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Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation

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ABSTRACT

Digital technologies are often seen as an opportunity to enable sustainable futures in agriculture and rural areas. However, this digital transformation process is not inherently good as it impacts on many aspects (e.g. economic, environmental, social, technological, institutional) and their relations. The responsible research and innovation approach calls for a better understanding and anticipation of the often unknown impacts. To meet this aim we have developed a framework that allows to gain insight on the relations between the social, the cyber and the physical, i.e. a socio-cyber-physical system and have described conditions for a successful digital transformation of such a system. These are design of, and creating access to digital technologies, and navigating system complexity. This framework allows for a better problematisation of digital transformation and has been illustrated through an example of digital dairy farming. It supports an enhanced understanding of moral responsibilities regarding digital transformation, fitting within the responsible research and innovation approach, as well as a better understanding who is responsible or accountable for the identified (positive or negative) impacts, i.e. responsibilisation.

1. Introduction

Digital transformation in agriculture and rural areas is a policy priority at global level (Trendov et al., 2019; World Bank, 2017, 2019). In Europe, the European Commission set out as one of its objectives “fully connecting farmers and the countryside to the digital economy” in order to achieve a smarter, modern and sustainable future of food and farming (European Commission, 2017, p. 7). This was followed by the Green Deal in which digital technologies are considered “a critical enabler for attaining the sustainability goals of the Green Deal in many different sectors” (European Commission, 2019, p. 7), and in 2020 the Farm to Fork strategy indicates that “the CAP [Common Agricultural Policy] must also increasingly facilitate investment support to improve the resilience and accelerate the green and digital transformation of farms“ (European Commission, 2020, p. 16).

Digital transformation comprises a spectrum of activities, encompassing both digitisation and digitalisation. *Digitisation* can be described as the “technical conversion of analogue information into digital form” (Autio, 2017, p. 1) p. 1), while *digitalisation* is the term often used to describe the socio-technical processes surrounding the use of (a large variety of) digital technologies that have an impact on social and institutional contexts (Tilson et al., 2010). Digitalisation goes beyond the level of a single business or entity, linking on- and off farm data and managements tasks, which are enhanced by context- and situation awareness and triggered by real-time events (Rose and Chilvers, 2018; Wolfert et al., 2014). Digital transformation is thus a process whereby

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over time the options of digital technology use, the associated complexity (i.e. interactions between the various aspects of a system, such as (digital) technologies; institutions; organisations; people; and the environment) and their related impacts on society, either positive or negative, increase (Vial, 2019).

Many consider digital transformation as the solution to the challenges that agriculture and rural areas face (Trendov et al., 2019; World Bank, 2019), as part of a transition towards 'Agriculture 4.0' (Klerkx and Rose, 2020) contributing to agrifood systems transformation (Herrero et al., 2021; Klerkx and Begemann, 2020). However, lessons learned from past technological revolutions suggest caution (Bronson, 2019b; Eastwood et al., 2019a), as (agricultural and rural) innovation is not an inherently good and value free process, but normatively laden and driven by different worldviews and visions. Correspondingly, different development directions exist, each with its own winners and losers (Brooks and Loevinsohn, 2011; Klerkx et al., 2012; Thompson and Scoones, 2009; Vanloqueren and Baret, 2009) and trade-offs (Herrero et al., 2021), also in relation to digital transformation (Cowie et al., 2020; Klerkx and Rose, 2020; Lajoie-O'Malley et al., 2020). Current digital technologies may have several undesirable, unseen and unknown impacts, e.g. emergent effects that only become clear once these technologies are brought into practice (Klerkx and Rose, 2020; Pansera et al., 2019; Scholz et al., 2018). It has for example been argued that instead of transforming agriculture and rural areas, digital technologies reinforce current systems which are deemed unsustainable economically, socially and ecologically and favour incumbent large players (Clapp and Ruder, 2020; Cowie et al., 2020; Miles, 2019; Prause et al., 2020). Given the game-changing potential of digital technologies, strategies for digital transformation of agriculture and rural areas will therefore need to take the socio-economic conditions, that influence and are influenced by processes of digitisation and digitalisation, into account (Klerkx and Rose, 2020). Bearing in mind that different social and technological configurations, also referred to as 'socio-technical bundles (Barrett et al., 2020), may lead to a different distribution of impacts on stakeholders (Klerkx and Rose, 2020; Rotz et al., 2019a).

Hence, digital transformation in agriculture and rural areas comes with a range of (ethical) concerns, and therefore a growing number of authors has argued for a responsible research and innovation (RRI) approach to digital transformation in agriculture (Barrett and Rose, 2020; Bronson, 2018; 2019b; Eastwood et al., 2019b; Klerkx and Begemann, 2020; Lajoie-O'Malley et al., 2020; Rose and Chilvers, 2018; Rose et al., 2021; van der Burg et al., 2019) and rural areas, where Cowie et al. (2020) propose "responsible rural research and innovation" (RRRI) as a sub-field of RRI. RRI anticipates the impacts of innovation, reflects on and is responsive to its unintended, consequences (Bronson, 2018; Klerkx and Rose, 2020; Owen et al., 2012). Stilgoe et al. (2013) capture the RRI approach in four main principles: anticipation, inclusion, responsiveness and reflexivity.

While the RRI approach has often been suggested, application has however been limited, and is at best patchy. For example, Eastwood et al. (2019a) found that innovations around smart farming have focused on technological development and on-farm use without taking socio-ethical implications into account. Several other authors indicated that the RRI approach also fails to engage certain agrifood system actors (e.g. citizens, consumers, other rights holders) in the innovation process (Bronson, 2015, 2018, 2019b; Eastwood et al., 2019a). It has also been argued that digital transformation processes are sometimes hard to grasp for stakeholders (Dufva and Dufva, 2018; Rijswijk et al., 2019), which may lead to a limited readiness to innovate responsibly (Eastwood et al., 2019a). Blok and Lemmens (2015) indicate that practical applicability of RRI is problematic and requires a more thorough examination of RRI, because of a mismatch between the ideal of responsibility and the realities of existing innovation processes. This also requires capacity building of actors such as researchers (Eastwood et al., 2019b; Regan, 2021), and tools to support them in these efforts. To deal with these issues that affect satisfactory enactment of RRI, a comprehensive framework is needed that guides the (upfront) assessment of the impact of digital transformation processes in agriculture and rural areas, thus supporting the ability to undertake digital transformation in a responsible manner. Rose and Chilvers (2018) therefore call for: 1) a more systemic approach to map innovations associated with digitalisation of agriculture; 2) broadening of notions of inclusion in RRI in order to include a diversity of participants; and 3) testing responsible innovation frameworks in practice to estimate if innovation processes can be made more socially responsible, in order to make RRI more relevant and robust for upcoming agri-technology. In this article, we focus mainly on the first element of Rose and Chilvers' (2018) proposal, informing a more systemic approach to map innovations associated with the digital transformation of agriculture and rural areas, in connection with the second element, informing who is responsible for what and should be included in RRI.

