Technology, digitalization, and AI for sustainability

Digitalization for food system transitions: an assessment

Gianluca Brunori, Manlio Bacco, Silvia Rolandi

ABSTRACT

This chapter discusses one of the most urgent and significant challenges we must face, which is the transition towards sustainable food systems. In this context, we discuss the role digital technologies may play in this regard proposing the use of 'socio-cyber-physical system' as a reference framework and extension of its ICT (Information and Communications Technology) version, the 'cyber-physical system' paradigm. Key digital technologies with the potential of being game changers are identified, and their role in supporting a transition towards greater sustainability. Risks are identified and discussed related to the adoption of digital technologies in the food system, as well as policy conditions for digital technologies to operate in the societal interest. Recommendations about the embodiment of socio-economic principles in the digitalisation process are also provided, in line with the socio-cyber-physical approach.

KEYWORDS: digitalization, sustainability, food systems

1. Introduction: sustainable food systems and digitalisation

Transition towards sustainable food systems is widely recognised as one of the most significant challenges facing the planet and the urgency of such transformations is now irrefutable (Balafoutis et al., 2017). Research is considered a key driver for the transition. In this spirit, the European Commission's Standing Committee on Agricultural Research's (SCAR) – a body that coordinates the member states' research policies in the field of agriculture - launched its 5th foresight exercise with the aim of providing a frame of reference for national research strategies, EU-level partnerships, and joint programming initiatives. Thee experts, were commissioned to explore the pathways to achieve a 'safe and just operating space' for the primary systems in Europe. Three pathways - healthy and sustainable diets for all, circularity in food systems, and diversity - were identified through workshops, expert inputs, and deliberation. They provide different entry points and key 'battlegrounds' and require integrated and coherent efforts by a wide range of actors.

The first transition pathway relates to what we eat: everyone should have access to healthy diets, and at the same time diets should reflect the need to reduce the pressure on the environment (Van Wassenaer at al., 2021). This pathway implies a change in both food supply and demand. The second pathway relates to circular food economies, which aims at closing the material loops in all the subsystems of the food system, starting from primary production wherein circularity can be managed through ecosystems redesign and the mobilization of functional biodiversity (Araújo et al., 2021). The third pathway relates to social and biological diversity to augment ecosystem services and foster more resilient system. In this context, digitalisation has been highlighted as a key cross-cutting issue. Given its game-changing role, digitalisation can be a driver of progress and prosperity. However, depending on its application, it can cause social inequalities and environmental degradation: much will depend on the capacity to shape ICT technologies in view of the common good and to design appropriate legal, social, and economic frameworks to control its development. The present paper discusses the role that digitalization may play in each of these pathways. We will proceed by giving an overview of the main concepts related to digitalisation, and then we will identify, for each pathway, current and future ICT applications that may support the process and their potential impact. Discussion and conclusions will follow.

2. The digital transformation: main concepts

ICT technologies are the drivers of two distinct, albeit interconnected, processes: digitisation and digitalisation. **Digitisation** is the transformation of analogical signals into digital information. Digitisation increases exponentially the capacity to store, retrieve, exchange, and integrate data, allowing the so-called **datafication**, which is the growing production of data to support decision making (Serazetdinova et al., 2019). The exponential reduction of the costs of computing has made it possible to translate physical information into a digital format. This has generated an unpreceded possibility of access to knowledge and information, raising at the same time issues of privacy and intellectual property.

In more recent years, the development of sensing technologies has allowed a new wave of datafication based on automatic collection and storage of data with very limited human intervention. Among the most relevant sources of data, we can now count satellites, sensors and the so-called 'Internet of Things' paradigm, mobile phones and apps, censuses and surveys, publications and documents, citizen science, administrative data, finance data (Jensen & Campbell, 2019).

Digitisation allows the creation of digital representations of the physical world. The Internet allows the circulation of these representations that become part of the cybersphere, a world of informational objects. Through the cybersphere, humans can multiply the possibilities of acting remotely upon the physical world. To better grasp this interconnectedness, the concept of 'cyber-physical system'[1] (CPS) has been proposed. In a CPS, physical and cyber components are connected and communicate with each other to perform a given function (Bacco et al., 2020). Logically, CPSs can be described as

[1] Framework for Cyber-Physical Systems, Release 1.0, May 2016 - Cyber Physical Systems Public Working Group: https://s3.amazonaws.com/nist-sgcps/cpspwg/files/pwgglobal/CPS_PWG_Framework_for_Cyber_Physical_Systems_Release_1_0Final.pdf

