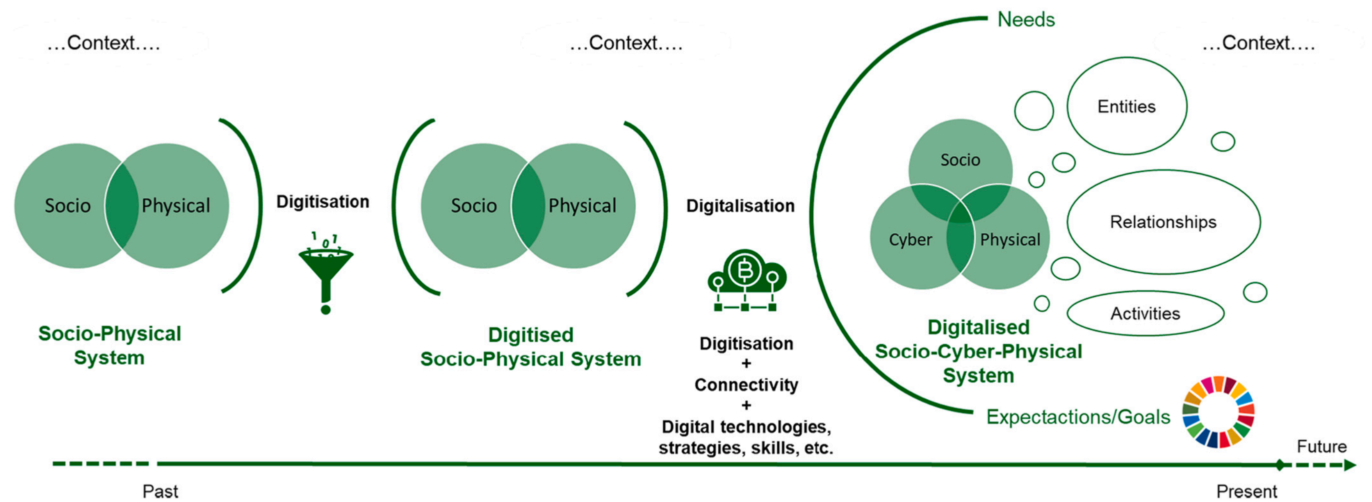

Fig. 1. Integrated, conceptual framework to assess impacts and support responsible digitalisation.

eu). The integrated framework is based on the concept of SCPS and serves to assess the impacts of digitalisation in line with the RRI approach and SDGs (Fig. 1).

The framework is built around different conceptual and analytical blocks: timeframe, context sensitivity, problem-solving, system thinking, and mission-orientation. Furthermore, digitalisation is considered as socio-technical transformational process in its multiple dimensions (involving digital infrastructure, technologies, strategies, skills). By marking the difference, but also continuous line with digitisation processes, the framework shed lights on the manifold integration of cyber-entities into socio-physical systems in which they are designed, used, dismantled, or recycled.

The timeline at the bottom of Fig. 1 displays the evolution in each examined system transitioning into the digital transformation (e.g., a farm, cooperative, sector, service, community). Although the RRI approach (Stilgoe et al., 2013) is putting increasing attention on predicting future, potential positive and negative impacts in advance which are seen as important by evaluation scholars (Kaplan et al., 2021; Rogers, 2009), other context-sensitive and utilisation-focus approaches (Patton, 2008) suggest flexibility in the design of frameworks and tools that can suit the specific conditions and questions of participatory settings. Adding a temporal element allows LLs to consistently frame and adapt the focal questions and data collection tools to different types of evaluations (e.g., ex-post, ongoing, and ex ante or foresight).

In our framework, time-frame decisions depend also on the exact purpose of the assessment (e.g., policy accountability, process learning, forecasting) and other situational factors in real-life settings (e.g., existing level of digitalisation, data availability, digital literacy). Without neglecting the reflexive dimension of the RRI approach, a focus on the co-evolution of innovation trajectories from past, present, and future can also inform digital scenarios forecasting by unveiling "how things changed and developed over time", "what causes what", and "how impacts have been distributed from past to present situations" (Renting et al., 2009; Zolfagharian et al., 2019).

By clarifying and agreeing on the time reference at the outset of the assessment, this framework allows stakeholders to harmonise data collection and facilitate the interpretation of findings. Indeed, findings like "digitalisation has contributed" versus "digitalisation might contribute if" have different meanings but can in fact complement each other.

Table 1 suggests more specific descriptions and guiding questions to help researchers, evaluators, and stakeholders to operationalise SCPS concepts and assess the implications of digital agriculture in line with RRI approach and SDGs. Through SCPS analyses, the assessments of context-specific phenomena are facilitated by the mapping and visualisation of the system, which is composed by entities (who), links or relationships (how things are connected), and their performed activities (what). In a multi-level perspective, the context refers to macro-level analysis, whereas the SCPS is the micro-level analysis to gain more in-depth insights on the phenomenon under study.

Contextual factors can include drivers or bottlenecks like new socio-economic opportunities, climate or financial threats, demographic trends, deeply-rooted values, or intangible heritage that can influence the problem and structure of SCPS. Arbitrary boundaries can be drawn for research purposes to delimit the subject of analysis in a specific time situation (when) and in relation to a specific focal question (why) (Midgley, 2006; Williams and Hummelbrunner, 2010). The focal question guides the evaluation by framing the problem or opportunity within a given context.

A SCPS is built on three main pillars that can be recognised and mapped out in a participatory fashion:

- **Entities** are distinguished as those of the social domain (people and their social rules, values, practices, private actors like start up, public organisations, animals, laws, markets); physical (natural or artificial things); and cyber domain (e.g. data infrastructure, software, digital devices and artefacts) (Rijswijk et al., 2021).
- **Relationships** are the mediators between entities' agency and social structure (Dépelteau, 2018). Simply put, relationships are how two or more entities are connected within the same domain (e.g. farmers associated with cooperatives through a membership agreement, mutual trust, and sharing of assets) or among different socio-cyber-physical domains (e.g. citizens and public authorities registered in online platforms to govern collective resources or public services).
- **Activities** refer to operative tasks, projects, or entire processes performed by individuals or multiple entities by mobilising resources (e.g. finance advisory service provided to citizens through mobile apps) (Vepsalainen, 1988).

In this framework, the contributions of digitalisation can also be appraised in relation to stakeholder needs and expectations. This enhances responsiveness and anchors the participatory assessment on quantitatively or qualitatively-defined criteria, goals, or indicators reflecting both bottom-up societal views and agreed sustainability goals rather than purely technological performances. SCPS's needs can be identified by stakeholders themselves as the qualitative or quantitative gaps between a current and desired sustainability state (Watkins et al., 2012). Expectations incorporate a normative selection or prioritisation of needs and enact stakeholders towards mission-oriented evaluations (Klerkx and Rose, 2020; Pigford et al., 2018). Expectations can be

Table 1
Integrated, analytical framework to assess impacts and support responsible digitalisation.

	Short description	Examples of guiding evaluation questions
Time-frame	Past, present, or future	Is the focus or LL question guiding the assessment towards what happened so far in relation to a specific sustainability problem (past, present) or is it rather related to what "could happen if" (future)? How digitalisation evolved so far and what can we expect in future in terms of SCPS configuration and impacts? Which specific actors, events, or insights might prevail or be implicitly excluded if the focus is on future trajectories of digitalisation?
Context	Established structural or behavioural conditions, trends	What are the causal roots, drivers or bottlenecks connected to the subject of analysis? Are there external or internal threats and opportunities?
System Needs	Gap between the current and desired state	Who needs what and why? Are the things described as needed necessary? At what costs? What additional needs are generated by fulfilling primary needs?
System entities (who?)	Socio, cyber, physical entities	Who are the social agents acting in the system (people, animals, businesses)? What are the artificial or natural elements playing a role (forest, road, park, birdlife)? What cyber-elements are involved so far (connectivity, technologies, data storage)? How do the values, norms, interests, and skills of different entities match or clash?
System relationships (how?)	The way in which entities are connected	How are social entities relating to plants and animals in the digital era? Who is the subject and who is the object? Are value chain actors vertically or horizontally integrated? How is trust and power built and maintained? What skills, codes and rules are used to govern socio-socio vs socio-cyber-socio relationships?
System activities (what?)	Performed operations, tasks, processes	Which of the performed business, administrative, or farming activities are we focusing on? What are the main attributes included and excluded in the analysis (solidarity, productivity, yields)? Are there other activities performed by the farmers (on- or off-farm)?
System Expectations	Normative selection of desired objectives, missions, goals (e.g., SDGs)	What are the specific goals or targets expected to be achieved by the system under analysis and why? Are they inclusive? Do they allow critically exploration of the links with socio-economic, political, ethical, and ecological matters?
Impacts	Consequences emerging as result of the mutual interaction between socio-cyber-physical entities	What are the changes brought about by digitalisation on entities, relationships, activities? How does digitalisation contribute to reinforce powerful actors or change the norms, values, practices of individual entities or groups? Who bears the costs and benefits of digitalisation? Does digitalisation meet or deviate from the identified needs, and why? How are expectations met and what are the trade-offs?

precise targets, goals, missions, or general prospects of changes starting from the identified needs. The SDGs are one example of pre-existing and international agreed expectations, but other missions or target indicators can be defined bottom-up, directly by stakeholders, to encapsulate more precise SCPS expectations at micro-level of analysis.

Lastly, impacts are understood as the direct and indirect implications of the digital transformation on the SCPS elements (entities, relationships, and activities), needs, and expectations vis-à-vis multiple intervening factors. While in counterfactual or quasi-experimental assessments, impacts are often quantified as net effects from a single factor like a policy intervention (Bamberger et al., 2019; Bieser and Hilty, 2018a, 2018b; Castaño et al., 2019), here impact is used interchangeably with terms like: contribution, effect, or consequence. The qualitative identification of impacts can complement quantitative evaluations and provide in-depth insights on the interplay and systemic nature of the digital transformation in a specific context.

