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4

Digital technology and agroecology: opportunities to explore, challenges to overcome

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Digital technology is going to have a significant impact on agriculture. But will this impact be positive or negative? Some, such as *Rotz et al.,* (2019), fear that digital technology will lead to an increase in market integration and corporate concentration; while others, such as *Bonny* (2017) contest this conflict, provided changes are made to governance and provided there is effective communication with the wider public. At the same time, a number of authors have mooted the possible convergence between agroecology and digital technology (*Bellon Maurel and Huyghe,* 2016; *Biradar et al.,* 2019; *Caquet et al.,* 2020; *Grieve et al.,* 2019; *Klerkx and Rose,* 2020; *Wegener et al.,* 2017). The term 'agroecology' is used to refer to both the scientific discipline and an agricultural movement or model based on a set of alternative practices, the aim of which is to build viable food systems which respect both mankind and the environment. As pointed out by *Altieri* (1989), it incorporates both technical and socio-economic aspects all the way along the production chain (what is produced, how it is produced and for whom). Agroecological production is designed to improve agricultural systems through the use of environmentally-friendly processes, with a particular focus on biological synergy between the component parts of the agroecosystem and balancing out the "inputs and outputs" of the system, a lever also known as "closing the cycle".

This chapter will focus on the opportunities and challenges presented by digital technology for agroecology in its broadest sense, i.e. sustainable food systems. As an "enabling technology", digital is capable of increasing the capacities of farmers to respond to four major challenges:

- improving production, in line with the principles of agroecology, by creating knowledge to support the agroecological transition and by adapting to exogenous factors, namely climate change;
- improving production by assisting farmers with the running of their farms;
- better establishing farmers within the agricultural ecosystem, i.e. regional ecosystems and value chains;
- improving sharing, learning and understanding by supporting the agroecological transition: sharing data, information and knowledge.

The specific challenges facing the Global South will also be explored.

4.1 Improving production: creating knowledge to support the transition towards agroecology

The scientific and technological knowledge that will support the transition towards new systems of production (including organic farming, integrated pest management and agroforestry) are still being developed. But in order to ensure the widespread deployment of agroecological models and to enable them to be scaled up, there is an urgent need to understand the mechanisms involved (*Altieri et al.,* 2012) and to establish points of reference (*Vanloqueren and Baret,* 2009). In agroecology, all levels of diversity and biological regulation – within species, between species or functional (plant-animal interaction, landscape ecology, etc.) – can be deployed in order to make systems resilient (*Caquet et al.,* 2020). The flipside is the abundance of possibilities – of varieties to choose, species assemblages, interaction between crops and livestock – which makes it impossible to create knowledge out following conventional paths. Faced with this challenge, new modes of building knowledge must be developed, and digital technology can contribute to this vital step for the agroecological transition (*Leveau et al.,* 2019) using three interconnected levers: (i) the modelling of agroecological complex systems, which requires a holistic approach; (ii) data collection on these new cropping growing and breeding methods, chiefly through the participatory collection of information; (iii) the inference of models on these new production systems, based on data.

Connected insect trap. © *Le mas numérique.*

Representing complex systems within agroecology

Modelling in agroecology is very much on the rise but it remains a complex subject.[44] Agroecological modelling can only have any meaning if it incorporates interactions within the farm, or even at a landscape level (Tixier et al., 2013). It is a delicate task. *Antle et al.* (2017) have identified a number of points which must be addressed in order to build next-generation models for use in agroecology: (i) improving existing modelling in order to factor in uncertainty or extreme events; (ii) transitioning from cropping systems to production systems; (iii) modelling complex rotations and crops; (iv) modelling links between crops and animal production; (v) upscaling , from fields to the wider landscape; (vi) interoperability. "Unit models" used to describe each compartment of the system must also be developed. Furthermore, looking towards the wider landscape leads to the emergence of new scientific frontiers relating to a "greater understanding of population dynamics and the role of interfaces between cropping environments and natural environments, about which little has been written" (*Caquet et al.,* 2020). More, there are a number of challenges linked to modelling within farms, owing to the fact that farms are complex systems, which should be managed using a combination of socioecological and sociotechnical models (*Bergez and Thérond,* 2019).