composed by five layers: *sensing* (data collection through sensors), *data exchange* (through wired or wireless connection), *computing* (data storing and processing), *intelligence* (application with a given purpose), and *actuation* (semi or fully automatic execution of actions). These systems allow 'smart processes', as they can adopt flexible decisions and carry out fine-tuned operations based on data. CPSs can radically change the patterns of interaction among people. Communication at a distance allows new forms of sociality, new labour organization patterns, new lifestyles. Robots can replace or support human work. Automatic translation opens new possibilities for communication. At the same time, different social patterns can give CPSs different shapes. The social, the cyber and the physical domains co-evolve. These changes are captured by the concept of digitalisation. **Digitalisation** departs from the potentialities created by digitisation and regards the transformation of socio-ecological systems in relation to it. The process of digitalisation cannot be captured properly by the concept of CPSs, as the social component is external to the system. For this reason, we have proposed the concept of **socio-cyber-physical system** (SCPS), which allows to describe technological systems as components of a broader set of relations and interdependencies. The SCPS concept emphasizes the two-way relationship between the social and the technological processes, stressing that different social patterns may shape different technological patterns and vice versa. This has important implications on innovation policies, as SCPSs approaches stress how to avoid technological determinism and proposes an approach that subordinates the technology development to the identification and analysis of social problems, thus to solutions that adapt technology according to the specific ecological, social, and organizational contexts (Rijswijk et al., 2021).

3. The impacts of digitalisation on the food system

Digitalisation has already changed the food system, but the technological developments in this field let us envisage even greater and deeper changes. The impact of digitalisation on the food system is briefly analysed in relation to its main actors and activities.

Digitalisation and farming

The impact of digitalisation on the future of farming is an object of increasing interest, as it is supposed to bring benefits to farmers. **Productivity gains** can be obtained through better insights into production variables and dynamics, informed decision-making based on insights and scenario analyses, and increased labour productivity. Accurate monitoring and optimisation of processes can bring higher quality and waste reduction. Digitisation can improve **access to markets** by improving product quality and available information to customers, and by allowing excessive dependency on intermediaries. Digitalisation can also improve the **quality of work,** relieving farmers from heavy or unpleasant tasks, and can improve the communication with administrations. **Benefits to the environment** are also envisaged as digitisation improves the efficiency of use of external inputs and the monitoring of the impact of agricultural practices on GHG emissions and other environmental indicators (García-Llorente et al. 2018, Garske et al., 2021; Nikolaou, et al., 2020). Biases toward specific agricultural paradigms (specialization, large scale) embodied into technologies represent a problematic aspect, as well as economic barriers to access (high initial investments to adopt the technologies), and technological ecosystem, potentially creating a not adequate context for new technologies to work.

Digitalisation and Agricultural Knowledge and Innovation Systems

AKIS (Agricultural Knowledge and Innovation System) is about knowledge management: AI, big data and cloud computing will make the organization of traditional AKIS obsolete. The mix of face-to-face and remote interaction will be radically reorganized, and the function of face-to-face activities will be much different from the past. As farmers will be able to have access to basic information autonomously through specialised sites and an increased peer-to-peer communication, advisors will move from information brokering to data analysis. Their services will be growing online, aimed at increasing the value of direct experience and trust generation. As data management will be more relevant for farmers, extension services and cooperatives, it will change their functions into data managers, analysts, brokers (Cobby, 2020). Machinery and input suppliers are already "connected" to farmers, and new digital services will be proposed. In terms of risks, lack of ICT skills will create new divides (Akyazi et al., 2020). Dismissing traditional services may prompt a further disconnection from the AKIS of farmers who do have not skills to interact with digital services. Another risk may be related to a technological bias: extension services may choose to support the technologies that are more digitalized, overlooking the ones which have less resources to invest.

Digitalisation and the other actors of the food value chain

Data availability allows the reduction of 'information friction' between actors of the value chain. Increased availability of data and of computing capacity will improve the processes of traceability, allowing the protection of the identity of the products along the chain, reducing the costs of certification, and improving its accuracy. Improved one-to-one or one-to-many communication allows disintermediation from traditional intermediaries, which will reshape the value chain patterns farmers can have direct access to distant markets and to consumers, and many of them are already developing new business models supported by platforms (Sam et al., 2021). Improvement in logistics due to automation and data management will foster new organizational patterns. 3D printing will allow a spatial reorganization of the food industry, allowing diffused manufacturing, but also creating a divide between 3D printed and 'authentic' food (Lipton, 2017). In this new scenario, technology design will be shaped by the actors who have more power in the value chain. Actors who have greater capacity to collect and analyse data will get even more power. Weak regulation over data property will generate new enclosures and creation of new monopolies. Farms left outside the value chains will undergo marginalisation. Unregulated access to sensitive data – such as polluting emissions or quality of soils - by consumers or media may generate inaccurate information and endanger actors' reputation.

Digitalisation and consumers

Digitalisation has given consumers access to an enormous amount of information about the products they buy, increasing their power of choice. Information about the product increases responsibility of both producers and users, as information links the choice to its consequences. Labelling and certification, nutritional parameters, environmental footprints will accompany the product allowing an assessment of its sustainability and healthiness. Information to consumers will constitute another field of competition between firms. Risks may be related to information overload, from trusting wrong sources of information to lack of skills to interpret the available data, and to the deliberate pollution of information sources. Information to consumers led by private actors may bring firms to carefully select which information must be disclosed and which will be kept hidden, increasing the level of confusion, and raising the risk of inaccurate claims.