3.2. Empirical application in Living Labs

Between May 2020 and March 2021, 21 Living Labs (LLs)[2] from across Europe were set up and trained to operationalise the proposed framework in a participatory setting. Research activities were heavily affected by the COVID-19 restrictions on off-line, on-site, physical interactions and required continuous adaptations. LLs are research platforms established to engage with stakeholders, key informants, and users in a real-life setting (Dietrich et al., 2021; Schwarz et al., 2021). During the activities, LLs aimed to explore past and present implications of digitalisation in relation to a specific focal question, which captures the subject of analysis.

Each LL is led by a central partner (university, research center, community organisation, private company) who acts as researcher and facilitator who receives funding and training to carry out research activities and animate stakeholders within an established or newly created network. To answer some of the guiding questions proposed in Table 1, a mix of data collection tools, ranging from desk research to semi-structured interviews, online surveys, and interactive workshops were designed and applied by the LLs themselves in three phases:

3.2.1. Phase 1: focal question setting, context analysis, and assessment of needs

In this phase, LLs followed a reiterative process going from defining a preliminary focal question and analysing the context in terms of strengths, weaknesses, opportunities, and threats at macro-level (SWOT analysis). By doing so, LLs fine-tuned their focal questions on their micro-level analysis and identified main stakeholders needs. This phase was important to ground the evaluation of digitalisation on a deeper and wider understanding of trends, conditions, and forces that influence the sustainability problem under analysis and the interplay with past and present digitalisation developments. Based on this multilevel perspective approach, the final focal questions structured and guided the LLs in their next steps (SCPS mapping and assessment).

In our ex-post assessments, focal questions defined the unit of analysis (farm, community, region, supply chain), the timeframe (i.e., past, and present impacts) and the subject or phenomenon under study (e.g., digitalisation and pesticide reduction, weed control, water management). For illustrative purposes, these are some examples from LLs dealing with digital agriculture which were part of the analysis:

- How has digitalisation contributed to weed control in Swiss organic vegetable farms?
- How has digitalisation contributed to the sustainability of fruit production in the Lake of Constance region (Germany)?
- How has digitalisation improved the management of public water resources in Trikala (Greece), while reconciling the interests and needs of farmers and citizens?

The SWOT analyses and need assessments considered various dimensions, such as social, economic, governance, environmental, and gender aspects. Among these broader considerations, the existing level of digitalisation in the subject under analysis was appraised both

[2] Living Labs' information can be retrieved on https://desira2020.eu/living-labs/.

quantitatively (secondary data, when available) and qualitatively, with an online survey structured around the dimensions of the Digital Economy and Society Index.[3]

3.2.2. Phase 2: participatory mapping and visualisation of socio-cyber-physical systems

To narrow down the focus of the assessment, LLs prepared a preliminary description and visualisation of their SCPS before its final validation and assessment with the engaged participants. This phase provided the opportunity to make a list of key socio-cyber-physical entities and visualise their relationships and activities. To facilitate the identification of existing and already in-action cyber-entities, the LLs relied on their own knowledge, stakeholders experience, and additional desk research. The use of taxonomies and inventory of digital technologies was suggested to facilitate the identification of digital technologies (Bacco et al., 2020).

3.2.3. Phase 3: Living Labs' participatory impact assessment

Impacts were assessed *ex post* (past and present). To engage stakeholders in the participatory assessments, impacts were defined as the direct and indirect, positive or negative implications of past or present processes of digitalisation upon the entities, relationships, activities mapped out by the LLs in their SCPS, as well as upon the 17 SDGs. These impacts were captured in qualitative terms based on the perception of the respondents and participants of LLs' research activities.

The findings obtained from each LL assessments were then compared with the others to identify common patterns and special instances that can increase our understanding about how digitalisation impacts sustainability problems in agricultural, forestry or rural systems, as well as hint at methodological challenges, recommendations, and limitations for future evaluations. Fig. 2 gives an overview of the dataset and methods used to compare the findings supporting this comparison.

Given the qualitative, exploratory nature of this framework and some of the methods used, like open-ended interviews and group discussions adapted to the specific circumstances and topics of the LLs, the evidence collected was summarised under general categories developed by the research team and authors of this paper after the individual LLs research activities. The general categories are then substantiated through detailed, anecdotal examples from LLs.

4. Findings

The findings presented in this section demonstrate some of the benefits, limitations, and challenges to implementing an integrated assessment framework in a participatory setting. Particularly as it implements some of the RRI dimensions, we discuss on how system-level evaluations can increase the understanding of direct implications, trade-offs, and side effects of digitalisation in a wide range of subjects and contexts. However, this paper gives more space to lessons stemming from the LLs dealing with digital agriculture.

4.1. Exploring the context and setting the focal questions

The complex political, economic, geographical, cultural, and regulatory matrix that digital agriculture has inherited set up an evolving context for studying SCPS. Here are some examples from two LLs dealing with issues in the upstream and downstream sides of the agri-food value chain.

The LL in West Flanders focused on the question: "*What is the impact of individual farm-based airborne monitoring of ammonia emissions, particulate matter, and odour from the intensive livestock sector on agriculture policy and society in Flanders*?". Ammonia emissions from livestock are a source of tensions between stakeholders in rural (Sulistiawati, 2008) and agri-food systems (Flanders Environment Agency, 2017). On one hand, citizens and nature organisations want a substantial reduction of emissions; on the other, farmers are concerned about their future, as they see the regulation on emissions as a threat to their business.

To respond to policy and societal expectations with more evidence, the Flemish government is investing in data and monitoring tools to keep track and reporting the level of emissions from agriculture, especially from livestock (Maarten, 2020). The possibility of designing future technologies to monitor real-time, airborne livestock emissions (ammonia, particulate matter and odour) or adapting existing official modelling from regional to farm levels, in this context, can operate both as a means for improving farm processes (as data useful to a better management of livestock), but also as an instrument of surveillance, with the risks related to the pressure of regulators and public opinion and to the falling reputation in case of transgression. Fig. 3 summarises some of the contextual factors underpinning the analysis of digitalisation and livestock emissions in Flanders.

On the other side of the value chain, another LL, this time in the Adriatic Region of Croatia, focused on the question: "*How has digitalisation contributed to strengthening the connections between farmers and rural economy (tourism), and how has it improved the position of small family farms along the food value chain?*". The LL focused on a wide range of factors to improve (small) farmers' access to rural tourism and fairer food supply chains, including cyber (e.g., interactive web platforms) and socio or physical entities (e.g., logistic infrastructure, nature, tourist offices, restaurants).

The Adriatic Region is experiencing a growing tourism demand in the last decade, but this largely exclude rural areas and farmers (Commins, 2004). Digitalisation was explored as alternative option to mediate the traditional connections between the agricultural and tourism sector and for its potential role in strengthening (or further weakening) the position of farmers along the supply chain and tourist economy. Fig. 4 summarises some of the contextual factors underpinning the analysis of digitalisation and on-farm diversification.

As part of the context analysis, the 21 LLs tried to appraise the baseline level of digitalisation in the area and subject of their focal questions. While data on internet connectivity can be easily retrieved from different European[4] or national statistical sources, other dimensions of digitalisation often lack the latest, harmonised statistical dataset, especially at lower administrative levels or for specific sectors (Clercq & Clercq and Buysse, 2021).

To overcome data gaps and explore the starting context before the SCPS' mapping and analysis, LLs deployed an online survey to ascertain stakeholders' perceptions on the six dimensions of digitalisation used in the Digital Economy and Society Index. The survey contained open-ended and closed questions, which helped to build a common and comparable knowledge baseline among LLs' stakeholders with different backgrounds and digital literacy. The survey results collected from the 21 LLs' stakeholders are reported in Fig. 5.

Besides the perceptions expressed in quantitative ways, this exercise allowed stakeholders to express their views on qualitative aspects that would have been hard to uncover through existing statistics. For instance, while the geographical coverage of internet connectivity was generally considered good or high (5.55 over a Linkert scale up to seven), stakeholders stressed the importance of other connectivity properties. These included: stability, speed, costs, ownership, or investment requirements, which emerged as critical areas especially in LLs dealing with forestry and agricultural issues in mountain areas.

[3] Due to the lack of data for the DESI index at NUTS3 or NUTS4 level, Living Labs gave a qualitative estimation (1 = low to 7 = high) in relation to the level of digital connectivity, skills, use of internet services by citizens, integration of digital technologies by business, public services, and women in the area under study.

[4] For instance, see the European Broadband Mapping (European Commission, 2021), which is a portal gathering various databases on internet connectivity in Europe.

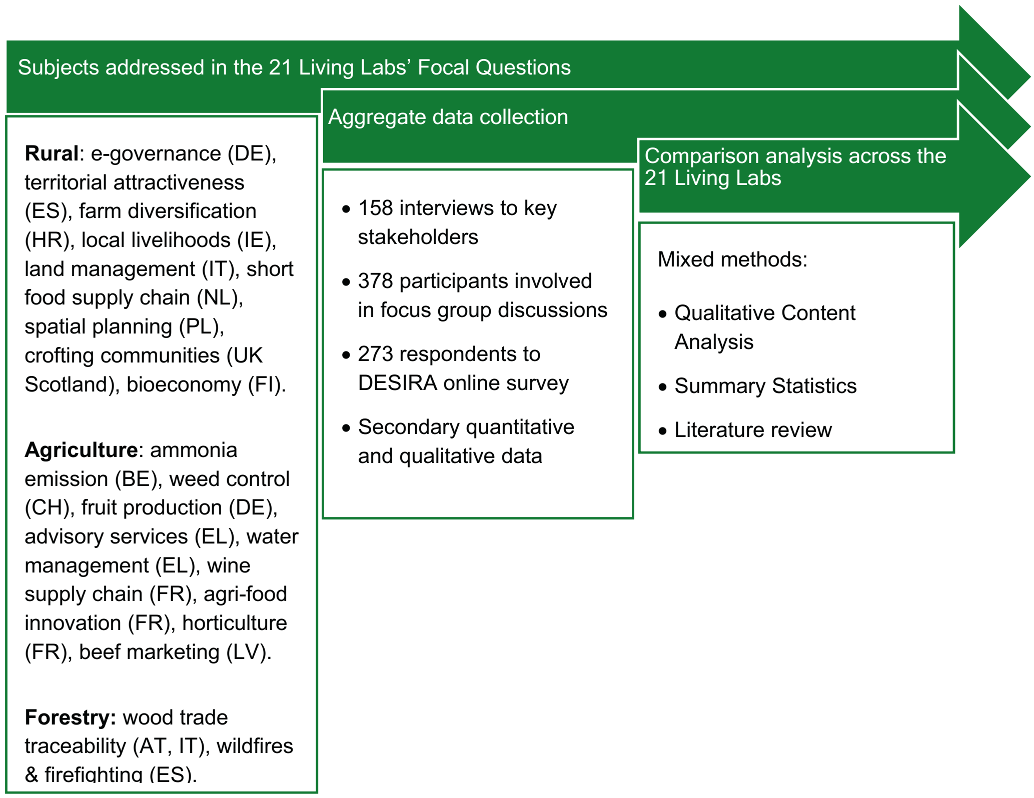

Fig. 2. Overview of data and methods underpinning this empirical analysis.