Large scale data collection for new agroecosystems

A lack of data and difficulties accessing it can prove a hindrance to improving and using models. However, there has been a phenomenal increase in the quantity of data on agriculture: in 2014 around 190,000 pieces of data were estimated to be produced each day on a farm in the USA, and by 2050 more than 4 million pieces of data could be produced each day (*Rotz et al.,* 2019). This data comes from connected objects (*Elijah et al.,* 2018), fixed sensors (weather stations, connected traps, various different types of alarm, etc.), sensors embedded into machines (used to monitor the machine or crops), sensors worn by animals (activity sensors, boluses for measuring temperature, trackers) or sensors carried by human operators (mobile phones). Given the variety and the volume of agricultural data, it may now become more and more appropriate to use the term "agricultural big data" (*Bellon-Maurel et al.,* 2018). Indeed, data is essential for the purposes of creating models of complex mechanisms within agroecology, which are difficult to model using a deterministic approach. In order to develop such models, systematic quantifications and observations must be carried out within agricultural production systems at different levels (*Biradar et al.,* 2019). *Chowdhary et al.* (2019) have discussed the issue of the lack of reference points, the phenotyping bottleneck which is

44. *Caquet et al.,* (2020) identified no fewer than 107 models at Inra in 2018.

holding back agroecology and agroforestry. For this reason, the development of knowledge in these areas will require an increase in high-throughput phenotyping capacities in diverse environments, through the deployment of high-throughput phenotyping on farms (in fields or in herds). This raises questions regarding devices for phenotyping. Phenotyping is currently performed by researchers and farmers using expensive measurement devices such as buggies or other automated platforms in fields[45]. A number of authors (*Caquet et al.,* 2020; *Grieve et al.,* 2019; *Ingrand,* 2018) have recommended developing phenotyping on a large-scale or the continuous monitoring of crops, animals and environmental conditions. This would require affordable and easy-to-use measurement devices, which either proximate – e.g. the portable sensors developed by the CAPTE unit – or remote sensors – e.g. Sentinel 2 satellites, which deliver resolution of ten metres with a three to five day revisit time (*Biradar et al.,* 2019) – to assess the physical and physiological characteristics of plants and animals (*Reynolds et al.,* 2019).

Data-based modelling: a step towards new knowledge

The possibilities which artificial intelligence opens up for extracting knowledge from data in agriculture – particularly "big data" or "smart data" – have been well documented (*Pham et Stack,* 2018; *Wolfert et al.,* 2017), but do not specifically concern agroecology. Those authors who have studied the use of neural networks in agroecology (*Jiménez et al.,* 2008; *Schultz et al.,* 2000) have noted several key aspects: (i) the issue of validating the models obtained and uncertainty; (ii) the need to organise systems into simpler sub-systems which neural networks will be applied to and (iii) the importance of considering inference, often compared to a black box, as a stepping stone towards a more analytical model.

4.2 Improving production: using digital technology to assist farmers with the running of their farms

According to *Caquet et al.* (2020), *"the capacity of digital technology and agricultural equipment to specifically support agroecology remains a challenge".* One of the five *"main sectors"* to come to terms with concerns *"the characterisation of environments, plants or livestock with a view towards improving management and analysis".*[46] The question of decision support is also posed, and all the more

45. See for example the *Field Scanalyzer* from *Lemnatec,* the *Phenomobile* or the buggy marketed by *Hiphen,* the *Fieldscan* from *Phenospex,* etc.

46. Others are: *"the sharing of information between regional stakeholders", "agricultural equipment for the specific needs of agroecology", "characterising the response of organisms for phenotyping purposes"* and *"traceability for operating methods".*

pressing given the multiple objectives in play on farms. "Scaling up" to a highly transformative form of agroecology (redesigning systems) will require new tools, and digital technologies could play a key role when it comes to (i) improving management along the season (which calls for precision agriculture or precision livestock farming) or at a strategic level (incorporating economic data); and (ii) improving agricultural operations, with agricultural equipment designed for more complex agricultural systems requiring more work.

