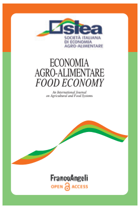
Economia agro-alimentare /
Food Economy

An International Journal on Agricultural and Food Systems

Vol. 26, Iss. 3, Art. 1, pp. 53-69 - ISSNe 1972-4802
DOI: 10.3280/ecag2024oa17771



The transition of food systems towards sustainability: The role of digitalization

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Abstract

The paper explores the complex relationship between digital and ecological transitions, particularly focusing on their interdependence and potential to drive sustainability. It acknowledges that digitalization, while offering numerous benefits such as efficiency and scalability, does not inherently lead to sustainability. The text highlights three critical aspects influencing digitalization's impact: the design of digital solutions, access to these solutions, and the complexity of systems integrating digital technologies. Challenges such as the risk of exacerbating inequalities and the necessity for comprehensive governance to mitigate negative effects are discussed. The paper also delves into the digital transition within the agri-food sector, emphasizing the contrast between conventional agriculture and agroecological approaches, which prioritize diversity and resilience. It argues that digital tools can support more sustainable and diverse agricultural practices if correctly aligned with ecological principles. Finally, the text calls for targeted innovation policies to ensure that digital transition contributes effectively to ecological goals, suggesting that a thoughtful and directed approach is essential for realizing the transformative potential of digitalization in fostering a sustainable future.

Article info

Type:
Article
Submitted:
30/04/2024
Accepted:
04/11/2024
Available online:
18/12/2024

JEL codes:
O33, O38

Keywords:
Digitalization
Ecological transition
Digital transition
Twin transition
Transformative innovation

Managing Editors:
Chiara Rinaldi
Vladi Finotto
Christine Mauracher

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Introduction

How, and to what extent, can the digital transition be a driver of the ecological transition? The question is relevant, as it cannot be taken for granted that digitalization generates sustainability. There is evidence that in many circumstances digitalization has accelerated the privatization of benefits and socialization of costs (Rolandi *et al.*, 2021). The recent debate over Artificial Intelligence (Novelli *et al.*, 2023) shows that the risks related to unregulated digitalization can be high.

To address this question, we need to consider that the impact of digitalization depends on three aspects: a) the design of the digitalized solutions; b) the access to digitalized solutions; c) the complexity of the systems wherein digital technologies are embedded (Rijswijk *et al.*, 2021). Even when the design of digital solutions links explicitly the technology to sustainability objectives (for example, reduction of inputs per unit of output) (Büyüközkan *et al.*, 2024), digitalization might fail to challenge the existing models, and we know that the room for improvement of agricultural conventional models is little (Webbs *et al.*, 2020). Access entitlements select who can capture the benefits of technology uptake: for example, if technologies are designed for large-scale farms, they will penalize small farmers, generating selection pressure (Carolan, 2018). Connectivity and human capital are other critical access entitlements (Scheerder *et al.*, 2017). Given the high interdependence of technologies and competencies involved in digital solutions, system complexity can be high, so system feedback and poor governance can generate negative impacts. One example concerns the lack of technology interoperability, which generates high transaction costs (Kerber and Schweitzer, 2017). Rebound effects, occurring when improvements at one level of complexity trigger negative impact at a higher level, are another example of system complexity: water efficiency at the farm level can increase consumption at the basin level because the attractiveness of the technology encourages many non-irrigated farms to adopt irrigation (Berbel, & Mateos, 2014).

The mission of innovation policies in the new context is to create the conditions for a twin transition (Brunori, 2022), that is, a sustainability transition accompanied, and fostered, by a digital transition. In this paper, which elaborates on the invited speech at the SIEA conference *Digital and environmental innovation for the sustainability of business models in the agri-food sector*, Venice 2024, I aim at contributing to lay down a narrative useful to link digitalization to transition in agriculture and rural areas.