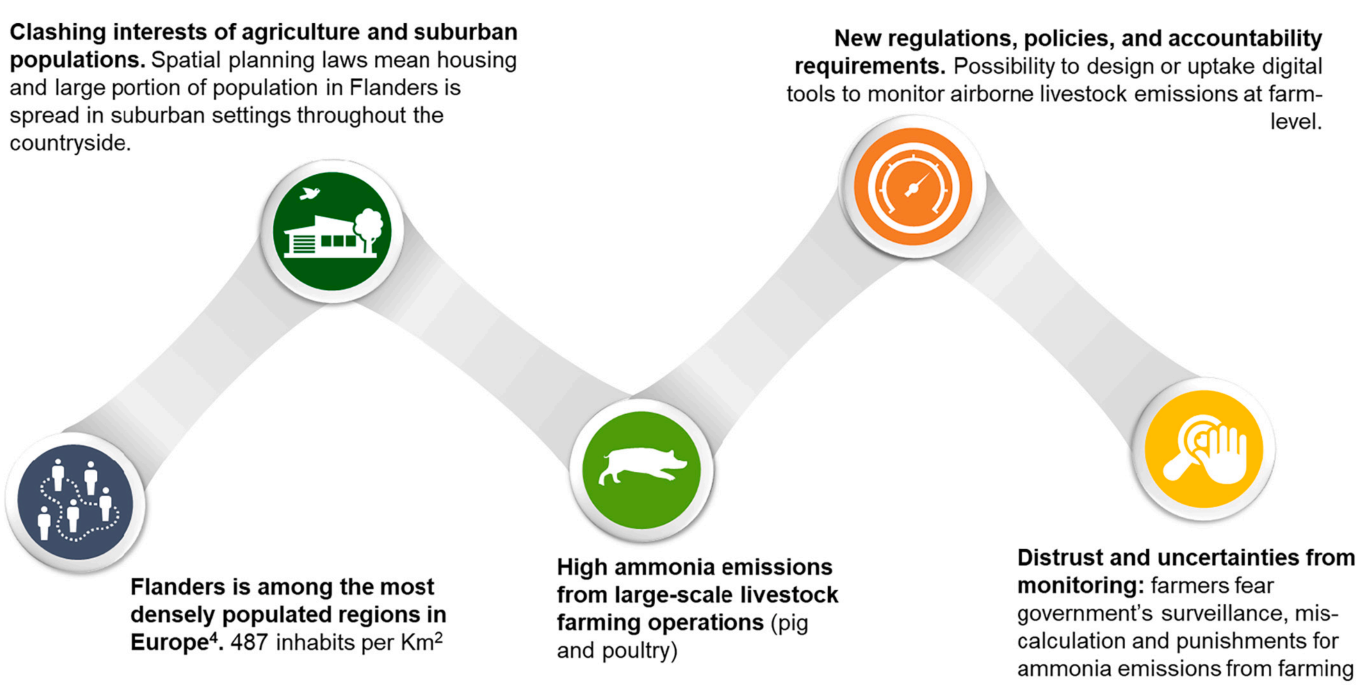

Fig. 3. Highlights on the socio-economic contextual factors underpinning the interlinkages between digitalisation and reduction of livestock emissions in Flanders (Belgium)(Statistics Flanders, 2020).

Similarly, stakeholders awarded an average score of 4,49 for women's participation in digital technologies, but their observations helped highlight obstacles hindering women's active participation in the design and use of digital technologies (cultural, domestic, educational, professional). For example, the inclusion of women was often reduced to the more tedious, back-office tasks emerging from digital agriculture, like e-booking, file storing, e-payments, managing orders. Comparable lower scores were awarded to the availability of digital skills (3.86) and digital public services (3.43), indicating that these areas require high policy attention.

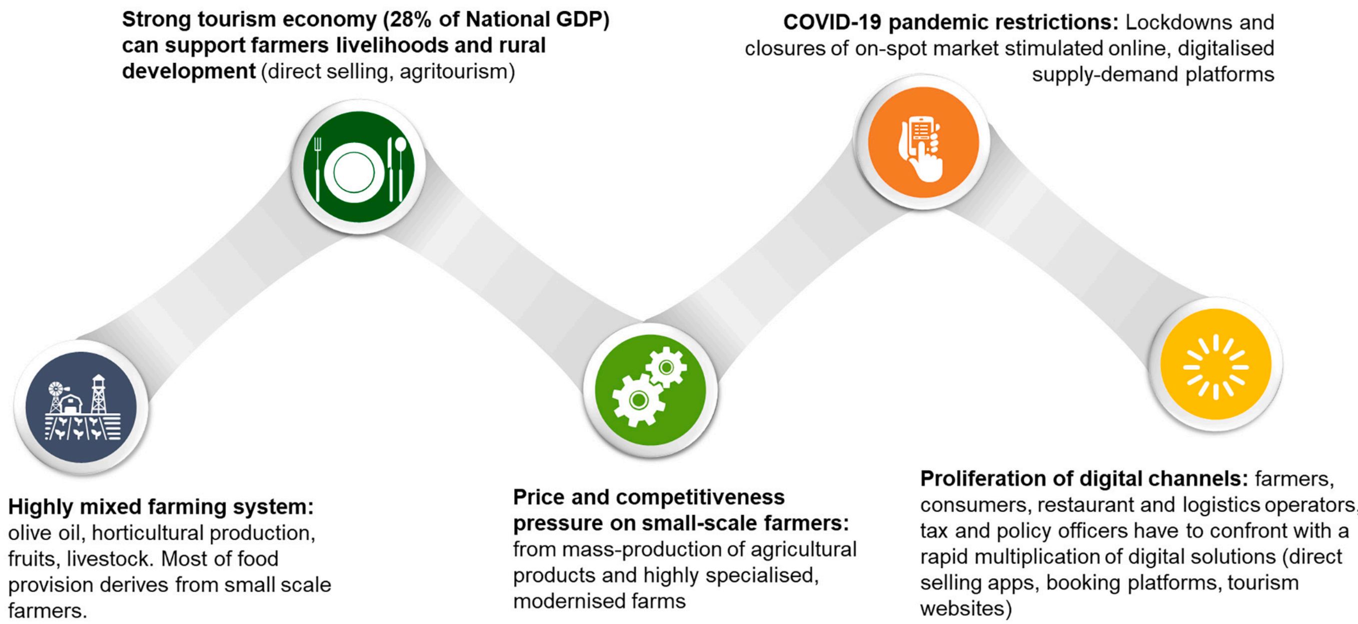

Fig. 4. Highlights on the socio-economic contextual factors underpinning the interlinkages between digitalisation and enhancing on-farm diversification in the Adriatic Region of Croatia.

4.2. Mapping socio-cyber-physical systems

Participatory mapping consisted in identifying and visualising the most relevant socio-cyber-physical entities connected to the LLs' focal question and reflect on the dynamic aspects such as the changing relationships among entities, or the adaptations in the performed activities' attributes. The full list of entities emerging from the 21 LLs' mapping was summarised in clusters as reported in Table 2. Rather than a static picture, the findings in Table 2 are to be seen as a dynamic assemblage that is subject to internal changes and contextual forces, like the COVID-19 lockdowns. Two further general observations were noted when applying the concepts of SCPS into practice.

4.2.1. Encompassing a wide constellation of entities involved in problem solving

When turning the attention from a specific digital technology to a socio-technical problem (e.g., reduce water use and improve water management in agriculture), LLs stakeholders benefitted from a broader frame to incorporate a wider constellation of entities and disciplines at stake, which otherwise could be neglected or underestimated. For instance, the participatory mapping of the LL located in the Adriatic Region of Croatia revealed that it is not just the farmers and their on-farm digitalisation that was worthy of inquiry (online direct selling platforms, digital branding strategies, online booking channels). Other social and cyber entities connected to the farm play a role in meeting on-farm diversification needs and achieving desired results, such as: logistic and delivery service providers; restaurants, taverns, and catering; agricultural cooperatives; insurance providers; tourist agents (hotel, camping sites, event organisers, tour providers); schools; and more.

A material, physical realm was also connected to these needs. Eco-tourism local infrastructure, food processing and packaging equipment, landscape amenities, biodiversity status, and more natural and artificial environments were considered key drivers or inhibiters depending on their status. Each of these physical entities brings its own constraints, potentialities, and networks. This also indicates that the harmony and tensions between the socio-physical worlds cannot be backgrounded as they ultimately affect the contribution of digitalisation in scale, time, and directions (positive or negative).