Adapting the principles of precision agriculture to agroecology: observing and taking decisions

The principles of precision livestock farming and precision agriculture can be applied to agroecology since they lead to interventions tailored to suit plants and animals needs. They centre around a four-stage: observation (measuring "symptoms"), diagnosis (identifying the status of a plant or an animal), recommendation (determining the action to take), and action. With precision agriculture it is possible to map diversity within crops and to apply different measures to different parts of a plot (*Bellon and Huyghe,* 2016): nitrogen fertilisation (using satellite sensors from the early 2000s onwards and now tractor-

Takeoff of a mapping drone in Senegal. © CIRAD.

embedded technology; precision irrigation (*Molden,* 2007), drawing on estimates of water scarcity using "proxies" (the temperature of the surface of leaves, visual estimation of physiological characteristics);[47] and crop protection, which is the most complex aspect given the wide ranging nature of phytosanitary problems (weeds, insects and other pests, and diseases). Precision livestock farming involves tracking environments conditions (measuring the atmosphere within buildings or external conditions) and animals. Over the past twenty years or so, sensors on animals or in their environments have been used, particularly on dairy farms: identification and tracking using RFID and GPS, imaging (2D, 3D, infrared), accelerometers, sounds, automated measurement devices (scales, water meters, milk meters, feed distributors, etc.) (*Chastant-Maillard and Saint-Dizier,* 2016). Various different parameters are monitored: growth, milk production, food ingestion, physiological status, behaviour, reproduction, health and well-being (detecting lameness, digestive issues, etc.)... (*Benjamin and Yik,* 2019; *Fournel et al.,* 2017; *Halachmi et al.,* 2019; *Knight,* 2020; *Neethirajan,* 2017; *Rowe et al.,* 2019; *Veissier et al.,* 2019; *Xin and Liu,* 2017). Currently, these techniques are primarily targeted at conventional livestock farming, but solutions are being developed for alternative systems. These include devices for monitoring animals and pasture (*Shalloo et al.,* 2018) in order to improve the efficiency of extensive grazing systems - which would otherwise be limited by a lack of data – and to guarantee consumers responsible livestock breeding (*Neethirajan,* 2017).

There are two crucial questions when it comes to the management of agro-ecological systems:

(1) Regarding observation, this relates to the early detection of malfunctions. For both cropping (*Divya and Santhi,* 2019; *Johannes et al.,* 2017) and livestock farming (*Ingrand,* 2018), this is crucial for alternative farms (agroecology, organic farming, integrated pest management) seeking to scale up without access to the same range of curative measures as conventional farms. Out in the fields, visual observation takes up a lot of time, is dependent on the experience and the availability of the observer (*Mul et al.,* 2016) and sometimes impossible to implement if the problem is undetectable. Technologies are marketed or still in the research phase: (i) optical devices for plants monitoring and detection of winged insects (*Brydegaard et al.,* 2014; *Grieve et al.,* 2019), (ii) quantification of spores using real-time analysis of bioaerosols, not yet satisfactory (*Sharma Ghimiri,* 2019), (iii) connected insect traps (*López et al.,* 2012), (iv) animal monitoring devices (*Li et al.,* 2020; *Moura et al.,* 2008; *Tullo et al.,* 2018; *van Hirtum and Berckmans,* 2004) and, more recently, so-called "portable" devices, which are worn by animals (*Neethirajan,* 2017).

47. Apex Vigne- https://www.hdigitag.fr/fr/application-mobile-apex-vigne-facilite-le-suivi-de-la-croissance-de-la-vigne/

(2) Regarding decision-support, this relates to building models to supply information which can be used in decision-making. *Lepenioti et al.* (2020) identified three types of data processing: (i) descriptive analysis, answering questions such as "What is the value of the parameter in question? How do levels compare to other producers or other years? What has happened?" (ii) Predictive analysis, answering questions such as "What is going to happen?" and "Why?" and (iii) prescriptive analysis, answering questions such as "What is the recommended course of action?". The level of complexity for these models is growing, as are problems linked to interpretability and uncertainty. There are methodological bottlenecks linked to how models are built: which symptoms are to be selected to incorporate, into the models?, how are symptoms expressed due to natural variability? and, when it comes to recommendations, what are the other factors inherent to plants or animals, the environment, production or breeding systems (factoring in other individuals from their group), the equipment used and the agricultural strategy employed?