We aim to support an RRI approach in building strategies for digital transformation in agriculture and rural areas, by instilling what Maye et al. (2019) have dubbed as responsibilisation, a concept which has close links with the notion of responsibility which is central in RRI. *Responsibility* has a double meaning, on one hand there is ex-ante, or normative, responsibility, which is about behavioural standards that on the basis of current knowledge allow for minimization of risks. This has mainly to do with moral duties and moral sanctions. On the other hand there is ex-post responsibility, i.e. the duty of actors to respond to undesired or unintended consequences of technologies or behaviour. This second meaning is much nearer to the concept of accountability, and can even be subject to sanctions. This also implies a cognitive link between information, decisions, practices, and their outcomes. However, if it is impossible to know, even with uncertainty, what the effects of one's choices are, it is impossible to allocate responsibilities. *Responsibilisation* (see Fig. 1) then is a process whereby, in relation to the improvement of shared knowledge on the links between action and its consequences, behavioural standards for involved actors are developed and enforced through accounting mechanisms and sanctions. The process of responsibilisation is fed by problematisation, through which the community reflects on the ethical (or even the legal) standards related to a given innovation in relation to new or disclosed information and improved knowledge. Problematisation calls into question actors' behaviour and provides the grounds for the community to distribute ex-ante and, when a greater degree of information is available, ex-post responsibilities. In complex systems, responsibilities are distributed (Barnett et al., 2010), hence everybody bears a fraction of responsibility for the outcomes of the system. I.e. the greater the information one can get about the link between action and its consequences, the greater the possibility to

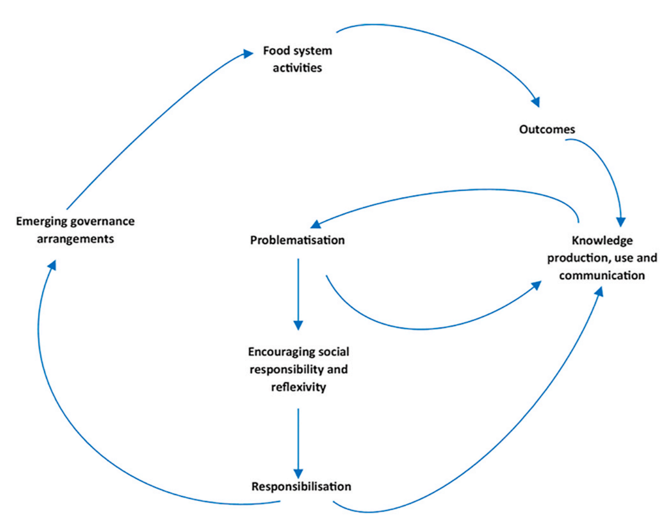

Fig. 1. The process of responsibilisation and its implications (Maye et al., 2019).

distribute responsibilities and to move from ex-ante to ex-post responsibility. In other words, responsibility is inherently linked to knowledge production, use and communication, but this requires a through and holistic understanding of the issues at hand. We therefore link responsibilisation is to the problematisation of effects of digital transformation of agriculture and more broadly rural areas.

In this article, we articulate a framework that supports the processes of problematisation and eventually responsibilisation, enhancing an understanding of systemic change linked to digital transformation, unravelling the multiple interactions created and affected by digital transformation in the context of agriculture and rural areas. Through the enrichment of the concept of 'cyber-physical systems', which has been forwarded as a way to understand the relationships between digital technologies and the environments they are embedded in (Klerkx et al, 2019; Lioutas et al., 2019; Wolfert et al., 2017), we aim to offer a way to sharper define problems and reflect on potential consequences of digitalisation. Processes of problematisation, as a part of RRI principles such as anticipation and reflexivity, can open new areas of responsibility and inform governance activities to shape future agriculture and food systems and other activities in rural areas.

The framework, developed within a project that aims to support the assessment and planning of digitalisation processes of agriculture and rural areas[1], aims at building a base for supporting participatory assessment, planning and design of digital transformation processes by offering a number of concepts to sharpen reflection on digital transformation and its potential impacts. This paper proceeds as follows: In the next section we will sketch a systems approach to digital transformation, introducing the concept of 'socio-cyber-physical system', also highlighting the conditions that create opportunities and threats to actors when exposed to digital transformation processes. Section three will illustrate the framework in the context of digital dairy farming, also showing the implications for responsibilsation. The fourth section will discuss research and policy issues and draw conclusions.

2. Unravelling socio-cyber-physical systems

Digital transformation can be considered systemic change, as it affects the way people, things and institutions coordinate themselves in order to perform their activities (Cowie et al., 2020; Klerkx and Rose, 2020; Nambisan et al., 2019). Digital transformation entangles digital, physical and social worlds through a multiplicity of technologies. We propose to study these entanglements using a systems approach. The nature of the systems referred to are hybrid, that is, relations among entities belong to both social and technical domains also encompassing biological and physical entities (and in this sense also connecting to concepts such as socio-ecological systems), which connects to recent discussions in rural sociology regarding a move to a 'more-than-human' approach (Legun and Henry, 2017) and a 'relational approach' (Darnhofer, 2020 ;) to transformative processes, and similar calls in agricultural innovation studies to better take into account materiality and biology (Berthet et al., 2018; Pigford et al., 2018).

As illustrated in Fig. 2, there is a range of concepts building on the idea of a system. Social scientists have developed the concept of *socio-technical system* to highlight that technology is embedded in social relations (Bijker, 1995; Hughes, 1987), and that there is a co-evolution between these domains (Kilelu et al., 2013). Scholars in technological disciplines have developed the concept of *cyber-physical system* to highlight the links between digital and physical entities in systems (such as agricultural systems, rural areas) wherein physical objects and processes are replaced, or complemented, by digital ones (Griffor et al., 2017). In this section we will briefly review the socio-technical system concepts that already connect social systems to technical systems (which may comprise physical and biological systems in our case), and will then propose the concept of *socio-cyber-physical system* as a heuristic tool to study the processes of digital transformation.