Digitalisation and rurality

Digitalisation reconfigures spatial patterns (settlements, mobility, resource flows, communication), disrupts goods and services provision, opens new opportunities for natural resources and ecosystem services management. In theory, digitisation has the potential to reduce distance and isolation in rural areas. In practice, market-led digitisation may enlarge the gulf between rural and urban areas. To reverse this trend and to enable rural areas to harvest the opportunities offered by digitisation, a strong effort to rethink the role and importance of rural areas is needed.

Digitalisation and public administrations

Digitisation offers a multiplicity of tools that policymakers can use to improve the efficiency and effectiveness of policies. Improved communication among farmers and administrations will reduce the transaction costs and reduce the power of the intermediaries. Better information about production processes will allow public administrations to grant 'licences to operate' to firms in a more accurate way. Environmental monitoring systems may activate performance-based policies (Bikomeye et al., 2021). Monitoring systems for food storage will improve food safety. Data sharing about risks will improve the capacity to respond to crises. Technology will allow the development of 'nudging systems' to orient consumers toward healthy and sustainable diets. Also, in this case, inaccurate disclosure of information may create panic, bias, and may undermine the reputation of some actors.

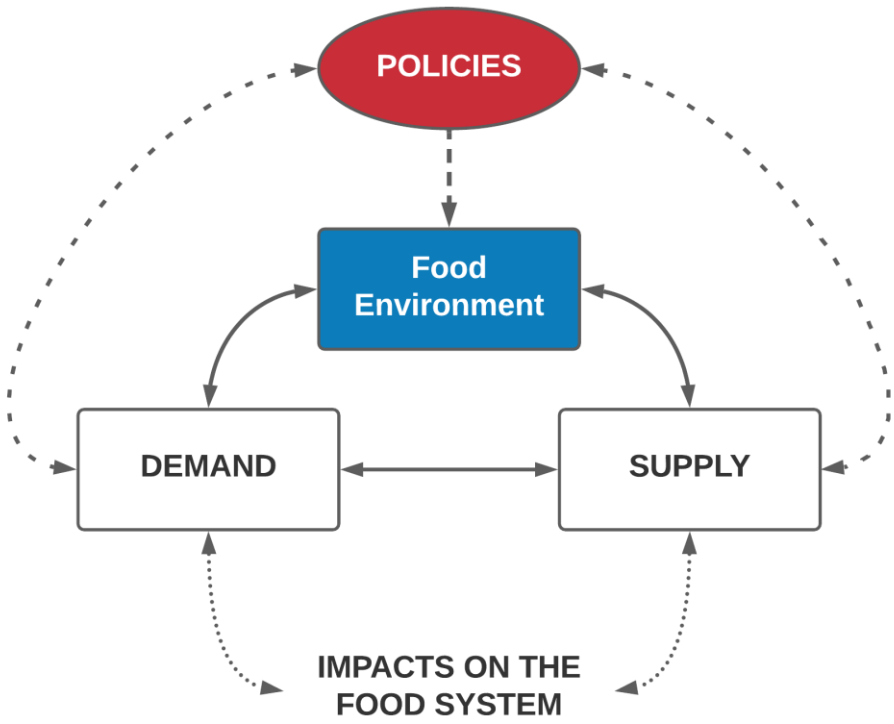
Lack of trust in the public administration may hamper data sharing, and excessive nudging practices could spark a sense of diminishing individual freedom.

4. Transitions to sustainable food systems: the role of digitalisation

The role that digitalisation may play in the transition to sustainable food systems will depend on the shape that the SCPSs will take. Defining transition pathways would include identifying technology pathways.

4.1 Pathway 1: Healthy and sustainable diets for all

The first pathway, "Healthy and sustainable diets for all" starts from the observation that current diets are both unsustainable and unhealthy. Change in diets will imply a change both in demand and in supply (Sadhukhan et al. 2020). The transition to sustainable diets will depend also on the capacity to shape the food environment, a set of physical and symbolic conditions that affect consumers choice (Bronson, 2020). Change of dietary patterns – on average, a reduction of food intake and an increase of the proportion of plant-based food – will stimulate producers to provide food with higher nutritional density and lower pressure on the ecosystem (McClements, 2020). Alternative sources of proteins will be available, food with higher nutritional density will be produced, diversification will increase the variety of food to which consumers will have access.



Reshaping demand

Digitisation offers a variety of solutions to foster sustainable dietary patterns (Smetana, 2019). Access to nutrition-related information can be improved and made accessible Apps connected to wearable biometric devices can provide personalized nutritional recommendations. Improved traceability will give consumers access to information about the impact of the food they eat, guiding their choice towards more sustainable patterns. The growing role of e-commerce in shopping will give the possibility to retailers to 'nudge' consumers by making sustainable solutions more visible and viable.