1. The digital transition

In the Green Deal, the digital transition is considered instrumental to the ecological transition. To understand the importance of the digital transition, and the new wave of system innovation that it can generate, we must consider that digitalization affects the human capacity to generate representations of the physical world (Floridi, 2014). Representations are generated by encoding expressions of the physical world into data (signs and symbols that represent the diversity of the world), frames (rules that allow the interpretation of information in given contexts), and concepts (abstract entities that identify regularities within the world diversity). Models assemble data, frames, and concepts into patterns to represent complex entities (May and Perry, 2017). The network of data, frames, concepts, and models, produced and stored in individuals' minds and various supports, gives rise to what we call, after Floridi (2014), the infosphere.

Digitalization has established itself as the driving force for a significant quantum leap in the formation and development of the infosphere. This process has radically transformed the way we interact with information, making it possible to encode physical signals into numbers. Once transformed into digital form, data can be easily stored, replicated, transmitted, and integrated, far exceeding the capabilities of traditional methods of information management. The speed, efficiency, and scalability offered by digital technologies have made data management extremely agile and powerful (Vial, 2021).

Digitalization facilitates a dynamic interaction between the physical world and the infosphere, mediated by technologies capable of performing two crucial functions: sensing and actuation. Sensing makes it possible to capture signals from the physical world and turn them into digital data. Actuation, on the other hand, is about the ability to translate information into action in the physical world (Alur, 2015).

Within the infosphere, digitalization has generated a specific subsystem, the digital sphere. This sphere is constantly expanding, fueled both by data generated through observation and interaction with the physical world and by the integration and processing of pre-existing data. Within the digital sphere, data are stored, transported, combined, and elaborated. The outputs of these processes are new data, which can be turned into new information. Digital technologies can create imaginary worlds and transform them into real sources of experience for humans, as in the case of "virtual reality". With generative AI, the infosphere can be further expanded without human intervention. The digital sphere thus becomes a dynamic environment of rapidly evolving information, a self-sustaining and exponentially growing ecosystem of knowledge. Given that the digital sphere is a key resource for human activities, the regulation of its access and its use is of primary importance for sustainable and equitable development.

2. A system approach to digitalization

The interaction between the infosphere and the physical sphere cannot be fully understood with reductionist approaches, which isolate a few variables and study them separately. Indeed, the potential of interaction between entities in the digital sphere is much higher than in an analogic world. Digitalization allows "presence without localization" (Floridi, 2014) so that actors very far from each other can communicate as if they were physically in the same place. Digitalization allows the dematerialization of all the objects that have information content: news, books, music, visual art, money, cables, tickets, invoices, games, etc. Dematerialization/rematerialization processes reconfigure economic activities and the mix between goods and services: in mobility, car sharing can replace the ownership of cars, in computing, local physical computing and storage units are replaced by 'virtual machines' accessible via the cloud (Estagnasié *et al.*, 2022).

As the economy is increasingly moving from the analogical to the digital sphere, there are important implications for the understanding of the economy. In the digital sphere, given the capacity of digital technologies to foster interaction, business success is linked to the capacity of firms to harness 'network economies', which are exponentially correlated to the number of members of the network a company belongs. The 'platform economy' has replaced the 'pipeline economy' (Parker *et al.*, 2016) because platforms, which are governed spaces within the digital sphere, can generate and regulate 'digital ecosystems' (Barykin *et al.*, 2020). The ecosystem metaphor highlights the role of cooperation, coevolution (also concerning changes in the environment), the evolving nature of organizational boundaries, and the functional differentiation within networks.

System approaches help to understand the direct and indirect, short-term and long-term, individual, and collective impact of digital technologies on complex environments. Without claiming to build a complete synthesis of system theories, I have considered in Figure 1 the key concepts of system approaches and provided only a few key references for system approaches.

To put it in simple terms, a system can be defined as a set of elements organized into activities to perform a function (Meadows, 2008)[1]. When systems are studied in the social realm, components are named actors, to

1. The literal definition of Donella Meadows A system is an interconnected set of elements that is coherently organized in a way that achieves something (Meadows, 2008).

underlie that components are endowed with agency, that is capacity to choose different courses of action.