Multi-objective decision-making in agroecology

Strategic decision-making with regard to how farms are run is quite different in agroecology because farmers objectives tend to be multivariate (optimising the three dimensions of sustainability)[48] and multitemporal (short and long term). This raises certain questions with regard to modelling such as: (i) determining the optimum in a multi-level, spatio-temporal system; (ii) incorporating the farmer's strategy into optimisation models (*Antle et al.*, 2017; *Groot et al.*, 2010); (iii) dealing with uncertainty. The use of alternative modelling methodologies and risk management protocols is also to be explored: the aim here is not to seek out an optimum compromise but to keep the system within possible desired outcomes.

Co-designing innovative agricultural equipment and agroecosystems

Technology has the capacity to play a key role when it comes to scaling up within agroecology, where the level of technical complexity is greater than in monoculture farming (*Wegener et al.*, 2017). Mixed culture farming (multiple species, multiple varieties) or intercropping could be implemented on a large scale through high-precision operations (from sowing to harvest) and the characterisation or the sorting of mixed products from harvests. In agroforestry, trunks are an impediment to the mobility of traditional machinery, preventing them from being adopted (*Mattia et al.*, 2018), but there are few technological solutions; Chowdahry et al. (2019) have suggested developing small, inexpensive "soft

48. The economic, environmental and social.

robots" with flexible arms, operating in networks. For livestock farming, milking robots capable of being transported into pastures could help to bring about a more generalized return to grazing (*Cloet et al.,* 2017). Lastly, in relation to the well-being of farmers or employees, the objective is to reduce tasks which are hazardous, tiring or time-consuming (*Vasconez et al.,* 2019). This concerns vegetable growing and arboriculture in particular: weeding robots sold for use in market gardens; inexpensive, open-source weeding robots for microfarms (*Farmbot, LettuceThink*); harvesting robots – currently a sticking point for market gardens and in arboriculture because of the expense – and most notably collaborative robots or cobots (*Vasconez et al.,* 2019).

Robots would be capable of overcoming constraints in new crop and livestock farming systems, with productivity equal to that of current practices. Collaborative work, either between small robots operating in swarms or between robots and humans (cobots) is a possible avenue to explore. Bottlenecks are the cost of robots (linked to their multifunctionality), how collaborative work is organised (between robots or with humans), perception and gripping, and safety (mobility, interaction with humans). In order to deploy this technology, challenges linked to its environmental impact (manufacturing, use, end of life) and resiliency (repairability, adaptability and autonomy) will also need to be overcome. Participatory design could provide a means of successfully developing robots for use in agroecology, reducing tensions between approaches based on ecology and those based on the benefits of technology (*di Salvo et al.,* 2014). In Denmark the ITU (IT University of Copenhagen) has sought to alleviate these tensions by considering robots as a part of the ecosystem ("robotics agroecology").[49]

Lastly, there is the issue of the divide between major farms are likely to adopt robots and smaller, unconventional farms which either do not adopt them or are late to adopt it (*Caquet et al.,* 2020). It could be avoided by combining a frugal approach with a high-tech approach, similar to the ones of the 'high-low tech' research group (MIT; [50] *Kadish and Dulic,* 2015) and "makers" approaches (*Anderson,* 2012).

49. https://real.itu.dk/projects/robotic-agroecology/

50. http://highlowtech.org/

4.3 Improving integration within the agricultural regional or economic ecosystem

Aside from the potential benefits for agricultural production, digital technology could reshape the way in which farmers – in the context of the agroecological transition – interact with the agricultural ecosystem, both in terms of the economic sector (upstream with agricultural services or downstream through value chains) and land management..

Agricultural services reshaped by digital technology

Advice – Advice is very much central to innovation systems in agriculture (*Labarthe,* 2009). It encourages interaction between stakeholders within these systems: agricultural organizations (including cooperatives), research institutions, NGOs, public bodies, industries both upstream and downstream, intermediaries, etc.