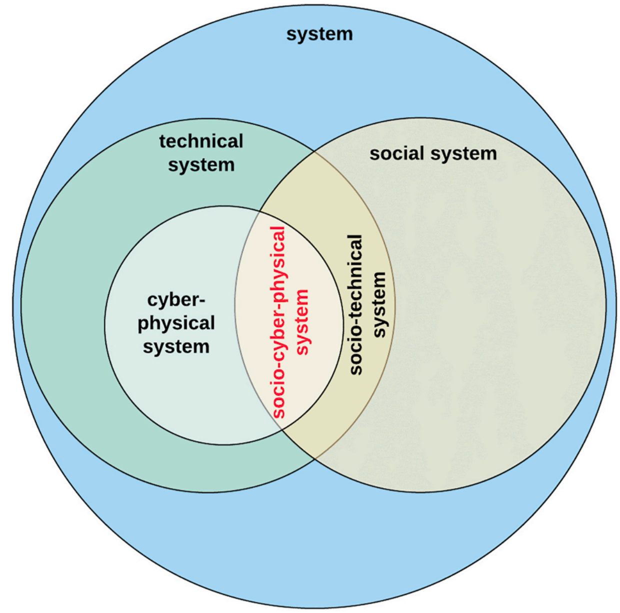

Fig. 2. Hierarchy of system concepts.

2.1. *Socio-technical systems*

A socio-technical system (Bijker, 1995; Hughes, 1987) refers both to the interrelatedness of social and technical aspects of an organisation or the society as a whole (Ropohl, 1999), whereby technology, besides material things, also includes organisational structures and processes (Botla and Kondur, 2018). Social actors that are part of the socio-technical system have different aims and interests among them, and are also endowed with varying levels of resources (knowledge, social capital, etc.). Furthermore, they hold different positions in society or in a specific organisation, and act according to varying routines, norms and social values. Additionally, some actors may hold a power position over others in which they, for example, can control the system's performance, influence other actors' activities, and restrict access to technology. At the same time, the use of new technologies or new regulations can also reset existing social asymmetries, depending on how socio-technical relations change the connections among technologies and social actors. Verbeek (2012), considers technologies as mediators between entities of a system, which play a constituting role on shaping the identities of the entities involved in the relation: they "help to constitute what means to be a human being" (Verbeek, 2012, p. 393).

2.2. *Socio-cyber-physical systems*

Digitalisation of socio-technical systems opens a new field of enquiry, given the nature and the characteristics of informational entities (Lioutas et al., 2019; Wolfert et al., 2017). In information science, *cyber-physical systems* (CPS) describe the mutual interaction between a *cyber domain* and the *physical domain* (Griffor et al., 2017). This implies the understanding of how digital information interacts with and transforms the physical world (which comprises both natural and manmade materialities). Digital technologies expand the world of artefacts as they disconnect reality from materiality (many of the practices we carry out have only informational content), location from presence (we can meet at distance, activate devices remotely, monitor behaviour at a distance), multiply the possible realities we can experience, and expand the time experience, expanding the multitasking possibilities (Floridi, 2014). Through for example digital twins, virtual replications of physical systems continuously updated by their twins' data (El Saddik, 2018; Pylianidis et al., 2021; Verdouw et al., 2021)), it is possible to predict harmful events in a physical system and intervene before the events

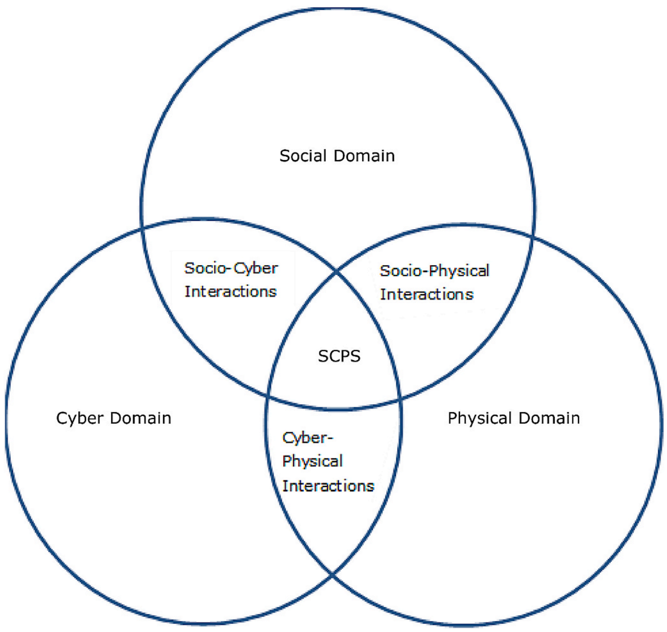

Fig. 3. The socio-cyber-physical system with related interactions based on the three domains (social, cyber and physical).

occur. Furthermore, there is a continuous exchange and integration of physical and informational objects (Floridi, 2014). Each time a digitisation event occurs, for example taking a photo with a digital camera, a part of the physical reality is replicated into the digital sphere. When a robot, a cyber-physical entity, acts upon the physical world, for example, a drone spraying a pesticide, it does it on the basis of the digital representation of the world it has. The efficacy of new generation robots, depends on the accuracy of the digital representation of the system upon which it acts. Given their storability, reproducibility and transmittability, data can be pooled with other data and used for very different purposes than the original one. This makes the digital component of CPS extremely dynamic, as it is only partially constrained by physical entities. This has important sociological implications that the concept of CPS cannot capture, as CPS do not consider social agency hence there is a need to introduce a *social domain* to the concept of cyber-physical systems.

In the social sciences field, Haraway (1990), with the concept of 'cyborg' that overcomes the human/machine dualism, opened the way to the development of the concept of *socio-cyber-physical systems* (SCPS) (Lioutas et al., 2019; Frazzon et al., 2013; Sheth et al., 2013; Zavyalova et al., 2017) as "systems constituted by the social world (people), the digital world (data), and the physical world (things)" (Rijswijk et al., 2020). If we consider that socio-technical systems are composed of actors, rules, and artefacts (Bijker, 1995; Geels, 2004), SCPS can be seen as socio-technical systems in which digital artefacts are an additional key factor in the system's existence and functioning (see Fig. 3). The cyber domain of SCPS therefore has the power to change radically social practices: as they replace or augment material objects, they reshape the meanings of both material and immaterial entities, generate new skills and make others obsolete. Thus, with the concept of SCPS, digital transformation is framed as a socially constructed process, allowing for the identification of key entities and their interactions across the three domains of which SCPS are composed.