The multiple entities becoming involved in the subject of the focal questions indicated different degrees of homogeneity and heterogeneity of SCPS. Like for the case of on-farm diversification in the Croatian LL, entities like restaurants, tourism officers, farmers, logistics operators were simultaneously working together to perform common functionalities (e.g., stimulate local food consumption), while also maintaining relations and performing activities outside the common scope and boundaries of the delimited SCPS. Even for focal questions dealing with a very narrow, specific problem (e.g., mechanic weed management in organic farming), SCPS were depicted as homogeneous body of connected entities for the sake of simplifying the follow up analyses (farmers, robots, plant identification apps, tech companies, farm advisors, farmer organisations). However, the LLs also recognised how the roles, activities and relations of each SCP entity stretches beyond the depicted system (e.g., biodiversity restoring movement, innovation and academic research, soil management).

Within the time and budget constraints of the participatory research done through the LLs, mapping the actors from the public, private, and civil society realms was a first step into reflecting on deeper, qualitative aspects of SCPS relationships, like their joint dependency on the quality of landscape amenities, power balance, trust, synergies, and tensions. Socio-economic players like international chemical input providers or business platforms were not easy to involve or less relevant for the micro-level focus of some LLs assessments (e.g., weed management in organic farming). Nevertheless, this does not exclude that they can play a big role in shaping digitalisation towards sustainable intensification or community supported agriculture (e.g., via cloud storage or services to freely share files, photos, registration forms), as well as in setting digital standards that regulate transactions and relationships across geographical areas.

Mapping served also to identify the gaps, overlaps, and bottlenecks in terms of resource management and coordination of multi-actor processes, for instance short-food supply chains (consumers, producers, delivery logistic operators, packaging, health authorities, etc.). As the configuration of SCPS changes along the time, this mapping exercise allowed LLs to identify new entrants, like business start-up mediating producers-consumers sales, or disappearing actors, like small tourism agencies mediating tourists and agritourism farms.

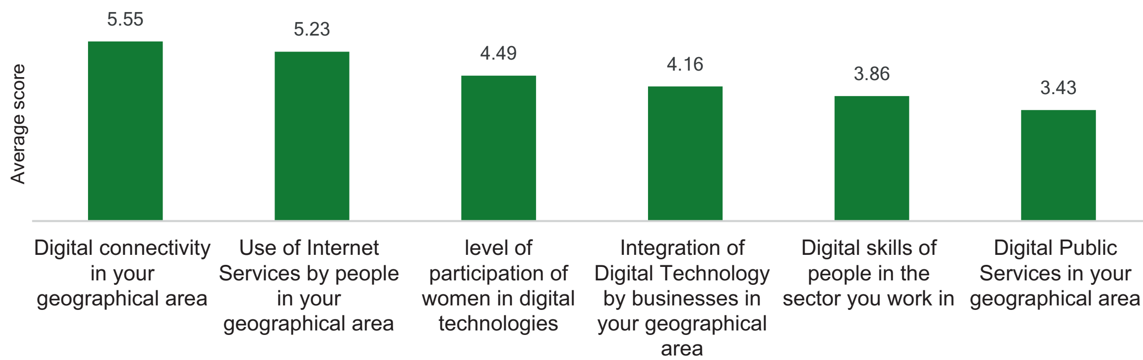

Fig. 5. Average scores (from 1 = low to 7 = high) given by online survey respondents on the current level of digitalisation in the Living Labs' focal question? (N of respondents = 273).

4.2.2. Unpacking digitalisation for participatory appraisals

In our experience with interviewing LLs stakeholders, opening the "black box" of digitalisation was one of the first steps to encourage participatory and transdisciplinary assessments. When the focus of a participatory appraisal is about how to meet a sustainable development problem or opportunity, the most implicit and granted cyber-entities widely adopted in contemporary society, like social media, geotagging in online maps, or cloud storing could emerge as influential or, at least, recognised as an established component of socio-physical relationships. Indeed, many interviews' respondents initially unnoticed, but then realised and explicitly listed various cyber-elements that were already part of the system under analysis for many years or that have been increasingly used in more recent days.

During interviews or focus-group discussions, taxonomies, inventories, check-lists, or guiding questions were deployed by LL researchers to stimulate stakeholders in self-inquiring and identifying any relevant digital technologies, tasks, and infrastructure already in use for the subject under their focal question. These analytical tools enhanced data collection even from those stakeholders who initially underestimated the level of digitalisation (literacy, use) or are deeply concerned on the use of digital means. At the same time, the presence (or absence) of cyber-entities is the starting point for reflexive analyses (e.g., Why is this technology present or not? Who benefits and who bears the cost?)

To give some concrete examples, Table 3 reports a list of cyber-entities emerged from the SCPS mapping conducted with LLs stakeholders around the topic of on-farm diversification (farmers, farm advisors, public authorities, farmers organisations, consumer groups, tourist operators).

The results of this participatory mapping suggest that the concepts of digitalisation need be debunked, unpacked, and appraised by using facilitation tools that stimulate a bottom-up, actor-oriented comprehension. This approach can harmonise the inclusion of both digital specialists and non-professionals along the appraisal. The focus on past or present cyber-elements around the subject under assessment can shed light on the dynamic evolution, assemblage/dis-assemblage pathways of socio-cyber-physical systems. The support of experienced facilitators and tools can unpack the general perceptions of digitalisation as a futuristic, high-tech realm that is beyond the competence or scope for many relevant actors. By bringing digitalisation concepts and practices closer to those with lower specialisation in digital technicalities, evaluations can add an empowering or awareness-raising layer to the exercise, while also benefit from gaining in-depth knowledge and insights from those who have knowledge and higher experience in the subject and context under analysis.

4.2.3. Growing interdependency between digital and developmental needs

From a societal point of view, need assessments reflect the normative views about what is required for achieving a desired goal or status (Asadi-Lari et al., 2003). Among the limitations of participatory approaches, the needs expressed by those involved might not match with all stakeholders operating in and outside the system under analysis (Culyer, 2001; A. Stevens and Gillam, 1998). Bearing this in mind, LLs tried to identify and check how digitalisation respond to stakeholder needs, but also question why the things needed in the SCPS were really necessary and for whom.

The results obtained showed that two broad typologies of needs can be outlined: a) digital and b) non-digital or development needs. The development ones are those related to the broader social, economic, and environmental conditions to be improved. Some concrete examples are sourcing energy from renewable resources or creating collective mechanisms for public goods management. Building communication skills among farmers to reach consumers and increase their direct selling capacity was another example of short-term needs expressed by LL's stakeholders in Latvia dealing with short beef supply chains. Digital needs are instead strictly concerning the socio-technical aspects of digitalisation, and range from functionalities, internet connectivity, data availability, security, skills, interoperability, and more.

Across the 21 LLs, digital needs were often presented as instrumental or necessary conditions to satisfy development needs. For instance, the (digital) need for more precise data collection was expressed by the French or German LLs to better monitor and forecast pest attacks in organic fruit and horticultural production. This (digital need) should ultimately meet the (development) need to reduce the use of plant protection products and production costs at farm level. However, in other cases, we noted that this interdependency emerged also in the opposite direction, in a sort of 'closed loop' or 'chicken and egg' situation (Fig. 6).

In other words, fulfilling key developmental needs was instrumental for resolving digital needs. For instance, to leverage the potential of big data and decision support systems (DSS), which give advice on multi-annual crop rotation plans based on the presence of nematodes or other pests in the soil[5] (digital need), other developmental needs were to be met in parallel. Namely, farmers should have access to soil monitoring tests and labs, access to a variety of seeds, develop fair contractual arrangements with machinery providers and workers to sow the recommended seeds at the right time, just to mention a few examples. Moreover, farmers still need collaborations and socio-ecological knowledge to interpret the agronomic advice of DSS vis-á-vis the signals of climate change risks and market price volatility (Thomine et al., 2022; van Evert et al., 2017). This observation suggests that digital and development needs might be complementary or interdependent.

Finally, negative correlations or tensions can exist between these two

[5] For instance, see decision support tool and database developed by the project Best4Soil https://www.best4soil.eu/database.

Table 2
Clusters of entities emerging from the LLs' participatory mapping of agri-forestry and rural SCPS.