Reshaping supply

Digitisation will make it possible – through data provided by satellites, drones, sensors - to measure the carrying capacity of agro-ecosystems, and therefore to set sustainable yields levels for regions. Inputs could be distributed in proportion to the capacity of the crops to respond and to the environmental needs. Monitoring systems will be able to check if agricultural practices trespass these levels. Good agricultural practices will be documented, and related information can be communicated to consumers. Environmental certification will accompany food products. Improved access to knowledge and tailored decision support systems can support farmers in the conversion of their practices (Tsolakis et al., 2021). Food safety can be improved through sensors, smart packaging, blockchain, or other technologies that hold the potential to increase trust and coordination between actors of the chain.

Supporting sustainable trade policies

Trade links together distant social and ecological systems. Sustainable trade occurs when this interaction does not harm the capacity of the systems to provide benefits for the future generations. Increasing evidence shows that a considerable share of international trade is not sustainable, and the increasing availability and accuracy of this information generates a clash between the principle of free trade and sustainability principles. The Lulucf regulation[2] is a key example of telecoupling, that is interaction at a distance.

Digitisation will allow a generalized use of footprinting, which will improve the awareness of the true cost of food among consumers and citizens and support policy making with substantial evidence (Rincon-Patino & Corrales, 2018). Available information about the impact of distant production processes will allow the problematisation of certain patterns of consumption and trade, and will increase the level of responsibility of firms, consumers, and policy makers.

[2]The LULUCF Regulation implements the agreement between EU leaders in October 2014 that all sectors should contribute to the EU's 2030 emission reduction target, including the land use sector.
https://ec.europa.eu/clima/policies/forests/lulucf_en#:~:text=The%20LULUCF%20Regulation%20implements%20the,including%20the%20land%20use%20sector.

4.2 Pathway 2: Full circularity of food systems

The second pathway implies a reorganization of the food system around principles of circularity. A circular economy is based on a) design of the product and production processes to minimize waste and to extend the product life cycle; b) reduce the amount of 'funds' being used in the economy by shifting from 'goods' to 'services'; c) an industrial ecosystem with 'functional diversity' that allows industrial symbiosis; d) improving the processes of reuse and recycling e) improving cooperation between firms for reusing and recycling; f) reorganizing logistics for optimizing flows between firms, g) connecting the individual stakeholders of the system. See Table 2 on the potential impacts of digitisation in this respect. The food system can rely on a great deal of naturally circular processes, related to the role of living species in the biogeochemical cycles. The key for a circular economy is the value of biomass to be recycled and reused, and the cost of biomass procurement and manipulation should be lower than its use value. At the level of primary production, this implies 'closing the loops' at farm or landscape level, with the soil (and living beings therein) having a pivotal role in the downgrading and upgrading of organic matter. This implies, for example, that composting (a practice that allows an upgrading of discarded biomass to increase the fertility of soil) should have a higher return than burning it. At the level of secondary production, circularity implies reorganising the 'industrial ecology' so as to give organic matter an exchange value that makes its reuse and recycle profitable (Canali et al., 2020 and Gkisakis & Damianakis, 2020).

Redesign products and processes

A circular economy needs an alternative approach to product and process design. Product design should extend the life cycle of the product and minimize the costs of disassembling the product after use. Diversity of input and output multiplies the possibilities that leftovers are turned into input for another process. This principle is translated into the construction of industrial ecologies (Marescotti et al., 2020). To maximize the (bio-)value that can be extracted from biomass, its hierarchy should be reflected in its exchange value and proportionally in the costs of procurement. This implies a rapid characterization of feedstocks, proximity between buyers and sellers, improved logistics and availability of data among potential users. The focus of research is to reduce the costs of manipulation of the feedstocks, of the transformation of biomass, and to reduce the friction between transactions. Robots can help manipulate the feedstock more rapidly and more safely. Sensors allow a rapid characterization of feedstocks. RFID systems can facilitate the logistics of feedstocks. Sharing this information between firms will reduce the transaction costs between firms. Big data will allow a real-time, locally based, assessment of hierarchies of value between biomass utilization (Dubè et al, 2018). Open data databases, platforms for B2B collaboration, monitoring tools and similar solution can be used to foster circular industrial ecosystems.

Increasing firms', consumers', and citizens' awareness

Circular economy represents a new socio-techno-economic paradigm, alternative to the linear economy, as its main principles are related to the efforts to design the product, the processes, and the legal/built environment around the optimization of reducing, reusing, and recycling activities. Adopting this new paradigm is an effort that involves all actors of the economic system, including policymakers, citizens, and consumers. This requires strong efforts in the field of education, training, access to information and support services. Digital education and training courses, open-source information, sharing experimental data, dedicated social media for peer-to-peer interaction can strongly support this process. Citizens and consumers fill an important role, as they can choose the products with lower environmental footprint, provide the first step of separation of domestic leftovers. At the consumers level, digitalisation can provide footprint tools, 'nudging' software to positively influence the consumers' behaviour, sensors to monitor domestic waste, and collaborative consumption platforms.