These three domains each consist of a variety of entities (see Table 1 for definitions). Intradomain relations and interactions (Fig. 3) are often governed by a particular type of entity within that domain, which is a set of rules. The domains also interact with each other leading to certain (wanted and unwanted, known and unknown) outcomes and adaptations to the system which they form together. In the process of digital transformation, special emphasis is put on the cyber domain, as the physical and social entities become encoded into digital entities and expand the possibilities for action in the other domains.

As can be read in Table 1 and alluded to in section 2.1, in the context of agriculture and rural areas, the physical world can also be understood to comprise the ecological world, so a socio-cyber-physical system may even be seen as a socio-cyber-physical-ecological system as has been tentatively argued (Kiselev et al., 2019; Klerkx et al, 2019). This already shows that it is difficult, in the real world, to isolate interactions between entities belonging to a single domain. Our social interaction is profoundly influenced by our physical world, and even when machines interact only amongst themselves, they have been designed by actors that can switch them off at any time. However, for analytical purposes, it is useful to make distinctions. Firstly, the interactions between cyber and physical domains occur through automation, data collection, management, monitoring and controlling, e.g. Internet of Things. This also includes feedback loops from cyber to physical, e.g. milking robots causing the cows to adjust their milking patterns (Bear and Holloway, 2019; Driessen and Heutinck, 2014), and connections between digitalisation and genome editing (Clapp and Ruder, 2020). Secondly, there is the interaction between the social and physical domains, which could include the governance of natural resources, e.g. irrigation systems or the legal requirements for buildings in a natural environment (Fischer et al., 2007; Lund, 2015). Other examples are ecotourism, the connection between farmers and their livestock, or the links between the quality of road infrastructure and rural entrepreneurship (Cowie et al., 2020). Finally, there are interactions between the cyber and social domains that for example influences jobs (see Rotz et al., 2019b), enhances sensing capabilities of people which may impact for example advisory systems and advisor-farmer interactions (Eastwood et al., 2019a; Ingram and Maye, 2020), creates new proximities affecting rural-urban and

Table 1
The configuration of domains of the SCPS.

Domain	Entities	Interactions
Social	Social actors, groups and communities, and institutions	Relations between entities in the social domain are regulated by *social rules*, such as routines, social norms, ethical norms, informal behaviour, policy, laws
Cyber	Cyber entities are composed of a) digital reproductions of the physical sphere created by digitisation processes, e.g. from a paper-based map to a digital model of a farm which can be used by a drone, as well as b) original digital constructs, such as software, big data, cloud computing, Internet of Things, etc.	The relations between entities in the cyber domain are regulated by *cyber-rules*. For example, communication between devices is regulated by specific protocols (such as WiFi, Bluetooth, 5G); another example is the data format (PDF, DOC, …), a specific arrangement of data so that they can be stored, exchanged, and correctly interpreted. Digital technologies can communicate with other technologies, digital entities interact with other digital entities, performing operations and making choices potentially independently of humans, while initially being designed by humans.
Physical	These entities can be natural or artificial, according to the degree of manipulation they have undergone as a result of human activities. This includes living organisms and natural resources (plants, animals, etc.) and physical things to support living and working in the (natural) environment (e.g. analogue technology, infrastructure, finances)	Relations between entities in the physical domain are regulated by *natural rules* and by *technical rules*. For example, wild animals select in the environment the entities – plants or animals – that suit their nutrition, avoiding harmful entities. Water cycles are regulated by natural processes, such as evaporation and precipitation, but also by technical processes, such as water extraction from wells or circulation into pipes.

spatial inequalities (Haefner and Sternberg, 2020), and develops social media networks – i.e. the cyber entities function as a multiplier of the social entities (see Klerkx et al., 2019 for an overview of multiple additional examples of effects). The social entities, such as values, in turn create the basis for, for example, programming and algorithm development.

2.3. Conditions for impact of digital transformation

As argued in section 1, having a better understanding of the SCPS undergoing digital transformation, can enhance problematisation which in turn informs RRI. However, we argue that in order to enhance social responsibility and reflexivity it also should be made clearer how SCPS relate to three conditions for successful digital transformation which can have (positive or negative) impacts (Rijswijk et al., 2020): the *design* of digital technologies (Cooper, 2005; Whiteley, 1993), creating *access* to digital technologies (Klerkx et al., 2019; Shepherd et al., 2020), and navigating *system complexity* (Mocker et al., 2014). They co-determine different interactions between social, cyber and physical domains (see Table 1 and Fig. 2), or emerge from them, and hence are related to *impact of digital transformation.* Table 2 provides a non-exhaustive overview of known (negative) issues of digital transformation linked to these conditions for each of the domains.

With regards to *design*, digital technologies are designed to realise a given (desired) outcome and impact, such as improved productivity, profitability and sustainability (Global e-Sustainability Initiative and Deloitte, 2019), i.e. to have intended consequences. However, digital technologies often also come with (known and unknown) unintended consequences, which can either be positive or negative (Klerkx and Rose, 2020; Scholz et al., 2018) In some cases, outcomes can be harmful to people, animals or to the environment. Design-related impacts can induce modifications of existing dynamics, both in the social and in the business context, causing a redistribution of risks, benefits, and burdens among actors (Yeung, 2018). The design of technologies may be value laden, e.g. programmers views of the world are (unknowingly) reflected in the software they design which may exclude certain (groups of) people, hence raising ethical concerns (Johnson, 2019; Leavy, 2018). At the same time technologies may also be vulnerable to environmental conditions, such as heat, wind, and humidity, or to espionage or cyber-attacks (Nikander et al., 2020). Furthermore, conditions not considered during design, e.g. temporary lack of Internet connectivity, may cause serious issues, not in the least the inability to use services when needed (Shepherd et al., 2020; Steinke et al., 2020). Taking into account indirect and long-term effects leads to design approaches that anticipate problems, such as ‘user centered design’ (Steinke et al., 2020) ‘secure by design’, ‘safe by design’ or ‘sustainable by design’ (Patrignani and Whitehouse, 2013; van de Poel and Robaey, 2017). More in general, responsible design involves users and stakeholders in the design process, aiming to reduce the above mentioned risks, by putting users’ need at the center through a human-centered design approach (stepping into users’ shoes) to address the large and diverse community of stakeholders. Novel strategies, such as design thinking, advocate for a deeper, more personalized, understanding of users, instead of identifying aspects equally common to most users. (Carell et al., 2018).