Social-entities	• **Public institutions and administrations** included their workforces, that firstly promulgate and then enforce rules and regulation at different territorial levels (European, national, regional, and local). They are often also responsible for financing the provision of public services (such as health, education, research, social services), initiatives of public interests from private companies (by means of European Structural and Investments funds and similar). • **Primary economic actors**, such as farmers and forest entrepreneurs carrying out farming, livestock and forestry (including their organisational arrangements, such as cooperatives, network, etc., and their associations) and workforces employed in these activities in rural areas, which use (material and immaterial) inputs to produce/provides goods (food, timber) and services (agritourism, ecosystem services). • **Other business** actors, such as input providers, banks, consultants, processors, and manufacturers (e.g., sawmill), retailers, restaurants, hotels and so on. • **Consumers in broad terms (including clients, end-users, and tourists)** that buy agri-food and forestry products and benefit of local services, facilities, and infrastructures in rural and internal areas. • **Civil society**, which includes **resident communities** stimulating public debate and collective actions and initiatives at local level as well as associations, environmental organisations, action committees, journalists and NGOs that animate rural and internal areas and small villages, thanks to bottom-up initiatives (e.g., Local Action Groups).
Cyber-entities	• **Connectivity**, either fixed or mobile, which are infrastructures providing internet services (e.g., fiber-optic network, WAN network, fiber broadband, 5G) also in peripheral and mountain areas such as Sigfox antennas. • **Social media and social network** (Facebook, Twitter, and so on), including messaging platforms (WhatsApp and similar), collaborating tools such as Agricommunity, Cerdys, Miro, Loomio, Only Office, etc., traditional email and video conferencing platforms for interaction (Zoom, Teams, GMeet, Jitzi, Zoom etc.) as well as specific Apps/software used for traceability, communication (Smoke Sense for firefighting, DorfFunk to connect digital villages in rural areas in Germany, La Era Rural to boost young entrepreneurship in Spain, and the Oosterwold platform to foster online transactions not only related to agri-food products in The Netherland), logistics, resource sharing and commercial and promotional activities (advertising, purchasing group). • **Web-based technologies,** IT portals, digital platforms and Apps to facilitate transactions, like accessing online public and private services (e-government tool such as E-loket in Flanders region and website of the municipal administration in Rhineland-Palatinate, the Intrastat and the specific Conlegno portal in the forestry sector in Italy, e-commerce tools such as QR codes or online marketplace in France, Latvia and Ireland, e-booking, weed and plot management, GIS services, data exchange, fires detections) or where data and information are safely stored in digital format (e.g. DJustconnect in Belgium and bg-aktuell.de in Germany). • **Autonomous systems, robots,** such as automated field work in fruit production in the Lake Constance region, Naio technologies, autonomous tractor without cabin and milking systems in France, weeding robot in Swiss organic vegetable farming or Remote Piloting Aircraft Systems, that allow for the management of production or drive fire attack strategy thanks to real-time large sets flows of data and information, as well as **drones** embodying proxy-detection for plant diseases and weed control; • **Cloud/edge computing**, for remotely storing resources and data in collaborative digital tools (such as Gdrive, Dropbox, Gdocs, OnlyOffice, SOBLOO, etc.). • **Remote sensing**, which allows for the capture of data from different sources (satellites and manned or unmanned aircraft, such as MODIS, Landsat) providing an enormous amount of information on the environmental, climatological and topographical conditions (such as digital mapping techniques for pest risk management in the LL FR Inno'vin, REDIAM in the Andalusia region containing relevant environmental information and humidity-irrigation sensors), as well as on water metering and diseases detection thanks to satellite imagery or machinery, in order to manage crop production or livestock (e.g. sensors on air scrubber in Flanders region, captors for cows to measure their health and wellbeing and tracking chip for flocks herds). Moreover, it can also provide accurate assessments of fire severity, offering valuable information for the design of restoration plans adapted to the real impact of the fire on the natural environment • **Data analytics software,** like search engines or predicting algorithms, used to collect and process **big data** and provide decision making tools (e.g. Loomio, Djustconnect, etc.) for several purposes (real-time production monitoring systems, computer-controlled climate management and watering systems as well as managing phytosanitary treatments and irrigation in France). • **Artificial intelligence and IoT** (e.g. machine learning), used to transform large amount of data into information for farming machinery, monitoring (e.g., IoT based smart water metering systems, GrainSense to analyse protein, moisture, carbohydrates and oil contents from crops) and building tools (e.g. digital callipers, laser levels).
Physical-entities	• **natural environment and its resources**, such as soil, air and water, raw materials, livestock and their emissions, forests, fields. • **climatic conditions**, affecting both production patterns (of crops, livestock, and timber) and living conditions of local population (e.g., fire, droughts, floods) in rural and mountain areas. • **material infrastructures** in rural and mountain areas, that include roads, pump stations, roads, power line, etc. as well as public facilities (offices, hospitals, schools, and so on). • **factories, firms** and their **equipment, physical investments, inputs,** that are used in farming, forestry, and related activities (e.g., animals, seeds, plants, fuels, tractors, sawmills, machineries, pesticides, offices, agritourism farms, solar panels for energy sourcing and so on) as well as their **final outputs and by-products**.

types of needs. For instance, the raising demand among farmers and consumers to trade food via online selling platforms (digital need) was positively correlated with the need to optimise food chain transactions, reduce food waste, and capture higher added value (development need). However, embarking on online food platforms (digital need) was also considered in tension with the (development) need to reduce farmers' workload (i.e. more time to be spent on website management) and the importance of maintaining informal social ties and on-spot knowledge exchanges in weekly farmers' markets that go beyond a consumerist or standardised transaction-based relationship.

4.2.4. Digitalisation as mediator between socio-physical relationships

Relationships have been the subject of extensive sociological investigations for a considerable time (Dépelteau, 2018), including in the field of digital sociology (Orton-Johnson and Prior, 2013) and digital agriculture (Driessen and Heutinck, 2014; Klerkx et al., 2019). Previous transdisciplinary analysis of relationships showed how digitalisation can influence the level of actors' vertical or horizontal integration in agri-food chains (Moreno-Miranda and Dries, 2022), farmers' social agency and self-identity (Riley and Robertson, 2021), or more general aspects like trust, reciprocity, solidarity.

LLs' visualisation and analysis of SCPS at least hint that the quality of interactions within and between socio and physical worlds is changing with the mediation of cyber entities, for instance in terms of coordination, control, predictability. As reported by the LL Toscana Nord dealing with the inclusion of farmers in ordinary land management (protecting against landslide, monitoring risks, alerting regarding damages, and requests for public interventions), previously loosely connected or bilaterally connected actors (e.g. farmers-authorities vs authorities-service operators) are gradually merging into a broader network coordinating relations and activities between physical resources (forests, forestry infrastructures) and social entities like farmers, agricultural cooperatives, local associations, public authorities, and operative bodies.

Over the years, scattered relationships are merging into an evolving and integrated system (the Toscana Nord Reclamation Consortium) mediated by a variety of data-driven communication tools (e.g., Software web-GIS, instant messaging platforms, GPS devices, databases). Ultimately, their interactions become governed by defined rules, skills, procedures, and standards to execute, control, and predict the results of a specific array of functions and activities, like alarming landslides and dealing with the reparation steps.

With the growing presence and use of digitalisation in agricultural systems, LLs observed that new relationships can be created, but existing

Table 3
Cyber-entities involved in on-farm diversification's socio-cyber-physical systems.

Digital technologies
• Online selling platforms and software (e.g., Gasdotto.net for Solidarity Purchasing Groups in Italy). • Farm Accountability software • Online booking channels for farm accommodation (e.g., ORC, a tool to manage multiple farm bookings) • Online banking, payment systems & devices for point of sales • E-governance platforms (e.g., transmitting permissions, downloading certificates) • Tourism and cultural event platforms • Online maps for geolocation and business registration • Social media and analytics • Farm photo gallery • Instant messaging platforms • Collaborative working platforms (e.g., cloud storing, project software) • Canvas software to produce flyers, leaflets, promotions.
Digital tasks
• Scanning, storing, sharing (documents, images, ideas) • Classifying (transactions, clients, products) • Tracing (orders, visits) • Visualising (images, stories) • Geotagging (businesses, touristic points) • Detecting (free riding behaviours, financial loss) • Managing remotely (e.g., collaborative teams via online platforms) • E-learning (complementing audio-visual to on-spot farmer trainings). • Optimising (reducing errors in booking transactions, online orders) • Recommending (memberships fees, new products, services) • Evaluating (dealing with consumer reviews on social media) • Protecting (data protection from cyber-attacks) • Troubleshooting (repairing software or hardware damages) • Digital planning (envisaging a digital strategy with clear objectives and ethical considerations).
Digital infrastructures
• Internet connectivity (speed, stability, price, coverage) • Computer and ergonomics • Mobile devices (smart phone) • Electronic cash registers • Monthly membership fees (shared clouds, advance social media features, collaborative platforms)

ones can also be altered, dismantled, or preserved. For example, in various LLs, digital maps and geo-localisation services were commonly cited examples of general-purpose technologies and skills that are influencing the connections between objects and people depending on the specific context and practice under study. With the advancements in geo-localisation, the LLs dealing with on-farm diversification activities found that tourists, students, or citizens have another (digital) option to discover and reach out to agritourism initiatives or on-farm markets located in remote areas, instead of relying on personal or orally transferred recommends.

Asynchronous interactions like transferring and acquiring information about the quality of farm services or products can happen online, via web commentaries between unknown people, as well as offline with the possibility to establish direct contacts with farmers. In some cases, interviewed farmers were not even aware of positive reviews or negative allegations left on their web account. This suggests that in digital agriculture, farmers are required to build and manage a coherent public and private profile between the virtual and real worlds, as indicated also by previous studies on social media hype around agri-food activism, scandals, and conflicts (Stevens et al., 2018). In other cases, farmers mentioned that reading or intervening in online conversations and social media avenues has become a new established task (e.g., online customers relationship management) but allowed them to take part of confidential exchanges traditionally confined to face-to-face, on-spot meetings.

To take another example in the livestock farming, sensors and digital control systems like the automatic robot milking are increasingly applied to mediate farmers-animals interactions like feeding, milking, health control. Several authors already reported on the effects brought about by smart farming technologies on the farmers-cows relationships (e.g., Driessen and Heutinck, 2014; Eastwood et al., 2019). Farmers are affected in terms of work welfare or professional identity, whereas cows can experience changes on their freedom of movement and physical environment (Driessen and Heutinck, 2014). Similarly, in our empirical analysis, we found that when it comes to social farming or educational activities in agriculture, the direct, on-spot, human-animal or human-plant interaction is a part of delicate relationship to maintain, and farmers tend to refrain from applying digital layers that can potentially detach and undermine the instrumental role played by animals and plants, including for rehabilitation, reconnection, building self-confidence, and reducing psychological stress.