In order to perform their functions, actors require the necessary resources, and the activities within a system are subject to the constraints of established rules. Rules regulate the utilization of resources, the categorization of actors who are permitted to engage in the activities, the interactions between them, and so forth. Systems can be open or closed. Open systems, the ones we consider, interact with their environment and adapt to it. A system environment provides rules, resources, constraints, and opportunities for system components: changes in the system environment are drivers of system change. Adaptation to the system environment implies modifying the activities, the actors, the rules, and the resources mobilized to perform system functions.

Rules and resources are generated within the system as well as outside the system. Internal rules and resources are generated through repeated interaction. Routines, customs, and traditions, for example, are 'emerging properties' of system components' interaction. They evolve as an effect of the system's activities and its adaptation to the system's environment.

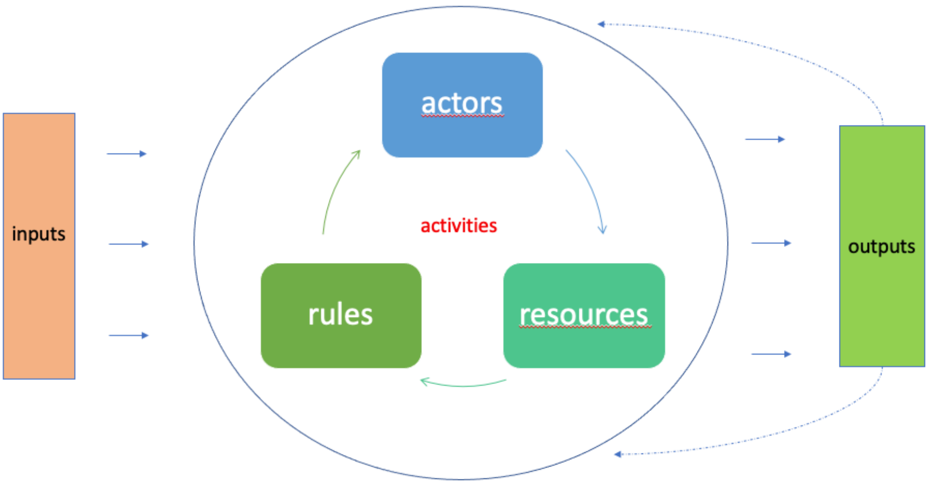
Another set of rules and resources is provided by the system environment: they are factors that cannot be modified by the components of the system.

The activities of a system affect the social, environmental, and economic spheres, and these outcomes are feedback on the activities, depending on actors' expectations and effects on other subsystems.

Systems can be characterized by components of different nature, such as social, ecological, and technological components. This implies that, for example, technological components are affected and affect social interaction. When considering and in this case, they can be analyzed, according to the purpose of the analysis, as socio-technical or socio-ecological systems.

Digital systems are based on the cyber-physical paradigm (Alur, 2015): they simulate the real world with models, feed these models through data taken from the physical world, and change the physical world based on the instructions that the model provides. For example, digital irrigation systems are based on representations of the relevant environment for irrigation: soil, plant, temperature, and water. The more accurate these representations are, the more effective these systems will be. Accuracy is related to the variety, the granularity, and the frequency of gathered data, as models are based on statistical inference. Sensors gather data from the components of the physical environment and send data to control units and storage units. Communication devices, communication protocols, storage, and software to elaborate the data, actuators use the input data to predict relevant variables (for example, water stress) and provide practical instructions (for example, when and how much to irrigate). In other words, digital technologies are 'assemblages', dynamic entities that tend to co-evolve.