The question of the impact of digitalisation on farming advice services has been the subject of recent research (*Fielke et al.,* 2020), and there are projects aimed at supplying farming advisors with the digital tools they need, drawing on participatory design.[51] Digitalisation has had a significant impact on the activity of advisors, both at front office level (new interfaces and applications linking advisors to farmers) and back office level (developing new services *via* the widespread use of data or agronomic models). But alongside digitalisation, we have also seen the emergence of new players (start-ups, firms from the IT sector) capable of completely overhauling technical advice services and the dynamics of agricultural innovation systems (*Fielke et al.,* 2019).

At the same time, a number of public policies have been introduced at EU, national and regional level in relation to farming advice, the aim being to contribute towards the sustainable development of agriculture (*Dhiab et al.,* 2020). Here there are two issues at stake. On one hand, digitalisation is set to transform the very nature of farming advice; on the other, advice must support the digitalisation of agriculture in the interests of sustainable development, overcoming social, economic or environmental contradictions linked to digital technology: possibilities of inequality of access to information, of unsuitability of digital solutions, of loss of autonomy, of risk of power imbalances or locking (see Section 5: risks).

51. See, for example, the EU projects https://www.h2020fairshare.eu/ or https://www.agrilink2020.eu/

Insurance – Financial protection is essential when it comes to improving living standards within agriculture, owing to its sensitivity to adverse weather. There are various different systems, either in the form of funds (e.g. 'agricultural disaster funds') or in the form of insurance, irrespective of whether or not this is private. These different systems provide compensation for damages, which digital technology can help to identify. Insurance is either "traditional" – based on claims for losses (harvests, yield, etc.) – or, more recently, "index-based", whereby clients are compensated based on indexes linked to these losses (*De Leeuw et al.,* 2014): regional performance indexes, climate indexes, indexes based on satellite imaging (*Vroege et al.,* 2019), composite indexes (*De Leeuw et al.,* 2014). Digital technology could help to improve index-based insurance through observation systems and modelling. When it comes to building indexes, information – traditionally taken from public authorities (weather forecasts, spatialised estimated yield) (*De Leeuw et al.,* 2014; *Rao,* 2010) and remote sensing (*De Leeuw et al.,* 2014; *Vroege et al.,* 2019) – must verify four principles, which is not trivial: it must be (i) worthy of trust and verifiable, (ii) closely correlated with the damage, (iii) continuously accessible and (iv) collected over a sufficiently long period of time (*Vrieling et al.,* 2014). In traditional insurance models are used to estimate contingencies, whereas in index-based insurance the data is linked to the damage using the index. The imperfect correlation between the index and the damage is the "baseline risk", which is sought to be reduced by creating composite indexes, e.g. by combining satellite data, climate data and even land use data (*De Leeuw et al.,* 2014; *Rao,* 2010; *Vroege et al.,* 2019). The dangers lie in (i) creating complex indexes which farmers are unable to interpret (*Vroege et al.,* 2019), (ii) incorrectly incorporating weather patterns caused by climate change, further complicating the relationship between meteorological data and output, and (iii) the incorrect use of big data – multisource, multiresolution, non-stationary – in the parametric statistical analysis of traditional actuarial models (*Ghahari et al.,* 2019).

Reshaping value chains with greater market connectivity

Digital technology opens up possibilities for remodelling both the food system and value chains. In global chains it can reduce commercial costs, ensure compliance with standards and facilitate international trade, while in shorter chains it can increase the visibility of and ensure transparency. In this way it gives power back to those at either ends of the value chain: small farmers and consumers (*Jouanjean,* 2019).

Platformisation – Platforms are central to new economic channels for sales of agricultural products, food or services (e.g. in agriculture cofarming.info, hellotractor.com) (*ANRT,* 2018). These open interfaces intermediate between suppliers and clients, delivering technical and economic synergy (*Tirole,* 2016). The fact that they are free and easy to use helps to get as many users as possible to engage with them, which is the main value proposition for encouraging suppliers to use a given platform (*Leibovici,* 2015). E-commerce in the agribusiness sector concerns giants such as Walmart and Amazon, but it can also be found at a local level, with a new model for rural and agricultural development borrowing from both modern approaches (based on globalisation) and postmodern approaches (centred around regional integration) (*Rieutort,* 2009). Many regional authorities are seeking to build platforms aimed at matching supply to demand and thus enabling isolated rural areas to access high-value market segments and to create stable relations with consumers in urban areas –, supplying school cafeterias and satisfying citizens expectations,, in both the Global North and Global South (*IPES-Food,* 2016). Through digital technology and platforms, the global market for "collaborative" consumption is expected to grow from 15 to 335 billion dollars between 2017 and 2030 (*Claquin et al.,* 2017). This level of development will require tailored logistics, which could also draw upon digital technology (*Messmer,* 2013).