Table 2: current and potential impacts of digitisation with respect to different targets

Target	Impact of Digitisation
Design of the product to minimize waste production and to extend its life cycle	Smart packaging and smart labelling (Skinner, 2015), design, simulations
Reduce the amount of 'funds' being used in the economy by shifting from 'goods' to 'services'	B2C platforms to manage durable goods services (Taranic, 2016), B2B platforms for sharing durable goods
An industrial ecosystem with 'functional diversity' fostering industrial symbiosis	B2B platforms; Improved genetic screening of biodiversity. Improved analytics for system biology (Kuzmin et al., 2018)
Redesign rural areas	e-government; e-services;
Improving reuse and recycling processes	Robots, sensors, advanced analytics, artificial intelligence= can be used by all
Improving cooperation between firms for reusing and recycling	Joint databases, Big data for characterization of feedstocks, sharing platforms[8]
Reorganizing logistics for optimizing flows between firms.	Inter-firm Blockchain, Robotization, sharing platforms, IoT, linking transportation planning to agricultural sensors
New consumption patterns	Footprinting, 'nudging' software, sensor to monitor waste, collaborative consumption platforms (Sposato et al., 2017), RFID to follow consumers, all information available

4.3 Pathway 3: Reversing the erosion of diversity

The third transition discussed in the SCAR foresight exercise focuses on diversity. Diversity is a key to resilience of socio-ecological systems in face of change. In fact, diversity broadens the range of the functions that a system can provide, as well the range of responses to factors of change. This applies to both biological systems and to social systems. "*In systems with low diversity, there is less chance to create new ideas, components, or connections. Tinkering, mutations, and fortuitous errors are essential to derive new components and links in a system*" (Young et al., 2006) A substantial increase of biological, social, and economic diversity requires a change of technical paradigms, consumers and citizens' awareness; access to information; an ecosystem of farms with 'functional diversity' surpluses to exchange; and availability of market and technical alternatives. Digitisation can give an important contribution to these efforts, as reported in Table 3.

Biodiversity data

One of the first steps of biodiversity conservation is improving information availability. Digital cameras, remote sensing, field data, citizens' observations can increase this availability. Satellite data are used to measure biodiversity indicators (Cazzolla Gatti & Notarnicola, 2018), analyse population dynamics, species interaction and community diversity, functional traits and functional diversity and biodiversity management (Tang et al., 2018). Data coming from biodiversity datasets can be used to train AI in recognising (Cope et al., 2012) and assessing living organisms and their features (Li, 2020). The challenge of development in this field is the possibility of integrating data of different sources and improving data quality (Zeb et al., 2021). The Global Biodiversity Information Facility provides a single point of access to specimen data from databases of biological surveys and collections. Biologists now have rapid access to more than 120 million observations (Yesson et al., 2007). The possibility of creating global databases of biodiversity has generated a new object of enquiry, the global biodiversity, opening new avenues for the policy agenda (Devictor & Bensaude-Vincent, 2016).

Building biodiversity-based value chains

Given the characteristics of conventional retailers, products that do not comply with the rules that retailers pose are not accepted. Even if they were accepted, farmers would not be able to communicate to consumers the differences between alternative and conventional varieties. Therefore, the value of biodiversity should be turned into market value through dedicated value chains, able to preserve the identity of the product and remunerate adequately all actors. In recent years, the use of e-mail, social networks or cloud-based tools have made it possible for networks of consumers to organize purchasing groups. E-commerce or B2B platforms have helped farmers to find market channels appropriate to product size and characteristics. Consumers are increasing interests in agro-biodiversity, along with conventional retailers. Digitalisation can reduce transaction costs and inform consumers about the identity of the products and producers. Distributed ledgers, for example, can conserve the identity of the genetic variety along the chain (Antonucci et al., 2019).

Supporting policies

Policies for biodiversity need appropriate data collection, analytics, and measurement methodologies for monitoring diversity, mapping biodiversity distribution and risk, assessing the impact of policies, and controlling individual practices (Ehlers et al., 2021).

Knowledge development

The current techno-economic paradigm of conventional agriculture is still influenced by the Fordist principle according to which efficiency is based on standardization. For more circularity in systems, a deep transformation of production processes and business models is needed. Digitalisation can foster education, access to information, training, and technical support. Moreover, as information about functional diversity is key to its use, sharing about trial data can accelerate dissemination and adoption of innovation. Knowledge about diversity can be enhanced through systematic data collection (also involving citizens), open data and knowledge sharing platforms.

Raising consumers' and citizens' awareness

An increasing demand to protect diversity can foster new techno-economic models. Despite the variety of brands that consumers can find in the grocery stores, they may have a limited awareness of the variety of food that nature offers. Access to information can be improved through digital communication channels and through decision support systems installed on smartphones. By reducing transaction costs between producers and consumers, digitalisation can support the establishment of biodiversity-based value chains clearly differentiated from conventional value chains.