Figure 1 - Scheme representing a system



When digital technologies are applied to human activities, they affect the social sphere, so that their assessment can be made considering the interaction between digital and social components as socio-technical systems. To be more precise, we can speak of socio-cyber-physical systems, the elements of which can belong to the social, physical, and digital spheres (Rijswijk *et al.*, 2021). The relevance of using the socio-cyber-physical concept is that it helps to assess to what extent any change to one sphere will generate change in the others. Likewise, rules and resources that characterize one sphere can affect the others.

3. Digitalization in the agri-food sector

The variety of tasks that digital technologies can perform depends on how different digital functions are assembled. To understand and evaluate the potential of digital transformation with a system approach, we must start by identifying and mapping the activities that digital applications perform. Among these activities, we can consider data gathering, storage and search, monitoring, classification, forecasting, coordination, content generation, automation, and communication.

Monitoring is the systematic collection of information to assess the state of the processes and their change. Digital monitoring technologies such as satellite imagery, drones, and IoT sensors collect biophysical, image, and movement data. At the processing stage, sensors monitor critical parameters during processing and storage. In the distribution phase, digital technologies track the location and condition of food items in real time. At the consumer level, applications for mobile phones provide information on the nutritional content of food products helping them to adapt their diets to desired targets. Digital technologies can also monitor the disposal and recycling of food waste.

Classification is the detection of differences between items based on multiple parameters. In the production phase, it can help to analyze data related to soil, crop types, pests, products, and customers. In the food processing phase, classification technologies can recognize the origin and quality of raw materials. In distribution, they help in managing inventory and optimizing logistics. Digital platforms classify consumer preferences and dietary needs, personalizing food recommendations and nutritional advice. In waste management, digital classification systems identify and sort organic waste for composting, recycling, or bioenergy production. By distinguishing between different types of food waste, these technologies facilitate efficient processing.

Matching is the association of items with complementary features. For example, matching can speed up supply and demand by identifying the right customer for a given seller and can identify alternatives for the same functions, speeding up product innovation. Charaka, an AI software developed by a US startup, has a database of around 1,000 plants and their properties and provides recommendations for replacing preservatives and chemical additives with 100% plant-based ingredients[2].

Prediction is the capacity to anticipate future events. Through the analysis of historical data and the development of simulation models that replicate the functioning of existing systems ("digital twins"), prediction systems can provide farmers with an estimation of crop yields, water and fertilizer needs, the occurrence of pest attacks, and machinery failures. Prediction can also regard inventory as well as supply chain disruptions (Purcell, Neubauer, 2023).

Coordination among the various components of the food system, including producers, suppliers, distributors, retailers, and consumers can be obtained through tools that, through data sharing and communication, allow to optimize operations in the space and in the time adjusting to others' activities in real-time.

Automation allows the replacement of humans in tasks that are repetitive, labor-intensive, or hazardous. Robotics in agriculture assists humans in

2. https://proteindirectory.com/company/the-live-green-co/.

planting, weeding, pest management, water management, and harvesting. In food processing, automated systems ensure consistent product quality and safety. Automation allows a dramatic reduction of administrative tasks: for example, ordering, invoicing, and payments. Digitalization of traceability allows seamless exchange of information between business partners and reduces sensibly the risk of fraud and the time to retrieve information about a product.

Communication technologies enhance the flow of information between components of a system. Within the food system, they enable stakeholders to stay informed, make timely decisions, and respond to market and environmental changes. Mobile applications, social media, and online platforms facilitate direct communication between farmers and consumers, promoting local food networks and enabling consumers to make informed choices about their food. In addition, these technologies play a crucial role in disseminating agricultural knowledge, weather forecasts, and market trends to rural communities.

The activities that digital technologies perform are combined into 'digital solutions', assemblages of a multiplicity of digital technologies to address socio-technical problems through the digitalization of analogic operations. For example, 'virtual fence' technologies are composed of collars worn by the livestock that get from the satellite the information about its position and send it to a control unit, satellites with which the collar communicates, wireless communication protocols, software for data management, cloud for data storage, actuators that provide an electric shock whenever the animal trespasses a given boundary (Muminov *et al.*, 2019). Often these solutions are connected to platforms that provide data-based services and collect users' data to create new solutions and new services. The performance of digital solutions depends on the capacity of its components to communicate seamlessly with each other and to respond to the specificities of the given context.