Impact is also related to *access* to technologies, i.e. the distribution of physical, social, human and legal resources necessary to get access to digital opportunities. A well-known problem is that as a result of lack of economic, physical, or educational access to the internet, (groups of) people suffer from social and economic marginalisation and uneven socio-economic development. I.e. different levels of access to information or capacity to operate will create inequalities in the distribution of the costs and benefits of digital technology use. This is known as the (rural) digital divide, and addressing the problem goes much beyond the coverage of broadband infrastructures, because the availability of digital resources in an area also involves the possibility to readily buy, configure, and use digital devices that can easily operate jointly with existing digital devices (interoperability) (Rotz et al., 2019b; Salemink et al., 2017; Wolfert et al., 2017). Assessment of access conditions should consider potential users of the technology and consider the costs and the benefits that could be created. A recent document of the European Network for Rural Development (2020) suggests assessing rural areas in relation to their readiness for digital transformation, as different readiness levels may imply different priorities. Consideration of access conditions would also frame digital transformation strategies as socio-technical strategies, addressing both the technical and the social conditions for generating value and implementing integrated policy mixes.

A third condition for (positive or negative) impact of digital transformation is *system complexity*. The more digitisation and digitalisation proceeds, the stronger the need to connect system entities to each other, and the greater the influence of the cyber domain. Increasing connectivity adds to complexity because of the multiplicity of ways in which

Table 2
Non-exhaustive overview of known issues of digital transformation.

	Design	Access	System complexity
Social	Poor usability leading to use-related difficulties (Human Machine Interaction) (Aleixo et al., 2012; Haapala et al., 2006) Biased technology (Johnson, 2019; Leavy, 2018)	Partial or total exclusion because of lack of digital skills or education (Van Deursen and Van Dijk, 2014) High costs (Higgins et al., 2017) Lack of skills to reconfigure systems after upgrades/changes (dependence) (Nylén and Holmström, 2015)	Too fast technological pace sometimes challenging for final users (Nylen and Holmstrom, 2015) Unintended consequences of algorithmic regulation (Lodge and Mennicken, 2017) Redistribution of risks, benefits, and burdens among actors (Mönnig et al., 2019; Piasna and Drahokoupil, 2017; Shepherd et al., 2020; Yeung, 2018) Difficult policy context not easing digital transformation (Hinings et al., 2018)
Cyber	Loss of data due to improper use or external causes (e.g. attacks) (Duc and Chirumamilla, 2019) Inability to work in some conditions, e.g. temporary absence of Internet connectivity (Shepherd et al., 2020; Steinke et al., 2020) Personalization and profiling (Zuboff, 2019) Bias in algorithms causing e.g. exclusions or difficulties to access services (Kaye, 2018) Technological lock-in (Kaye, 2018)	Poor access to Internet connectivity (Townsend et al., 2013) Lack of digital infrastructure and resources readily available (Townsend et al., 2013) Lack of interoperability features in hardware and software components (Fulton and Port, 2018) Dependence on previous innovation; exclusion due to technological lag (Fulton and Port, 2018)	Opacity (black box) (Meske and Bunde, 2020) Operational complexity – dependence on experts (Tantalaki et al., 2019; Zhang and Kovacs, 2012) Difficulty in developing diversified development trajectories (Clapp and Ruder, 2020)
Physical	Digital solutions not resistant to e.g. atmospheric conditions, work in the field, etc. (Von Känel and Vecchiola, 2013) E-waste and disposal (Pickren, 2014) as well as high energy use (Berkhout and Hertin, 2004; Cobby Avaria, 2020)	Availability of digital devices (computer, smartphone, etc.) and adoption rate (Andriole et al., 2017) Location dependence (Cowie et al., 2020; Salemink et al., 2017; Townsend et al., 2013)	Need for up-to-date hardware (computer, smartphone, …) (Andriole et al., 2017)

each entity interacts with others (see section 2.2). A too fast technological pace, enabled by the malleability of digital technologies (Nylén and Holmström, 2015), may be challenging for final users, who perceive technology as a black box on which they may depend for e.g. business operations. This causes a dependence on (technical) experts, adding to the economic costs. Assessment of system complexity should consider changes to entities and activities of a system in relation to the connections with other entities and other domains. According to Perrow (1984) complexity of a system combined with too tight coupling (strong cause/effect links between entities) leads to vulnerability of systems and to domino effects.

A combined consideration of all 3 conditions is often required in order to have a successfully operating SCPS which creates positive impacts and counteracts negative effects of digital transformation. E.g. social exclusion related to digitalisation can be caused by lack of access to the Internet and the cost of an application (*access* conditions), or the design of technologies with bias or intrusive forms of conditionality (Kaye, 2018) (*design* conditions), or to the difficulty to make all parts of a system work (*complexity* conditions). For example, social networks and lack of connectivity can amplify the stigma of farmers not complying with environmental regulation, extending the stigma to the whole category.

3. Illustration of the framework: a dairy system as socio-cyber-physical system

As indicated in the introduction, the process of digital transformation encompasses both digitisation and digitalisation, whereby digitisation is more often seen at the early stages of the digital transformation process, and tends to focus on the micro level, e.g. a single business or organisation. Digitalisation often encompasses more actors in for example a value chain (e.g. meso or macro level) and implies a more mature level of digital technology use (Eastwood et al., 2017; Fielke et al., 2019; Higgins and Bryant, 2020). The concept of SCPS, however, suits both stages of digital transformation. In order to illustrate the SCPS concept, we apply it to the context of dairy farming and how it has engaged with digitisation feeding into more comprehensive digitalisation. It has been noted that in dairy farming there are several interactions in digital transformation, e.g. between automated milking systems (AMS), farmers and cows (Finstad et al., 2021). We do not aim to display a full analysis of all SCP relationships across the three conditions (design, access, system complexity), as this would fall outside the scope of this article, but zoom in on some elements (see also Table 3.). This illustration is based on insights coming from several articles on digitalisation in dairy farming. Dairy farming, the second biggest agricultural sector in the EU, is dealing with ongoing intensification resulting in increased farms size, mainly in terms of herd size (Clay et al., 2020; Thorsøe et al., 2020; Vellinga et al., 2011). Therefore farm management, considering aspects such as animal health and welfare; milk production and quality; and feed production and quality, is increasingly undertaken with the support of various digital technologies.