As found out by the LLs dealing with fruit production around the Lake of Constance (Germany) and Bordeaux (France), farmers' relationships with farm advisors are also changing, in some cases even becoming obsolete when specialised skills and knowledge are transmitted or acquired online (e.g., input prices, plant disease diagnosis, etc.). On the contrary, the French LL Inno'vin showed how mobile applications like agricommunity.fr can reinforce this relationship by providing a collaborative tool to share observations on plant health among farmers and advisory. In line with previous research in the field of agricultural knowledge and advice (Fielke et al., 2020; Rijswijk et al., 2019), the two LLs noted how more digitalisation increases the need for advisors to adapt their services and skillsets to 'smart farmers', with new demands for interpreting technologically-driven decision-making tools, filtering the abundancy of online information, and helping to make

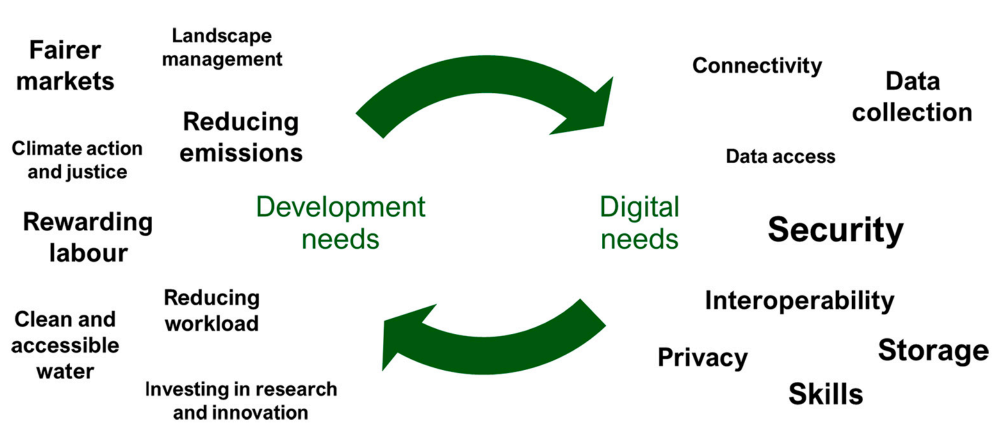

Fig. 6. Increasing loops between development and digital needs as emerged by the Living Labs' assessments.

sense (digest) of online information overload (videos, product advertisements, press & media).

4.3. Understanding the impacts of digitalisation

From our cross-comparison among LLs, digitalisation impacts emerged as multiple and interrelated. For a specific focal question, we found that this transformation is progressing at different levels (equipment machineries, organisations, people's skills) and often encompasses a bundle of connected or disconnected digital technologies, skills, infrastructures, rather than just one single cyber-entity. The direct consequences of digitalisation in one area spill over a wider range of complementary matters besides, going from energy to public governance, value chain distribution, animal well-being, risk management, equity, and social right, just to name a few examples. This view is in line with previous studies comparing the impacts of digitalisation (Berkhout and Hertin, 2004; Rolandi et al., 2021) and implies that the technical performances of digital innovations, like increasing efficiency in food supply chain (Eder and Ivanov, 2019) or livestock management (Kozina and Semkiv, 2020), spill over into other socio-economic, governance and environmental areas (Berkhout and Hertin, 2004; Herrero et al., 2021; Smith et al., 2021).

Even when LLs identified specific impacts closely related to technical performance measurements, like efficiency and effectiveness, we found positive and negative interrelations between them. *Efficiency* gains like saving time, streamlining procedures, or rationalising complex network interactions were influencing the *effectiveness* aspects, such as the accomplishment (or not) of a goal, activity, job, service. For instance, in the Croatian LL, the proliferation of online platforms to increase direct selling opportunities towards tourists or geographically disperse customers (effectiveness) was intimately linked to more time, training, knowledge, workload, and logistics resources that did not always contribute to significant improvements in the revenue/cost ratio for the farmers (efficiency), at least in the short-run period. This points to the presence of trade-offs emerging in different socio-physical entities, relationships, or activities impacted by the integration with cyber-entities.

By looking at the unstructured impacts reported across the 21 LLs, we observed four main typologies or clusters of impacts that can help to spot and understand the ex-post consequences, but also anticipate the potential effects of digitalisation in agriculture, forestry, and rural areas (Fig. 7). Further enactment and operationalisation of these proposals is a key step for future research.

Starting from situations were digitalisation had zero or minimal impacts at micro-scale (e.g., technologies were still in the piloting phases), in each specific context, our comparison of LL assessments indicate that digitalisation can impact socio-physical systems via:

- **Boosting impacts** refer to efficiency improvements of existing activities, for instance in terms of better resource allocation, time savings, higher precision, or output/input ratio.
- **Depleting impacts** refer to efficiency worsening of existing activities, for instance correlated to digitally enabled activities that increases the consumption of material resources, energy, repairing and maintenance costs, and production of waste disposal of digital devices or smart machinery.
- **Enabling impacts** refer to the creation of new activities, products and services that serve a specific function or a given goal, as well as the ability offered by digital skills or technologies to do things and achieve objectives which otherwise were not achieved in that specific context.
- **Disenabling impacts** refer to the dismantling of existing activities, entities, or relationships that serve a specific function or are used to achieve a given goal, making them obsolete or force to leave, stop, change location.

Table 4 presents some specific examples of impacts as reported by the LLs dealing with digital agriculture. By using these insights, we reach similar observations and expand previous studies (e.g., Marinoudi et al., 2019; Rotz et al., 2019) that seek to explore the complex tensions, rebound effects (Sears et al., 2018), and complementarities among multiple impacts, rather than juxtaposing the positive and negative effects of digitalisation. In the vein of the RRI approach, our findings raise complexity-aware evaluation questions that look at system dynamics like: *Do the efficiency gains of a digitalised farming system lead to effective reduction of agricultural input use and costs at level of farm, sector, or region, and how? Which social norms or values ("rural codes") are lost or must adapt to newly established data-driven practices and transactions in agriculture and rural areas?*

4.4. The nexus between digitalisation and societal expectations on SDGs

Disentangling the impacts of digitalisation from other contributing factors (e.g. level of education), and measuring its exact contribution towards the achievement of quantitative target indicators raises its own challenges and constraints (Bamberger et al., 2019; OECD, 2016). In our experience, the SDG framework served to focus the attention of the LL stakeholders on the positive and negative convergence between digitalisation and all the sustainability dimensions, whose nexus remains still understudied (Del Río Castro et al., 2021; Herrero et al., 2021). In this attempt, Fig. 8 displays the positive and negative links identified by the LLs stakeholders in relation to the 17 SDGs. Two main observations emerged from this qualitative exercise.

Firstly, studying the links with all 17 SDGs is possible and promising, but it is an exercise that requires facilitation efforts, time, and resources to explain the benefits and to motivate all stakeholders in this endeavour. Secondly, not all SDGs were considered relevant for the LLs' focal questions (Fig. 8), which left some sustainability areas poorly explored (especially gender, climate action, life below water).

Environmental issues related SDGs like SDG 6 (Clean Water), SDG 7 (Affordable and clean energy), SDG 13 (Climate Action), SDG 14 (Life below water), SDG 15 (Life on Land) were among those with the least number of links and explanations provided by the LLs in their respective focal questions. However, most of the links unpacked by LLs stakeholders covered mainly socio-economic goals, like SDG 8 (Decent work and economic growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 10 (Reduced inequalities), and SDG 12 (Responsible consumption and reproduction). SDGs 8, 9, and 12 were also among those with the highest number of both positive and negative links. When looking at the explanations provided by the LLs, we observed the presence of trade-off effects and negative externalities within the same and other SDGs, e.g., with SDG 3 (Good health and well-being), SDG 4 (Quality of education), SDG 10 (Reduced inequalities) and SDG 13 (Climate action).

To give an example of trade-offs, risk management tools like private insurance schemes are widely promoted by farmers unions and governmental organisations as a solution to ensure resilience and stable agricultural incomes in the context of climate change's threat. Following this line, digitalisation in risk management shall positively contribute to several SDGs (e.g., SDG 1 No poverty, SDG 8 Economic growth, etc.). However, LLs dealing with horticulture and fruit production noted that highly standardised software used by private risk insurance operators were not designed to include diversified polyculture in small-scale farms (e.g., 50 crop varieties rotating each year in less than 6 ha), nor was their algorithm able to assure crop production during the most critical moment of the production cycle (i.e., winter cold).

The designing features of digitally-provided insurance schemes (apps, software, and business model behind them) appeared to reflect a risk management approach going in favour of specialised farming systems, while excluding other complex agroecological systems better adapted to the biological cycles, climate risks, and embedded in diverse local food provision (i.e., negatively impacting on SDG 11 Sustainable cities and communities). On the other hand, LLs noted that access to internet, digital equipment and skills, and investments in soil

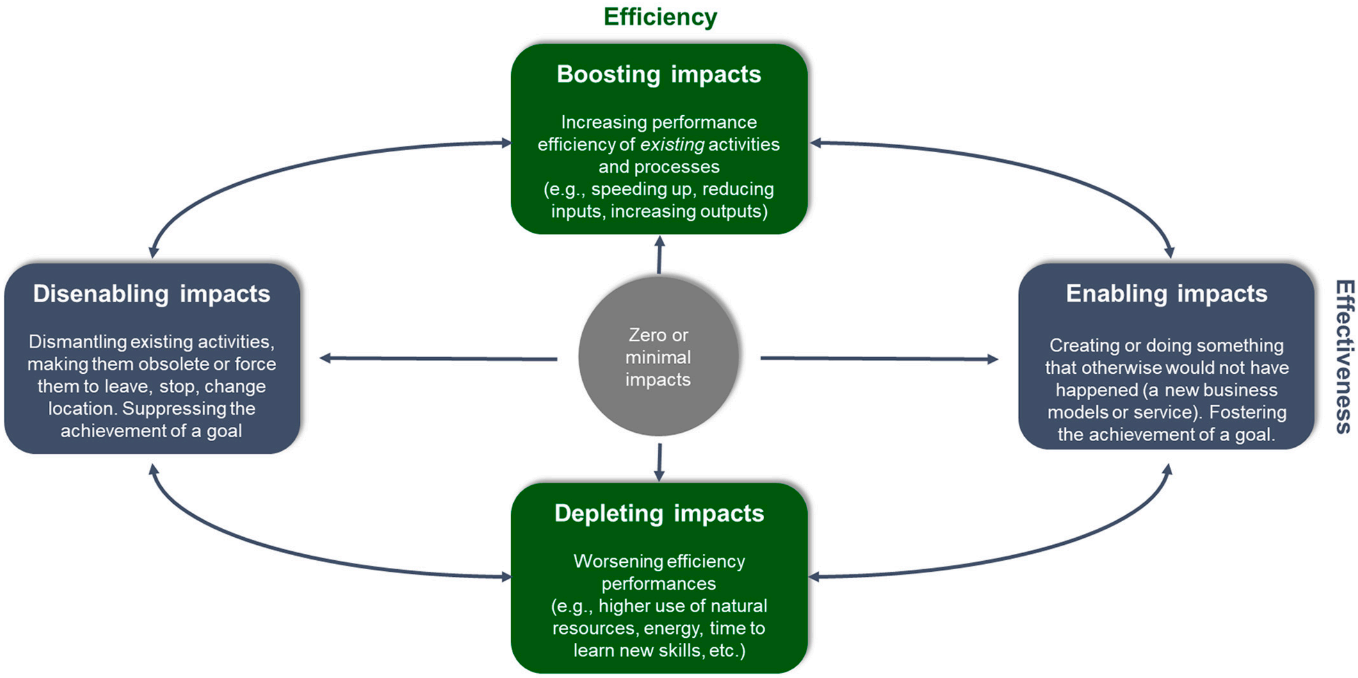

Fig. 7. Understanding the complex impacts of digitalisation in agriculture, forestry, and rural areas.