4. Digital Innovation and transition

Transition can be defined as the process of transformation of socio-ecological systems from their initial configuration to a new one. Transformation implies a radical change of activities, actors, and artifacts in the system. The food system is considered one of the key areas of the ecological transition (Geels *et al.*, 2019).

As any system is endowed with mechanisms that provide its stability, we can expect that the components of an established system will resist transformation, and more so as the transformation goals are more radical. In the multi-level literature (Geels, 2005), the tension between transformation and stability is explained through the interaction between the 'regime', that is, the system of rules that guarantee the stability of the system, and the 'niches', local subsystems which operate with rules that deviate from those of the regime. The rules that constitute the regimes are of several types: they can be legal (that tell people what is allowed and what is sanctioned), ethical (rules that regulate what is considered right/wrong), and technical (rules that establish how to make things). We can thus speak of economic regimes, technical regimes, and so on. Among the rules, cognitive rules are particularly important for innovation (Ingram, 2018). They establish which information is relevant and which is not, what are the appropriate interpretation frames, and, in the end, what is considered true and what is not. Cognitive rules are created and maintained by specific organizations that provide research, education, advisory services, training, and inspire technical rules.

Challenging the existing regimes can be hard, as regimes sustain strong coalitions of interests. Conservation forces can also inhabit organizations the mission of which is innovation, such as universities and research centers. Back in 1962, Kuhn demonstrated how academia can be a conservative institution, defending 'normal' science from scientific revolutions. In 1982 Dosi noticed that innovation can proceed along pathways fed by knowledge paradigms, in which enterprises are locked in by past investments in knowledge and infrastructures (Dosi, 1982). Understanding that knowledge-related institutions can be sources of conservation implies that public policies need to work to address the self-conservation defenses of the regime and manage the birth, proliferation, and scaling up of the niches and their successful incorporation into the regime. Innovation policies are key to this process.

The dynamics of socio-technical systems imply that innovation niches challenge the regime by experimenting with new socio-technical configurations through rule-breaking practices. Existing routines are put into discussion, and the interests of the actors are affected. The regime can react by defending itself from the innovation. In the cognitive realm, the effectiveness and even the scientific validity of alternative practices are questioned in the public sphere and the scientific sphere. In the legal realm, the sanctions of rule breakers are tightened and new conservative rules are introduced.

In some cases, niches are so disruptive that they scale up and replace the existing regime, as has happened in the field of entertainment or the field of tourism (Buhalis, 2019). To avoid this, the regime can try to adapt to the new situation by relaxing its rules and incorporating successful niches. The regime can be changed also with a top-down intervention: in the field of mobility, hardly the regime based on combustion engines could shift to an electric car-based regime without acting on infrastructures, incentives, technical standards, and regulations.

With the challenge of climate change, public policies are encouraged to recognize that ‘business as usual’ is no option: in this case, ‘normal’ innovation policies don’t work, and transformative innovation policies are needed. Transformative innovation aims at changing current socio-technical regimes (Novy *et al.*, 2022). In this regard, it is radically different from ‘normal’ innovation, which aims at stabilizing the existing regime by improving its efficiency and effectiveness. Transformative innovation mobilizes the agents of transformation, proposes new paradigms, builds new infrastructures, and leverages the dynamics of the interaction between niches and regimes. Transformative innovation is both creative and destructive, as it removes the obstacles to change while building new configurations.

Innovation, in this regard, is not only technological but also social and institutional. Without a synergy between these three types of innovation, transition can be much more difficult. Institutional innovation is needed to change the rules of the regime embedded into administrations, business associations, and policy networks (Olsson and Galaz, 2012). Social innovation is necessary to let different mindsets emerge from society, let new business goals and operating principles consolidate, let new actors find a space in the institutional and market networks, and create new coalitions and partnerships (Avelino *et al.*, 2017).