Table 3: impact of digitisation on functional diversity

Target	**Impact of Digitisation**
A change of technical paradigms	Digitisation can support education and access to information and training. Platforms to share trial data
Raising consumers' and citizens' awareness	Social media to share knowledge; educational tools, support for decision tools
A system of interconnected biodiversity databases	Biodiversity Digitisation (Edwards et al., 2000), Knowledge sharing platforms (Hertz et al., 2016), Open Big data
Monitoring biodiversity in the systems	Satellites, drones, sensors, cloud, advanced analytics; AI for decision support systems
An ecosystem of farms with 'functional diversity' surpluses;	Improved communication between firms: B2B platforms
Availability of market and technical alternatives	Digitisation can substantially accelerate the phenotyping and genotyping (ICT applied to life sciences), improve the capacity to

	recognize and characterize genetic diversity (open database, AI), monitor biodiversity (sensors, citizens' science) (Duro et al., 2007). Decision support systems based on AI for recognition of biodiversity at farm level (Lin et al., 2019).
A change of business models	Blockchain can help to conserve identity of the genetic variety along the chain (Antonucci et al., 2019). Disintermediation can foster diversification of the B2B relationships to find market channels appropriate to product size and characteristics. Sensors and improved analytics can make social responsibility reports more accurate (Efimova & Rozhnova, 2018)
A change of consumers' practices	Education, improved access to information (footprinting)
Supporting policies	Monitoring impact of policies, mapping biodiversity distribution and risk

5. Recommendations and conclusions

New generation of ICTs are potential game changers. Their embodiment into existing socio-technical systems will change societal organization, generating winners, losers, and opponents. The risks related to digitization and able at diminishing a transition towards sustainable diets, already mentioned above, can be classified into three types. **Design-related risks** are inherent to the purpose and the quality of the technology design. For example, technologies may 'nudge' users to specific patterns of behavior, supporting existing unsustainable industrial agricultural models (e.g., monoculture, heavy use of external inputs, high degree of mechanization); could be vulnerable to cyber-attacks, have in-built bias, give inaccurate responses, lead to missed opportunities, be characterized by fast obsolescence, and cause privacy breaches. Risks related to **unequal access** to digital opportunities, that is the distribution of physical, social, and human capital necessary to get access to digital practices. Non-adoption or late adoption may enlarge the gulf between social groups and territories, generating social and economic marginalization. **Systemic effects** are related to the dynamics activated by the introduction of a given technology into a socio-technical system and generating consequences at a 'macro' level. Impact may be related to delayed, cumulative, or indirect or feedback effects. Here, we also see the risk of relying on single technologies and ignoring the full system. One of the issues raised about agricultural ICT is the need of technological ecosystems: given the interdependency between technologies, the introduction of a new technology would be ineffective without the right contextual conditions; e.g., increased productivity at farm level may generate unemployment at industry level; information on pollution may ignite social stigma on those who have, also accidentally, polluted; power imbalances related to data ownership may bring the creation of monopolies and loss of autonomy by weaker actors.

Considering these potential risks, for digitalization to be channeled toward societal interest will require a deep revision of the regulatory and governance contexts also in relation to food production and consumption. As ICTs can be game changers, anticipation of risks and benefits of digitisation should be strongly encouraged at all levels. When possible, regulation should avoid already known consequences, like breaches to privacy, concentration of power, cybersecurity (Demestichas et al., 2020). A key area of intervention in the food system is the digital divide. Besides the importance of ensuring regional access to broadband, it is important to prioritize access for disadvantaged groups, to launch broad programs of training to give all the opportunity to achieve basic ICT skills, and to develop design standards that avoid bias. Research and innovation policies should encourage the development of innovations tailored to small farming and small food business. Initiatives such as 'smart villages' aim at encouraging rural communities to look for digital solutions to their problems. Furthermore, a strong emphasis on **open data** would reduce substantially the cost of initiating service-providing start-ups, and affordable technological solutions would be possible. Increased information availability, linked to a distributed capacity to produce, use, and communicate knowledge, can increase the level of responsibility of actors.

In conclusion, technological advancement is so far largely separated from the assessment of socio-economic consequences since the approach to technology design is based mainly on performance remunerated by the market. Ethical considerations should be embodied into innovation processes and legislation and governance should ensure potential risks effects are not left just to individual innovators.

REFERENCES

Akyazi, T., Goti, A., Oyarbide, A., Alberdi, E., & Bayon, F. (2020). A Guide for the Food Industry to Meet the Future Skills Requirements Emerging with Industry 4.0. *Foods,* 9(4), 492.

Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L., & Menesatti, P. (2019). A review on blockchain applications in the agri-food sector. *Journal of the science of food and agriculture,* 99(14), 6129-6138.

Araújo, S.O.; Peres, R.S.; Barata, J.; Lidon, F.; Ramalho, J.C.. (2021) Characterising the Agriculture 4.0 Landscape—Emerging Trends, Challenges and Opportunities. Agronomy.

Bacco, M., Brunori, G., Ferrari, A., Koltsida, P., & Toli, E. (2020). IoT as a Digital Game Changer in Rural Areas: the DESIRA Conceptual Approach. In 2020 Global Internet of Things Summit (GIoTS) (pp. 1-6). IEEE.