3.1. Digitisation at the farm level

To describe the application of the SCPS concept at the farm level we focus on one aspect of farm management, namely milk production and quality. A large number of dairy farms in the EU make use of automatic milking systems (Jacobs and Siegford, 2012), of which the next step is robotic milking, as milking robotics can perform the whole milking process in an accurate manner, with minimal human intervention (Kiselev et al., 2019). Thus, it creates more flexibility for a farmer, reduces physical labour (e.g. effort) and may also cause a decrease in (external) labour costs on farm (Rodenburg and House, 2007). The increased flexibility in labour requirement affects farmers' wellbeing through a better job satisfaction, mental health and family-work balance (Hansen et al., 2020). In Fig. 4 the process of digitisation of the milking process is illustrated. It shows the replacement of the social-physical activity of milking done by the farmer and an automatic milking system, with a cyber-physical activity of a robotic milking system.

While at first glance the replacement of the farmer's involvement in the milking process seems simple, it entails numerous social, cyber and physical changes (Hansen et al., 2020). In the basis, the robotic arm replaces the task of the human in applying the cluster to the udder of the cow (socio-physical becomes cyber-physical). In the *cyber domain* this implies however, a) digitisation of the information necessary to apply the cluster (position of the udder, state of health of the udder) and Artificial Intelligence (AI) to command the robot (Simões Filho et al., 2020); b) digitisation of the information necessary for AI to check if the robotic arm has performed its task correctly or to adapt tasks due to changes in external or internal conditions such as heatwaves or abnormal milk production (Fuentes et al., 2020); c) control tasks (start/stop) taken over by the control unit (Kulatunga et al., 2017); d) storage of the data in the control unit or in the cloud (Kulatunga et al., 2017).

Within the *physical domain* additional entities have been placed, namely the old milking system is being replaced by the robot, requiring reconfiguration of the milking shed, additional space for the computer system, but also the cows need to adjust to this new milking method

Table 3
Application of the SCPS framework to identify issues around digital dairy farming.

	Design	Access	System complexity
Social	Increased flexibility of the farmer. Reduced labour costs on farm. Less physical effort required. Farmers need the right to repair and to own their own data (FAIR and ELSI principles).	(Re- and De-)Skilling of farmers and workers to operate AMS. Financial in- or exclusion due to investment costs. Marginalisation or unemployment of farm workers. Advisors need to take new roles. Reduced autonomy of farmers and workers. Farming becomes more attractive to young people.	Changing organisation rules of the farming household. Different allocation of labour time. Evolution of social values of the farmer and the farming community. Tracking & tracing for retail purposes and compliance through data sharing for policy purpose can cause biases towards farmers. New power dynamics between all actors (e.g. farmer and advisor).
Cyber	'Datafication' of all components of the dairy farm to allow for the technology to communicate. Added value for farmers of through farm management tools.	New markets for service providers, e. g. online data platforms	Data gathered by automated milking systems is linked to manufacturers databases and to regulatory systems.
Physical	Breeding needs to be attuned to AMS. Increased animal welfare due to tracking of animal behaviour.	Cows need to be trained to adjust to AMS. Discharging cows which do not fit AMS. Reduced animal autonomy.	Restructuring of milking sheds and farm lay-out to accommodate AMS with possible effects on landscapes and biodiversity.

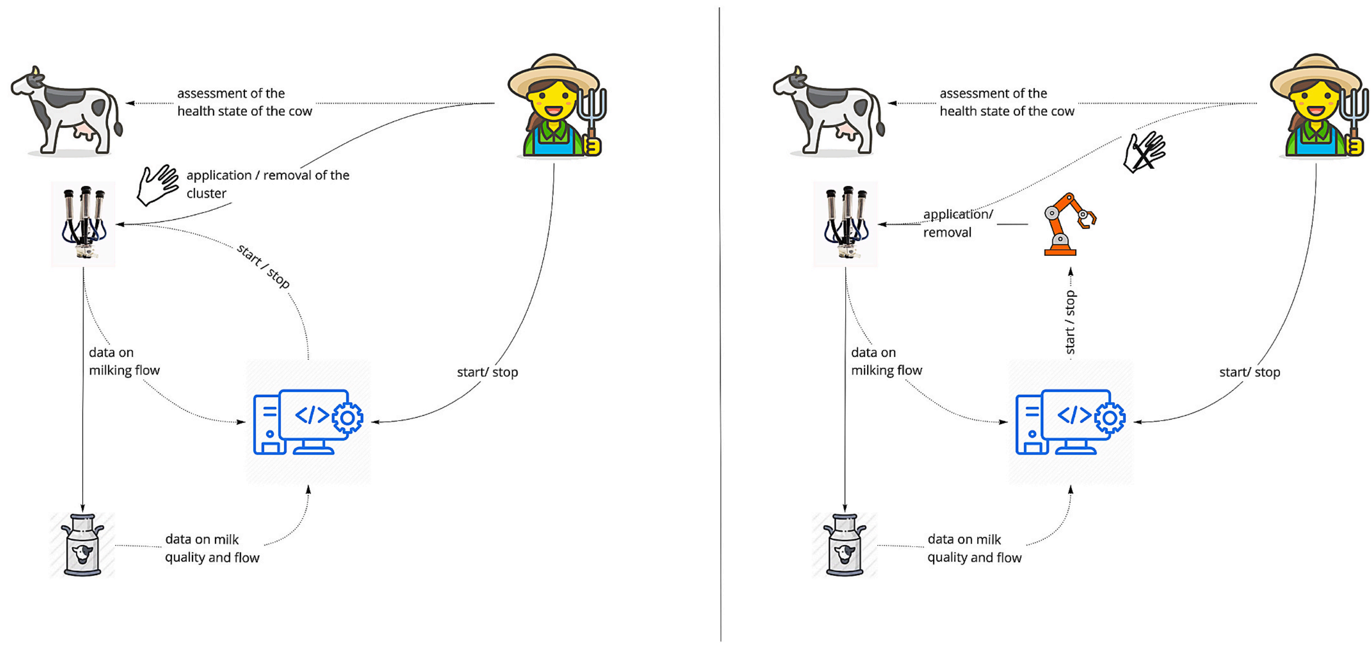

Fig. 4. Digitisation of a milking system.

(Wildridge et al., 2020). The cows, for example, can now get milked whenever they want, instead of 2 or 3 times a day at fixed hours (Hogeveen et al., 2001; Jacobs and Siegford, 2012). Moreover, walking into a robotic milking system and not having a recognizable process is something that needs to be taught to the cows and may take up to several weeks (Jacobs and Siegford, 2012). Some cows will never adjust to this new system and have to be taken off farm.