Table 4
Examples of enabling, disenabling, boosting and depleting impacts of digital agriculture.

Enabling impacts	Disenabling impacts
• Farmers can systematically track, monitor and control agro-environmental and productivity variables. • Remote holding assets can be guarded (surveillance). • Farmers can remotely and directly control marketing channels and business activities to capture higher added value from farming. • Farmers can pool their stock and assets with other farmers. • The poor appeal of labour-intense crop systems (horticultural production) is revamped and more attractive for young farmers.	• Small holders and mixed farmers are gradually displaced by specialised and competitive agri-tech corporations. • Workers and manual jobs are replaced by increased automation and mechanisation. • Farmers can be discouraged to undertake higher costs and risks for more ethical and environmentally sensitive farming when these can be accused or denigrated through online, uncontrolled digital media. • The on-spot and rich experience between agricultural farms, nature, and community can be eroded or homogenised by increased connectivity and digital mediation of the countryside life.
Boosting impacts	**Depleting impacts**
• Labour productivity and field-work welfare are increased. • Quality controls, management decisions, and traceability are optimised. • Inputs use is controlled (water, pesticides, fertilisers). • Business transactions are simplified and accelerated. • Predictability in business transactions is reduced, while risks for human errors are cut. • Resource use for direct sales is optimised (time, energy, and staff costs).	• Production costs for upgrading equipment and learning/training new skills are increased. • Farmers experience increased stress and mental tension for being constantly connected to digital devices and dealing with multiple and new digital tasks (e.g., customer relationships). • Primary producers and consumers miss the richness of social and cultural interactions in digitalised food markets and transactions. • Farmers' dependency on technology and external input providers is increased.

monitoring or plant disease recognition technologies are examples of digitally mediated options to reduce risks, by offering new on-farm and off-farm income opportunities for communities, farmers, business entrepreneurs in remote rural areas (positively impacting on SDG 1 No poverty).

Based on these insights, we learned that one of the added-value to use broader sustainability frameworks in concrete participatory settings was obtained when unpacking the links and nuances, instead of counting the links or qualitatively appraise the contributions to pre-established goals, unless the evaluation exercise is predominately concerned with accountability objectives (e.g., measuring the exact fulfilment of, or distance to pre-defined targets).

In our comparison, we also noted that the identified links between digitalisation and the SDGs were complex in the sense that they did not only depend on the digital technologies themselves. Certainly, the design features of digital technologies constituted a key factor in shaping the impacts and the distribution of the effects among winners, losers, opponents, and proponents behind the digital transformation. However, other socio-technical and political aspects were instrumental too. Based on these insights, we outline three contribution factors or pathways that can help explain how positive or negative impacts of digitalisation emerge and affect entities, relationships, activities, needs and expectations in agriculture, but also forestry and rural area's issues in general.

- **Design:** refers to any built-in properties and settings related to the digital technologies. Some examples of design features are the functionalities of digital tools (e.g., predicting, connecting, storing, sharing, filtering, comparing, collecting, matching, verifying), flexibility, adaptability, transferability, security, compliance with data protection regulation, scalability of data-driven network.
- **Access**: relates to the preliminary conditions to gain access to, and benefit from the use of, digital technologies. For instance, digital literacy and skills, ownership costs and rules, quality requirements for internet connectivity, opportunity cost for learning, easiness of mastery, purchasing capacity, and other socio-economic and geographical entries barriers in agriculture and rural areas.

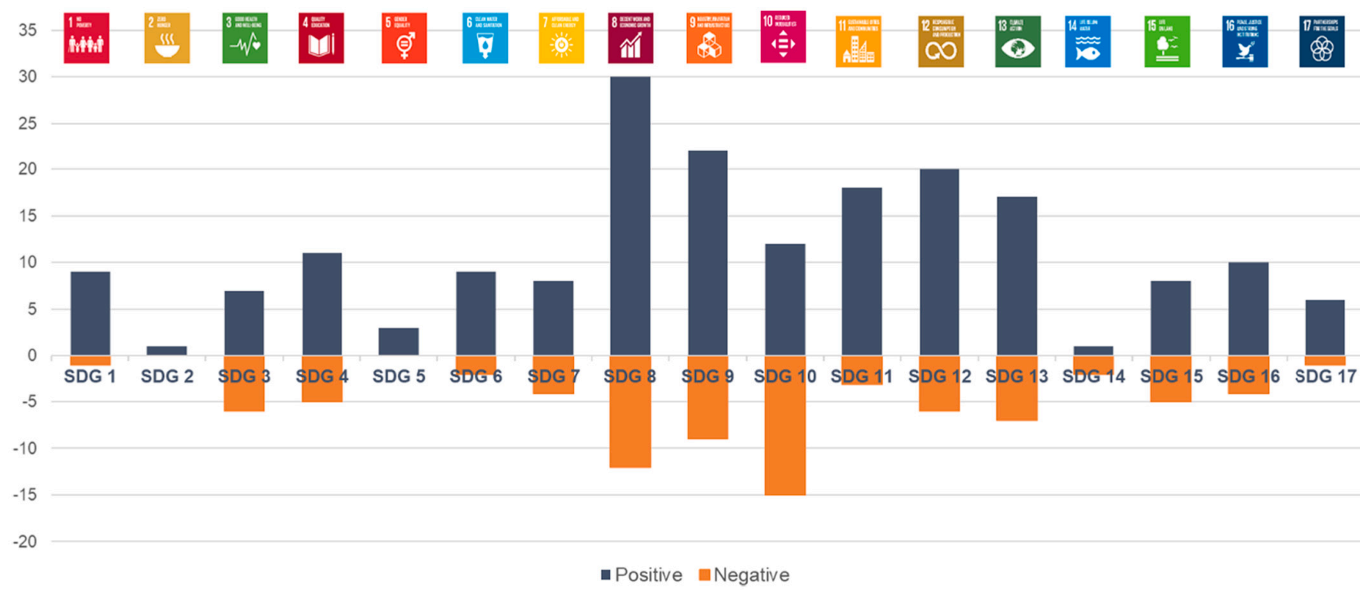

Fig. 8. Positive and negative links between digitalisation and SDGs as identified by the 21 DESIRA Living Labs.

- **System dynamics:** any aspects concerning the relations within the SCPS, or between the system and the broader context in which digitisation/digitalisation happen. For instance, in the LL assessments, these were the COVID-19 restrictions, policy incentives, market opportunities, regulatory framework, demography (e.g., aging population), level of education & entrepreneurial capacities.

These understandings can have implications on policy directions, suggesting that responsive actions to steer digitalisation in agriculture and rural areas need to take place at three, interconnected levels: technological design, access, and system dynamics. This holistic view would avoid the situation whereby investments and technological advancements in the design features of digitalisation remain disconnected from the conditions necessary to achieve desired goals and prevent the exacerbation of structured inequalities. From the evaluation point of view, these causal pathways bring the attention of both quantitative and qualitative impact assessments to the intersections between multiple contributing factors.

5. Discussion and conclusion

The purpose of this paper was to outline a framework to operationalise the concept of SCPS, in line with the RRI approach and SDGs. Therefore, we further elaborated on the concept of SCPS as introduced by Rijswijk et al. (2021) to facilitate an in-depth, participatory, and reflexive analyses of impacts at levels of system entities, relationships, and activities. These would include better targeted and more finely-tuned analyses of how specific target groups, type of connections, or process performances fare with versus without digitalisation, e.g., in terms of efficiency, displacement, or bearing the costs. Henceforth, we provide some concluding reflections on the utility of the framework and how it broadens earlier assessment frameworks. We also reflect on the limitation of this first tentative application of the SCPS concepts to LLs.

5.1. The utility of using the SCPS concepts in Living Labs to enhance anticipation and reflexivity

Our experience with connecting RRI dimensions and SCPS concepts shows that an integrated framework can be beneficial for participatory, exploratory-type of evaluations dealing with the complexity of digital transformation. However, flexibility is needed to meet the different objectives and circumstances of participatory settings, as well as to strike a balance between opening and narrowing down the system boundaries under analysis.

As regard the level of analysis, what emerged from our experience is that such a framework can be advantageously applied on sub-systems or single actors (e.g., the SCPS of a diversified farm), but it can be also easily scaled-up in multiple stages to build a broader system picture encompassing multiple stakeholders, experiences, and views (e.g., farm advisors, policy makers, insurance providers, consumers, cooperatives). This is beneficial for grounded, bottom-up evaluations that stimulate reflexivity at multiple levels (e.g., from local practices to national legal frameworks, market and technological regimes). More practically, it encourages the inclusion of those actors who are harder to reach out in certain working seasons or group thinking sessions (in line with Bronson, 2019; Smith et al., 2021).