Balafoutis, A., B. Beck, S. Fountas, J. Vangeyte, T. Van der Wal, I. Soto, M. Gómez-Barbero, A. Barnes, e V. Eory. (2017). Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. *Sustainability* 9(8), 1339.

Bikomeye J.C., Rublee C.S., Beyer K.M.M. (2021). Positive Externalities of Climate Change Mitigation and Adaptation for Human Health: A Review and Conceptual Framework for Public Health Research. *International Journal of Environmental Research and Public Health,* 18(5):2481. https://doi.org/10.3390/ijerph18052481.

Bronson, K. (2020). A digital "revolution" in agriculture?. In Duncan, J., Carolan, M., Wiskerke J. (Eds.), *Routledge Handbook of Sustainable and Regenerative Food Systems*. Routledge.

Canali, S., Antichi, D., Cristiano, S., Diacono, M., Ferrante, V., Migliorini, P., . Colombo, L. (2020). Levers and Obstacles of Effective Research and Innovation for Organic Food and Farming in Italy. *Agronomy* (Basel), 10(8), 1181.

Cazzolla Gatti, R., e C. Notarnicola. (2018). A novel Multilevel Biodiversity Index (MBI) for combined field and satellite imagery surveys». *Global Ecology and Conservation* 13.

Cobby Avaria, R. W. (2020). Searching for sustainability in the digital agriculture debate: an alternative approach for a systemic transition. *Teknokultura. Revista de Cultura Digital y Movimientos Sociales*, 17(2), 225-238

Cope, J.S., Corney, D., Clark, J.Y., Remagnino, P. & Wilkin P. (2012). Plant species identification using digital morphometrics: A review. *Expert Systems with Applications*, 39 (8), 7562–73.

Demestichas, K., Peppes, N., & Alexakis, T. (2020). Survey on Security Threats in Agricultural IoT and Smart Farming. *Sensors* (Basel), 20(22), 6458.

Devictor, V., & Bensaude-Vincent, B. (2016). From ecological records to big data: the invention of global biodiversity. *History and Philosophy of the Life Sciences*, 38(4).

Dubé, L., Du, P., McRae, C., Sharma, N., Jayaraman, S., & Nie, J.-Y. (2018). Convergent Innovation in Food through Big Data and Artificial Intelligence for Societal-Scale Inclusive Growth. *Technology innovation management review*, 8(2), 49-65.

Duro, D. C., Coops, N. C., Wulder, M. A., & Han, T. (2007). Development of a large area biodiversity monitoring system driven by remote sensing. *Progress in Physical Geography*, 31(3), 235-260.

Edwards, J. L., Lane, M. A., & Nielsen, E. S. (2000). Interoperability of biodiversity databases: biodiversity information on every desktop. *Science*, 289(5488), 2312-2314.

Efimova, O., & Rozhnova, O. (2018,). The corporate reporting development in the digital economy. In *The 2018 International Conference on Digital Science* (pp. 71-80). Springer,.

Ehlers, M. Huber, R., Finger, R. (2021). Agricultural policy in the era of digitalisation. *Food Policy*, 100, 102019.

García-Llorente, M., Rubio-Olivar, R., & Gutierrez-Briceño, I. (2018). Farming for Life Quality and Sustainability: A Literature Review of Green Care Research Trends in Europe. *Int J Environ Res Public Health*, 15(6), 1282.

Garske B, Bau A, Ekardt F. (2021), Digitalization and AI in European Agriculture: A Strategy for Achieving Climate and Biodiversity Targets? *Sustainability*,13(9):4652.

Vasileios, D., Gkisakis and Damianakis (2020). Digital innovations fo the agroecological transition: A user innovation and commons-based approach. *Journal of Sustainable and Organic Agricultural Systems*, 70(2), 1–4.

Herz, A., Matray, S., Sharifova, H., Wolck, A., Sigsgaard, L., Penvern, S. & Kelderer, M. (2016). EBIO-Network: a web-based platform for knowledge sharing on functional agrobiodiversity in organic apple production. In Ecofruit. 17th International Conference on Organic Fruit-Growing: Proceedings, 15-17 February 2016, Hohenheim, Germany (pp. 277-278). Fördergemeinschaft Ökologischer Obstbau eV (FÖKO).

Jensen, D., Campbell, J. (2019). The Case for a Digital Ecosystem for the Environment: bringing together data, algorithms and insights for sustainable development.

Kitano, H. (2002). Computational systems biology. Nature, 420(6912), 206.

Kuzmin, E., VanderSluis, B., Wang, W., Tan, G., Deshpande, R., Chen, Y. & Koch, E. N. (2018). Systematic analysis of complex genetic interactions. *Science*, 360(6386), 1729.

Li, C. (2020) Biodiversity assessment based on artificial intelligence and neural network algorithms. *Microprocessors and Microsystems* 79 (2020).

Lin, C., Wang, J., & Ji, L. (2019). Notes of Life: A platform for recording species observations driven by artificial intelligence. *Biodiversity Information Science and Standards*, 3.