This combination has a big impact on the *social domain*. The initial intended outcomes, or the needs of the farmer that initiated the digitisation process, namely increased flexibility, less physical effort and a reduction of labour costs (Rodenburg and House, 2007), will also have secondary effects on organisational rules of the farming household, the allocation of labour time of the farmer, a change of the skill portfolio of the farm, up to an evolution of social values of the farmer and the farming community (Floridi et al., 2013; Hansen, 2015; Oudshoorn et al., 2012; Rodenburg, 2017; Was et al., 2011) as well as the cows in the process of what has been called the 'domestication of technology' (Finstad et al., 2021). It also has inclusion and exclusion effects, because the initial investment of implementing milking robots is high and therefore often these robots are only within reach for medium to large farms, requiring the development of robust financial plans (Shortall et al., 2016).

Describing the changes in the SCPS with the introduction of robotic milking on a farm starts with considering the necessary conditions to be in place in order to avoid negative unintended (albeit often unknown or unseen) impacts. One of the *design* conditions could for example be that the robotic arm needs to be designed in such a way that it does not negatively impact on animal health and welfare, despite the cow having to adjust to this new way of milking. For all intents and purposes, the robotic arm may actually increase animal health and welfare, due to a more secure disinfection of the udder or the ability of the cow to be milked whenever is needed, hence possibly reducing the risk of mastitis (De Mol and Ouweltjes, 2001; Krömker et al., 2010). An example of an *access* condition related to the design of the robotic arm and its software is that the farmer must be able to understand and interpret the data gathered throughout this milking process. In terms of *system complexity*, all the different elements as discussed before become connected, and this requires adjustments in the ways farms are structured and new organisational arrangements as regards the way data are stored and exchanged (Eastwood et al., 2017).

3.2. Digitalisation of the dairy value chain

Besides an automatic milking system, there are often numerous other digital technologies on a dairy farm, such as neck collars or feed sensors, which all generate data and are increasingly connected through means of IoT (Wolfert et al., 2017). This data can be combined to gain new insights, supporting farmers with additional farm management information and tools, thus aiming to provide added value to farmers. This exponential on-farm data generation also provides new opportunities for agribusinesses. Integration of data at all steps of the production chain (pasture/crop data, animal feed, weather, animal health, milk production and quality) multiplies the potential of the use of data at all levels of the chain (Pesce et al., 2019), and opens new markets for digital services and equipment. This in turn also impacts the farm-level digitisation as technologies need to be designed in such a way that they can communicate with each other or that data can be shared and combined. Digitisation of dairy farms thus implies a restructuring of the dairy value chain (Eastwood and Renwick, 2020). I.e. a digitalisation process, whereby for example advisors need to be able to support farmers in understanding and using the digital technologies, or technology providers provide tools that are interoperable with other digital technologies of other providers (Eastwood et al., 2017).

The above shows that changes in the *cyber domain* (e.g. combining different data sets) affects the *social domain*, such as the relations between actors on- and off farm, in this case between farmers and (digital) technology and service providers. This can include many other actors as well, such as suppliers, processors, regulators, the community, and many others. In the example mentioned above advisors and technology providers need to define a new role and adjust their relation with farmers to some degree (Rijswijk et al., 2019). Moreover, digital technologies may positively affect farmers' social status, making the profession more attractive for young people. On the other hand, automation may bring to deskilling of workers, marginalisation and unemployment (Sparrow and Howard, 2021).

In the *physical domain*, several effects can also be seen. For example, dairy systems, and livestock systems in general are among the most critical for their impact on the environment as they contribute to Green House Gas (GHG) emissions, to pollution of water, soil and air, and have a low efficiency of conversion into nutrients in comparison with other food sources (Duru and Therond, 2015; FAO, 2018; Smith et al., 2014).

ICTs are increasingly considered in relation to dealing with these challenges (Tullo et al., 2019), e.g. sensors can detect odours (Pan et al., 2007), polluters, GHGs (Banhazi et al., 2012). These sensors can also detect behaviour, indicating whether the animal is undergoing stress (Tullo et al., 2019). Through means of blockchain, a technology based on distributed databases of encrypted data, this data can turn into non-modifiable information that accompanies the product and allows for tracing back to the farm that has generated a given outcome (Kamilaris et al., 2019). While aiming to enhance sustainability and animal welfare this can, however, also have negative consequences on both farmer, worker, and animal autonomy who could become to some extent 'servants' of automated dairying systems (Bear and Holloway, 2019; Holloway et al., 2014a, 2014b; Rotz et al., 2019b; Vik et al., 2019).

Regarding the conditions, when moving from digitisation to digitalisation the different conditions become even more interlinked encompassing a multitude of entities in each domain of the SCPS, thereby in itself showing the increasing *system complexity*. Referring to the example above of data generation and combination on- and off farm *design* conditions can include the interoperability between different technologies, as mentioned above, and preferably the data generated on- and off farm is FAIR (findable, accessible, interoperable and reusable) (Jouanjean et al., 2020; Mons, 2018) to those who need it, while as well as considering ethical, legal and social implications (ELSI) (van der Burg et al., 2020). For example, *access* concerns the right of farmers to repair their machines or own their own data, which sometimes is restricted due to intellectual property rights of the manufacturer (Bronson, 2018; Carolan, 2018).

Future developments in value chain transparency, compliance, digital policy enactment can further increase system complexity. For example, retailers could be interested in data about milk quality, including its environmental footprint, as this information may add value to the product if communicated to consumers (Ridoutt and Hodges, 2017). Health authorities could be interested in data about state of health of the herd, so they can build epidemiological models, and environmental authorities can check if the farm complies with emission limits (OECD, 2019). Policy support could be conditioned to the respect of minimum standards. Hence, the technologies have broader structural systemic implications (Vik et al., 2019).

3.3. Implications for responsibilisation

The illustration highlights that an analysis of the SCPS along with analysis of the conditions of design, access and system complexity supports the identification of the different (potential) positive and negative impacts of the digital transformation process in agriculture and rural areas (see a summary in Table 3 of some issues identified in the illustration). Hence, it enables a sharper problematisation, which in turn helps to elucidate who may be responsible for understanding and dealing with these impacts. It shows that for some issues actors have a direct responsibility to attend for example animal welfare issues during the operation of the technologies, but also ex-post responsibility, i.e. a duty to respond to undesired or unintended consequences.