Transformative innovation can be pursued through encouraging bottom-up initiatives. It needs to rely on the agency of actors, on their capacity to build networks and coalitions for change, and on the capacity to motivate other actors to innovate (Molas-Gallart *et al.*, 2021). Even when it is based on top-down intervention, transformative change cannot be designed once and for all, but needs to emerge from trial, error, and learning.

5. Digitalization and the agroecological transition

In the agri-food sector the sustainability transition, envisaged by the Agenda 2030 and underpinned by the climate-related goals that the international community has set, takes the shape of an agro-ecological transition. According to FAO, agroecology is a framework based on ten principles that address social, economic, and ecological components[3]. The agroecological transition implies a shift from homogeneity to diversity,

3. www.fao.org/agroecology/overview/overview10elements/en/.

from linear to circular economies, from the primacy of market laws to the primacy of social and human values, from top-down innovation to co-creation and knowledge sharing. The agroecology transition implies a system transformation that affects agricultural practices, market configurations, power relations, and knowledge production processes. About practices, it advocates nature-based solutions and respect for traditional knowledge.

The Green Deal and the Farm to Fork strategy mention agroecology as one of the drivers of the necessary system transformation, and many of its principles are already embodied in European policies. The CAP has introduced agroecology principles into its measures such as 'ecoschemes' and 'agri-climate payments'. According to its proposers, agroecology is at the same time a science, a set of practices, and a social movement (Wezel *et al.*, 2009), and this multidimensionality makes it fit to address the system dynamics that policies can generate. It reminds us that transition implies a change of mindsets, and this change can be achieved through action in the cultural field.

When considering the intersection between digital transition and ecological transition, the real question is not just whether digitalization is transformative, but how and to what end it drives transformation. Digitalization, for example, plays out differently when applied to conventional agriculture versus agroecological systems.

Agriculture is part of a regime established originally in Western countries and then exported globally, that links together legal, ethical, technical, and cognitive rules for production and consumption. The agricultural regime known as the 'green revolution' (Kiers *et al.*, 2008) defines the activities, the actors, the resources, and the artifacts related to agriculture, making it easier to adopt conventional practices rather than alternative practices. Conventional agriculture has largely been about achieving uniformity to increase efficiency and productivity (Misra and Gosh, 2024). This approach relies on creating homogenous environments where high yields are pursued through the reduction of variability in crop performance – known as reducing the yield gap. Digital technologies in this realm, including precision agriculture tools like GPS-guided tractors, drones, and sensor networks, aim to optimize this homogenization. They provide farmers with the means to apply inputs (like water, fertilizers, and pesticides) precisely where and when they are needed, minimizing waste and maximizing yield. However, this precision can lead to a simplification of agricultural systems. The push for uniform high-yield crops can lock in agricultural systems into monocultures, reducing biodiversity and potentially increasing vulnerability to pests, diseases, and changing climate conditions. In this sense, digital technologies, while transformative in terms of efficiency, can also entrench a system that is arguably less resilient and less sustainable in the long term.

Agroecological agriculture takes a contrasting approach. Here, performance is tied to diversity – the idea that a variety of plants, animals, and microorganisms can work together to create a more resilient and sustainable system (Mouratiadou *et al.*, 2024). Diversity in agroecology is not just tolerated but celebrated and encouraged, as it can lead to systems that are more robust against shocks and stresses. In this context, rather than harnessing diversity to homogenize, they should harness diversity to diversify. Digital solutions in agroecology might include decision-support systems that help farmers understand and enhance the complex interactions in their fields, or mapping tools that allow for more diverse planting that can mimic natural ecosystems (Bellon Maurel, 2022).

Such technologies encourage the management of complexity rather than simplification. They support polycultures, intercropping, and other practices that build soil health, conserve water, and enhance biodiversity (Mouratiadou *et al.*, 2024). Digital solutions in agroecology can guide farmers in managing these complex systems in a way that aligns with natural processes and cycles, potentially leading to systems that are more sustainable and just as productive, if not more so, than conventional systems.