Marescotti, A., Quiñones-Ruiz, X. F., Edelmann, H., Belletti, G., Broscha, K., Altenbuchner, C. & Scaramuzzi, S. (2020). Are Protected Geographical Indications Evolving Due to Environmentally Related Justifications? An Analysis of Amendments in the Fruit and Vegetable Sector in the European Union. *Sustainability*, 12(9), 3571.

McClements, D. J. (2020). Future foods: Is it possible to design a healthier and more sustainable food supply?. *Nutrition bulletin*, 45(3), 341-354.

Nikolaou, G., Neocleous, D., Christou, A., Kitta, E., & Katsoulas, N. (2020). Implementing Sustainable Irrigation in Water-Scarce Regions under the Impact of Climate Change. *Agronomy*, 10(8), 1120.

Rijswijk K., Klerkx L., Bacco M., Bartolini F., Bulten E., Debruyne L., Dessein J., Scotti I., Brunori G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. *Journal of Rural Studies*, 85, 79-90.

Rijswijk, K., Klerkx, L., Bacco, M., Bartolini, F., M., Bulten, E., Debruyne, L., Dessein, J, Scotti, I., Brunori, G. (2021). Digital transformation of agriculture and rural areas: A socio-cyber-physical system framework to support responsibilisation. *Journal of Rural Studies*, 85, 79-90.

Rincon-Patino, J., Lasso, E., & Corrales, J. (2018). Estimating Avocado Sales Using Machine Learning Algorithms and Weather Data. *Sustainability*, 10(10), 3498.

Sadhukhan, J., Dugmore, T. I. J., Matharu, A., Martinez-Hernandez, E., Aburto, J., Rahman, P. K. S. M., & Lynch, J. (2020). Perspectives on "Game Changer" Global Challenges for Sustainable 21st Century: Plant-Based Diet, Unavoidable Food Waste Biorefining, and Circular Economy. *Sustainability*, 12(5), 1976.

Sam, A. K., & Grobbelaar, S. S. (2021). Research Trends, Theories and Concepts on the Utilization of Digital Platforms in Agriculture: A Scoping Review. In *Conference on e-Business, e-Services and e-Society* (pp. 342-355). Springer, Cham.

Serazetdinova, L., Garratt, J., Baylis, A., Stergiadis, S., Collison, M., & Davis, S. (2019). How should we turn data into decisions in AgriFood?. *Journal of the science of food and agriculture*, 99(7), 3213-3219.

Skinner, G. A. (2015). Smart labelling of foods and beverages. In Berryman, P. (Ed.). *Advances in Food and Beverage Labelling* (pp. 191-205). Woodhead Publishing.

Smetana, S. M., Bornkessel, S., & Heinz, V. (2019). A Path from Sustainable Nutrition to Nutritional Sustainability of Complex Food Systems. *Frontiers in nutrition*, 6, 39-39.

Sposato, P., Preka, R., Cappellaro, F., & Cutaia, L. (2017). Sharing economy and circular economy. How technology and collaborative consumption innovations boost closing the loop strategies. *Environmental Engineering & Management Journal*, 16(8).

Steenweg, R., Hebblewhite, M., Kays, R., Ahumada, J., Fisher, J. T., Burton, C., & Brodie, J. (2017). Scaling-up camera traps: Monitoring the planet's biodiversity with networks of remote sensors. *Frontiers in Ecology and the Environment*, 15(1), 26-34.

Tang, Z., M. Jiang, J. Zhang, e X. Zhang. (2018). Applications of satellite and air-borne remote sensing in biodiversity research and conservation. *Biodiversity Science* 26(8) 807–18.

Taranic, I., Behrens, A., & Topi, C. (2016). Understanding the circular economy in Europe, from resource efficiency to sharing platforms: The CEPS framework. CEPS Special Reports, 143.

Tsolakis, N., Niedenzu, D., Simonetto, M., Dora, M, Kumar, M. (2021). Supply network design to address United Nations Sustainable Development Goals: A case study of blockchain implementation in Thai fish industry. *Journal of Business Research*, 131, 495-519.

Van Wassenaer, L., van Hilten, M., van Ingen, E., van Asseldonk, M., (2021). Applying blockchain for climate action in agriculture: state of play and outlook. Rome/Wageningen, FAO and WUR.

Yesson, C., W. Brewer, P., Sutton, T., Caithness, N., Pahwa, J., Burgess, M., Gray, A. et al. (2007). How Global Is the Global Biodiversity Information Facility?. *Plos one*, 2(11), 1124.

Young, O. R., Berkhout, F., Gallopin, G. C., Janssen, M. A., Ostrom, E., & Van der Leeuw, S. (2006). The globalization of socio-ecological systems: an agenda for scientific research. *Global Environmental Change*, 16(3), 304-316.

Zeb, A., Soininen, J, Sozer, N. (2021) Data harmonisation as a key to enable digitalisation of the food sector: A review. *Food and Bioproducts Processing*, 127, 360-370.