In our dairy farming example the on-farm data generation and the subsequent disclosure would increase responsibilisation of farmers, as they would be accountable for product and environmental quality and animal welfare. Additionally, those requiring the data disclosure, and those that set the standards for product and environmental quality as well as animal welfare have an even bigger responsibility of supporting farmers in meeting these requirements, as trade-offs and ethical dilemmas may also arise. As digital technologies require an investment small farmers may not be able to finance this, causing an additional problem of being unable to demonstrate their performance regarding the quality of their product and environmental compliance. Land prices could also be affected; retailers may decide to exclude underperforming farmers from their supply chains. Disclosure of data about farm pollution may generate stigma of the community over polluting farmers (OECD, 2019), and misuse of data may cause reputation damage to compliant farmers. These aspects show that the impact of technologies – and their game-changing potential - would depend on the broader SCPS in which they are embodied, and should thus be considered in early stages of technology design and including the governance and regulatory implications and requirements. Designing different socio-cyber-technical solutions may change the distribution of costs and benefits of information flows, as it shapes the way data are made available, accessed and owned. Depending on the availability, access, ownership of data the relations of power between actors of the system could be strongly affected, as shown by the debate about data sharing arrangements (van der Burg et al., 2020). Furthermore, and this is perhaps different from SCPS in other settings where this may be a more indirect or remote environmental effect (Berkhout and Hertin, 2004), in an agricultural and rural setting, there may also be a direct impact on the ecological system (Klerkx et al., 2019), as shown by the example in Table 3 'restructuring of milking sheds and farm lay-out to accommodate AMS with possible effects on landscapes and biodiversity'.

These aspects also show that a range of actors are involved, such as farmers, advisors, animal welfare NGOs, regulators, equipment manufacturers connected in different ways to different issues, and that issues may play out at different scales (on-farm, near farm, regional, national, global) (Eastwood et al., 2017) Also, in view of the sometimes unintended consequences which perhaps not be fully captured in design, ex-post responsibility should be a continuous concern to adapt and adjust where and when necessary during further diffusion and scaling of technologies, also addressing institutional and power dynamics that affect inclusion and exclusion of actors (Klerkx and Rose, 2020; Kok et al., 2021; Rose et al., 2021; Wigboldus et al., 2016).

4. Discussion and conclusion: unravelling socio-cyber-physical systems to support 'responsibilisation'

In this article a framework was developed connecting three domains of SCPS and their relationships to conditions for successful digital transformation (design, access and system complexity). Digital transformation changes the distribution of costs, benefits and responsibilities in system, requiring involved actors to act upon possible negative effects of costs and benefits. This is in line with claims that digital transformation of agriculture and rural areas should not be technology driven, but problem-driven and be open to different transition pathways (Klerkx and Rose, 2020; Lajoie-O'Malley et al., 2020; Rose and Chilvers, 2018). Past experiences of agricultural and rural modernisation have demonstrated that 'technology push' without addressing the underlying socio-economic (and ecological) dimensions risk to generate unpleasant or unwanted outcomes (Horlings and Marsden, 2011; Pingali, 2012), and calls have been made for 'just transitions' (Lamine et al., 2019). For this reason, the issue of digital transformation cannot be only a matter of catching up with the digital divide, rather, digital transformation of agriculture and rural areas should be linked to a broader transformation of the socio-economic patterns of development and linked to coherent strategies.

Following calls in the literature to further elaborate RRI for application to digital transformation in agriculture and rural areas (Bronson, 2018, 2019a; Cowie et al., 2020; Eastwood et al., 2019b; Rose and Chilvers, 2018; Rose et al., 2021), this paper offers a framework to support articulation of the digitisation and digitalisation situation at hand. The lens of SCPS can assist in highlighting consequences of altered relations between the social, cyber and physical domain, and thus how the structure and power dynamics within the system may change. The framework aids in problematisation of the potential digitisation and digitalisation impacts (i.e. anticipation), informs the process of defining social responsibility (i.e. moral responsibilities and accountabilities), and supports reflexivity.

Anticipation of consequences could improve the design capacity, for example through transdisciplinary involvement of relevant stakeholders. By gaining deeper awareness of the systemic impact of digital technologies, researchers and technology developers learn to associate their work to its impact, so to better appraise the pros and the cons and to anticipate any unintended consequences in terms of access and systemic complexity. This enables them in their capabilities to grasp 'the digital' and its effects (Dufva and Dufva, 2018; Fielke et al., 2021; Rijswijk et al., 2019), and turns this into 'responsibilisation capability'. Developing this capability can be part of capacity building in RRI for researchers or process facilitators (e.g. innovation brokers) to better support digital transformation in agriculture and rural areas (Eastwood et al., 2019b; Regan, 2021). It also enables highlighting a wider range of relevant actors and the (ir)responsibilities they have, and what this implies for designing the arenas in which RRI can be enacted (e.g., living labs, transformation labs, innovation platforms, see Pereira et al., 2020; Turner et al., 2020). Beyond an initial RRI exercise, given the relational nature of and complex interactions in SCPS which affect transformation dynamics (Kok et al., 2021), and beyond initial phases of design, technology development and implementation, this could also be a continuous reflection in the process of what has been dubbed 'responsible scaling' (Wigboldus et al., 2016).

In terms of policies, which are both affecting and are affected by digitalisation (Ehlers et al., 2021), the SCPS framework can support performance-based and mission-oriented policies around research and innovation for agrifood systems transformation or digitalisation strategies (Barrett et al., 2020; Klerkx and Begemann, 2020). The framework has the potential to connect science-policy-society interfaces, for example through improving technology foresight, giving methodological strength to multi-actor projects and providing facilitation tools for innovation platforms. Furthermore, the framework could help to identify needs for support to agrifood system and rural actors to address access and complexity issues related to digitalisation, as it can be applied to regional contexts. Embodied into criteria for funding and for policy assessment, frameworks like the SCPS can form the missing link between technology development and sustainable development of agriculture and rural areas.

This framework, however, only sets out the broader contours for supporting participatory assessment, planning and design of digital transformation processes. Hence further work is needed to operationalize criteria for assessing both the SCPS and the conditions for impact, and to see how this framework can be extended to other Agriculture 4.0 technologies which are enabled by and co-evolve with digital technologies, for example in the case of protein transitions (Helliwell and Burton, 2021; Lonkila and Kaljonen, 2021). This can be part of future RRI efforts connected to specific digital transformation processes in agriculture and rural areas.

Author contribution statement

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