There are two bottlenecks for these new channels: visibility of the offer and logistics. The offer is currently scattered across multiple platforms, limiting the network effect (Metcalfe's law) and, therefore, the appeal of platforms, which find it difficult to identify an economic model. Furthermore, a lack of digital and logistical flexibility are significant obstacles to farmers joining these platforms. Collective catering requires food to be sourced locally (EGAlim law): how can this be ensured and kept secure with a fragmented offer? Research – particularly operational research – could be called upon for the purposes of planning this fragmented supply, for the management of distributed databases (across various platforms) and to devise logistics systems compatible with these fragile but low added value products.

Traceability and trust – The traceability of both human and animal food is mandatory between companies (the EU's General Food Law from 2002) and optional within companies. Intra-company monitoring has become widespread in factories through automation and information systems (*Fountas et al.,* 2015), but take-up has been less common in agriculture (*Galliano and Orozco,* 2011): in France, technical and economic monitoring software is used by an average of 7% of farmers within collective organisations, with a significant amount of variability (between 2 and 35%)[52] This is a growing market (in the USA it is expected to double between 2016 and 2023, growing by more than 14% year on year)[53]

52. http://agrotic.org/observatoire/2017/11/06/usage-du-numerique-pour-la-gestion-technico-economique-des-exploitations-agricoles/

53. https://www.marketsandmarkets.com/Market-Reports/farm-management-software-market-217016636.html

given the desire to automate data capture in order to prevent input errors and to reduce people's workloads: optical codes (barcodes, QR codes), electronic codes such as RFID (*Luvisi,* 2016), voice recognition (*Bellon-Maurel et al.,* 2014), etc. The recording of practices will result in the massification of private data, which could be valued by providing consumers with better information on production conditions, meeting their expectations (*Jouanjean,* 2019). The emergence of "hyper-transparency" (*Kos and Kloppenburg,* 2019) has transformed the way in which the value chain is governed, with new roles for consumers – who influence distributors and processors – and for small farmers, who are better paid by buyers willing to pay a higher price for desired "properties", including a fair price for farmers (*Jouanjean,* 2019). This has a double effect in that it helps consumers to make an informed choice while also helping producers to show that they have adopted improved practices and standards through labelling (*Gardner et al.,* 2019; *Kos and Kloppenburg,* 2019) justifying the willingness to pay (*Caquet et al.,* 2020). Similarly, this is a key aspect of (largely voluntary) sustainability certification initiatives (*Mol et Oosterveer,* 2015), which could contribute to participatory guarantee systems – eliminating the need to pay third parties for checks – or assist with carrying out "automatic" LCAs (Life-Cycle Assessments) (*Bellon-Maurel et al.,* 2014, 2015; *Miah et al.,* 2018).

In this push for transparency, technology which helps to build trust – a key issue – can be drawn upon (*Jouanjean,* 2019). Blockchain technology is a good example of this. The blockchain is a transparent and secure means of storing and sharing information which operates without any central control body[54]: it is a distributed system with no central authority. It creates a database recording all previous exchanges that is shared by different users, allowing the validity of the data to be verified. However, in supply chains, implementing blockchains is far from straightforward. The problem is that while the blockchain guarantees the validity of the information shared (its origin, its integrity and its temporality), it cannot guarantee its truthfulness, i.e. consistency between data flows and product flows. This issue is currently dealt with using data consolidation (building confidence indexes in relation to the data) or technology (RFID,[55] combining RFID/3D videogrammetry/digital fingerprints (*Gopalakrishnan and Behdad,* 2019). Lastly, given that food products are perishable, it is worth tracking them across the logistics chain, particularly if they are long, by recording data during transport: quick identification of who is responsible in the event of a defect, anticipated reassignment of products in the event of a breakdown, preventing food waste, detecting the falsification of products during transit (*Jouanjean,* 2019).