By starting from a specific problem or opportunity, selected as subject of the LLs' focal question, we were able to understand how socio-cyber-physical entities have assembled and brought about changes at level of needs, entities, their relationships, and activities. The grounding of the assessment on specific needs and inclusive mission-oriented targets like the SDGs can offer a solution to overcome the researchers' own agency or broader interests of the institutions in which they operate, such as focusing exclusively on a pre-selected technology or potential digital game changer. More broadly, it can support enactment of digital transformation as part of 'mission-oriented agricultural innovation systems' (Klerkx and Begemann, 2020). This integrated approach was able to reveal how social actors combine a broader set of digital technologies and tasks to deal in a different way with agricultural activities, like on-farm diversification, farm advisory services, risk management and more. Furthermore, this framework helped us to understand how digital needs like learning new ICT skills or storing larger data volume can deviate, interact positively, or put further pressure on broader social and physical developmental needs.

In terms of timing, our framework provided sufficient flexibility to incorporate the RRI dimensions like inclusion and anticipation. By adding a timeline to the concept of SCPS (Rijswijk et al., 2021), we explicated the historicity, contingency, and evolutionary nature of SCPS, thus avoiding confusions between ex-ante, ongoing, and ex-post impact assessments and setting the ground for more synergies in longitudinal studies.

Time flexibility was also important when designing and implementing data collection tools. For instance, by switching the priority and chronological order of questions from cyber- to socio-physical subjects (e.g., governance issues in natural resources, animal welfare), certain actors with a lack of self-confidence in their digital literacy and capacities felt more comfortable to start a deeper socio-technical reflection on their own role in digitalisation and its impacts.

Still, in terms of time and research workload, the preliminary analytical tools and steps used before the actual impact assessments (like setting focal questions, mobilising stakeholders, assessing needs, analysing the contexts, or mapping the SCPS) required multiple reflexive rounds among stakeholders. For many LLs, studying the context and visualising the multiple relationships and entities was a learning journey that helped having a better grasp of the big picture and facilitated in-depth discussions on specific issues at stake. However, this came at the costs of continuously updating the system or creating multiple versions to account for the contingencies and evolving dynamics, especially those triggered by the COVID-19 lockdown.

Therefore, if LLs are equipped to flexibly tailor the research terminologies and tools for each stakeholder group, our framework has the potential of revealing unique and common threads among individual stakeholders, identify areas of agreements, tensions and synergies, and sketch out a bigger picture to foster collective learning and steer digitalisation in multiple, interlinked steps, e.g., from past to present and future digitalisation impacts. At the same time, this framework can also provide valuable insights to configurational research or geography studies interested in how entities and contingent events interact and assemble (or dis-assemble) relations to perform functions within, between, and outside the SCPSs (see e.g. Anderson et al., 2012; Gorman, 2016; Kohtamäki et al., 2019; Veidal and Flaten, 2014).

To leverage the potential utility of the framework, this paper underscores the importance of setting up experienced multi-stakeholder platforms, which in this case were helpful in bridging technical and socio-political knowledge in the field of digitalisation. To accomplish RRI-proofed evaluations based on system thinking that stretches beyond cyber-physical boundaries (Verdouw et al., 2021), LLs not only need to be equipped with transdisciplinary knowledge (Schwarz et al., 2021), but also with adequate resources and facilitation techniques to reach out actors and embrace topics from a wide range of fields. To steer digitalisation towards desirable societal needs, particular attention must be paid also on the organisational structure, political legitimacy, conflict of interests, and governance abilities of multi-stakeholder platforms to integrate participatory assessments and findings into fast-changing policy windows, technological developments, societal debates, and investments (Ferrari et al., 2022; Kaplan et al., 2021; Patton, 2008).

5.2. The distinction between enabling, disenabling, boosting and depleting impacts of digital agriculture

Our comparison of the impacts emerging from the 21 ex-post assessments outlines concepts to guide the identification of direct and indirect effects of digitalisation on the basis of different evaluation criteria, like effectiveness, efficiency, relevance towards needs, coherence towards societal expectations. In our analysis, digitalisation simultaneously enable and disenable activities in agriculture and rural areas, with consequences on individual entities and configuration of relationships. The consequences on the dismantling of existing activities, entities and relationship (disenabling) as well as the effective realisation of new activities and goals (enabling) are also connected with efficiency transformations in terms of boosting and depleting effects. The fact that digitalisation can generate new trade-offs in sustainability issues, but can also resolve existing ones, acknowledges the complexity of these system changes, whose net outcomes are hard to measure (Ciliberti et al., 2022; Schnebelin et al., 2021; Zhang et al., 2021) or might be different compared to what is expected (e.g., absolute reduction of chemical pesticides, generational renewal, higher labour remuneration).

These findings corroborate previous research warning on the side effects of digital innovations on, for example, labour, natural resources, energy, relationships (Berkhout and Hertin, 2004; Orton-Johnson and Prior, 2013; Rotz et al., 2019; Scholz et al., 2018), and those more specifically of those related to digital agriculture (Daum, 2021; Herrero et al., 2021; Macpherson et al., 2022; Prause et al., 2021; Rose et al., 2021). We however sharpen earlier assessments, going beyond a pessimistic or optimistic dichotomy associated to digitalisation (Daum, 2021), by specifying effects and trade-offs in terms of enabling, disenabling, boosting and depleting impacts of digital agriculture, forestry and rural areas. Leveraging on these concepts and observations, this paper contributed to the existing body of literature aiming to explain, classify, and anticipate the consequences of digitalisation (Martin et al., 2022). Our concepts might be used to interpret general mechanisms by which digitalisation can (positively or negatively, and with different intensity) influence multiple sustainability domains and areas of impacts (Rolandi et al., 2021) or to anticipate the emerging trade-offs to achieve the Sustainable Development Goals (Herrero et al., 2021). Besides contributing to future empirical work, they can be used also to reflect on the meaning of new and established social theories relevant for digital agriculture, like creative destruction (Schumpeter, 1976), Jevons's paradox and rebound effects (Sears et al., 2018), or more largely, Weberian theories of rationalisation and bureaucracy processes associated with capitalism and modernity in agriculture and rural areas (Weber et al., 1947).

Additionally, the framework allowed to identify key conditions to keep in view of steering digitalisation towards sustainability (Rijswijk et al., 2021), namely design, access, and system dynamics. By equally considering these three conditions, we added special considerations on issues of accessibility (e.g., digital literacy and skills, internet connectivity, opportunity cost for learning), thus extending beyond the socio-economic and technological factors proposed by Herrero et al. (2021) to explain the impact pathways and trade-offs of digitalisation towards the achievement of SDGs. Meanwhile, this allows for deeper scrutiny of the intrinsic technological attributes, rules, and functionalities of complex agroecological systems and rural dynamics that will require additional orchestrating efforts.

5.3. Limitations of the framework and future research

In applying our integrated framework with the LLs, we recognised three sources of methodological biases. The first one lays in the setting up of the LLs' focal questions. Although LLs were encouraged to frame and refine the questions in different rounds with engaged stakeholders and following the guidelines outlined in this paper, this initial step could still be subject to the LLs' own research agency or preliminary funding agreements; whereby this step might have influenced the following decisions on inclusion, exclusion, or research priorities. Another source of bias can result from the composition and nature of the LLs (e.g., non-profit community organisation, research institutes, private organisations), and the type of stakeholders they engaged with. Finally, especially during the COVID-19 circumstances, the digital tools used to collect primary data might have influenced the selection or the outcomes of stakeholders engagements (e.g., online focus group discussion, online interviews, online surveys).

Conceptually, while the proposed framework aims to be comprehensive and open to emerging socio-cyber-physical interactions, we noted that our participatory impact assessments struggled with the complexity and multiple dimensions of the research topics. As outcome, some sustainability goals or aspects, particularly gender and environment, were often overlooked or underweighted. In other cases, they required more statistics at local administrative levels or evidence based on strong scientific rigor. As suggested by Mulrow et al. (2021), accounting for the environmental impact of digitalisation is not only a matter of multi-stakeholder platforms being conscious about the materiality and ecological dimensions, but also about the availability of statistics and well-modelled quantitative assessments that support fact-based scenario analyses, while recognising also the inherent difficulties in conducting holistic, quantitative environmental assessments. Therefore, we call on for more *ad-hoc* research on minority and gender dynamics in digital agriculture, as well as research efforts to support participatory assessments with increased information and understanding of the environmental dependencies, costs, and impacts of stand-alone and combined digital technologies.

Among other limitations in relation to the RRI approach, we learned that being sensitive to multiple views, ethical concerns, and unexpected consequences of digitalisation does not necessarily mean that multi-stakeholder platforms and their surrounding institutional constellations are ultimately prone or equipped with strong tools to steer digitalisation, or at least we were not able to report here some concrete examples of follow-up actions taken by the LLs. Therefore, besides offering a deeper understanding of the dynamics and issues at stake, this paper invites future research to investigate and share lessons on strategies, bottlenecks, and tips to achieve responsiveness in different real-life innovation settings committed to responsible digitalisation, extending earlier studies by Kernecker et al. (2021) and Smith et al. (2021). We are however confident that the developed analytical tools, social interactions, and dialogues underpinning the LLs research and facilitation efforts, although we could not report them extensively here, they still set the bases for raising awareness and building collective action-oriented capacity to steer digitalisation.

Finally, even though the scope of the paper was mainly exploratory rather than to test a pre-defined set of hypotheses or provide robust quantification of digitalisation impacts, this framework is limited to qualitative examination at micro- and macro-level. We believe that its contribution can strongly benefit from complementary qualitative and quantitative assessments, especially in relation to how great the net enabling effects are compared to disenabling ones, how single technology efficiency gains at micro-level lead to rebound effects and increased macro-level use of external inputs in digital agriculture (Pohl and Finkbeiner, 2017), or whether the short term efficiency loss expressed here as depleting effects will be finally overcome by efficiency gains in the long-run period, and vice-versa. At the same time, we call for further application of this integrated framework across different contexts, especially to unveil the re-organisation of relationships and work, and the deeper transformations of norms, rules, identities, knowledge in agriculture, forestry, and rural areas.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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