Facing the imperative of 'food system transformation', digitalization can be definitively a driver for agroecological transformation. Business disintermediation, digital ecosystems, and data availability on the performance of socio-technical systems are powerful drivers of change, able to encourage the actors to change practices to build new networks and to look for innovative innovation pathways.

6. Principles for a transformative digitalization

Digitalization has rapidly reshaped the landscape of our societies and economies. However, to assume that market forces alone can guide this revolution is naive and potentially perilous. Access to data, new market concentrations, power structures, and dependencies, changing knowledge requirements for farmers, and information asymmetries may cause potentially negative effects on the social fabric and even on food security (Zscheischler, 2022). Digitalization can also be a strong force of conservation when regime rules are encoded into opaque algorithms (Dourish, 2016).

The true sustainability potential of digitalization can only be unleashed when it is directed with intention and consideration for its wide-ranging impacts. The market is driven by profit, and without guidance, digitalization could exacerbate inequalities, overlook important societal needs, and fail to secure critical data and infrastructure. Therefore, for digitalization to be transformative it requires thoughtful policy directionality and actors' responsibility.

Directionality implies a clear set of priorities (Duncan *et al.*, 2022). As we have seen, innovation per se does not create sustainable outcomes and less so market-driven innovation. On the contrary, innovation should be able to shape markets to generate practices coherent with sustainability, and the public sector should play an entrepreneurial role (Mazzucato, 2011). However, directionality without participation would risk falling into top-down approaches, generating resistance and rejection within society.

Transformative innovation entails a certain degree of responsibility on the part of the actors involved in the innovation process.

Responsibility implies procedures that encourage researchers and research organizations to look beyond the specific field where innovation operates and to look to the broader societal impact that research and innovation could have. Responsibility implies the availability of researchers and research organizations to involve stakeholders in the design and implementation of research, the capacity to anticipate the impact of research at the system level, the attitude to reflect on past results of innovation and to act accordingly, and commitment to pursue a common endeavor aimed at the public good (Owen *et al.*, 2013).

Moreover, transformative research and innovation should investigate the role of rules, infrastructures, skills, coordination, and leadership. Clear regulations are needed to ensure data privacy, benefit sharing of the value of data, data security, and ethical standards. This includes intellectual property rights, user protection laws, and standards for interoperability. Robust digital infrastructures are the foundation of digitalization, including not only connectivity but also platforms that can support digital ecosystems. The public sector and cooperatives will have an important role in this regard.

So far, digitalization strategies have been technology-centered, while food systems and rural areas need coordination of instruments and resources around well-defined problems and priorities. Leadership, at all levels, is needed to navigate the complex landscape of digitalization. Successful niches presuppose visionary leaders, able to identify opportunities, anticipate challenges, and mobilize social resources around ambitious objectives. Policies should be able to create the environment for these individual and institutional leaders and provide them with the necessary resources.

Digitalization strategies should be flexible enough to adapt to these diverse contexts, as different regions and sectors have unique needs and challenges: local communities should be involved in the definition of digitalization strategies. Experimental policy approaches should be encouraged, allowing for trial and error to find the most effective ways to integrate digital technologies into socio-technical systems to provide sustainability. Policy assessment is crucial to ensure they are delivering desired outcomes and to learn from bottom-up initiatives.

The path to digitalization is complex and multi-faceted, demanding a well-thought-out approach that is attuned to the needs and realities of different stakeholders. It is a process that calls for regulation, infrastructure development, skill enhancement, coordination among different actors, and insightful leadership. It also requires an adaptive mindset that values diversity, experimentation, and evaluation to integrate effectively with market forces. Only with a directed and adaptive approach can digitalization serve as a transformative force for good, fostering inclusive growth, innovation, and prosperity in the 21st century.

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