54. https://blockchainfrance.net/

55. https://www.wwf.org.nz/what_we_do/marine/blockchain_tuna_project/

Find out more

Was hypertransparency in 2017 driven by the launch of the brand *"C'est qui le patron?"* (CQLP - which translates as "Who's the boss?")? Using the internet, CQLP worked with consumers to design a range of ethical products (in terms of the price paid to producers), questioning them on products' technical and social specifications and willingness to pay accordingly. Another example is Yuka, an application which provides "information on health impact" based on the open database *Open Food Facts*[56] (670,000 products referenced by consumers in April 2020), helping to change consumption patterns and influencing manufacturers, who will change the formulation of products which receive a low score.[57]

However, some authors have expressed concerns regarding the risks of this hyper-transparency: it is only partial and will guide our priorities (Gardner et al., 2019), it could exclude small farmers (*Jouanjean,* 2019; *Kos and Kloppenburg,* 2019) and it could require assistance from private intermediaries, increasing the asymmetric nature of information. Lastly, there is no guarantee that it will benefit farmers. It also assumes that consumers will be willing to pay for these attributes (quality, origin, social/environmental footprint).

Managing resources at a regional level

Regional governance can be defined (*Rey-Valette et al.,* 2011) as *"a dynamic process of coordination on the subject of regional issues held between public and private stakeholders with multiple identities and asymmetric resources, working together to set objectives and initiatives by implementing multiple schemes centred around collective learning and which contribute towards both institutional and organisational innovation at a regional level."*

Agriculture is taking on an increasingly prominent role in regional projects, not only because of its impact on land planning, but also because of the reterritorialisation of the food production, which is now seen as a way of promoting regional resilience (*IPES-Food,* 2016). The agroecological transition is strengthening the position of agriculture within this regional dialogue owing to the fact that

56. https://fr.openfoodfacts.org/
57. https://www.franceinter.fr/yuka-l-application-qui-force-intermarche-a-revoir-ses-recettes

landscape ecology – which is crucial to the success of the agroecological project – requires a collective approach at a regional level. Furthermore, the closing of the cycles (nitrogen and carbon), – an essential lever of agroecology, can take place beyond the farm at a regional level, employing a "circular biomass economy". Digital technology is opening up various types of opportunities in this field.

Within regions, new biobased and circular economies are being established: agricultural waste is becoming a resource (*Klerkx et al.,* 2019), with the recent emergence of specialist platforms, marketplaces for organic materials (e.g. *Organix* from *Suez*) or for trading food products with short shelf lives (the app *toogoodtogo*). Knowledge of the material flows involved at each stage of the process (production, processing, exchange, consumption, waste) is gaining interest when it comes to (i) questioning the use of natural resources and identifying any problems with competing uses (e.g. first generation biofuels vs. food use, feed for livestock animals vs. food for human consumption), (ii) understanding vulnerabilities both upstream and downstream (e.g. dependence on imports), and lastly (iii) estimating environmental footprints (e.g. carbon, energy, water, chemical pollution, soil use, etc.) (*Bioteau et al.,* 2013). Over and above these purely quantitative aspects, involving both environmental science and digital science, the social sciences will have a vital role to play in understanding how the networks controlling flows or affected by them operate. There are two issues at stake here: the re-integration of agricultural production at a regional level (material and social integration) while staying within planetary limits. What is more, the deployment of a biobased economy at a European, national and local level will require consistency between levels and between regions when it comes to implementing plans of action; but, presently, there is little evidence of such a multi-level vision.

Digital technology will also expand the "tool kits", helping regional bodies to promote dialogue both within agriculture and with other regional stakeholders. This should help with the coordination, participation and education of stakeholders and with the adoption of new digital-based practices. More generally, it should serve the development and management of regional projects, ensuring their development models allocate an inclusive, explicit place to agriculture.

Further research will be needed in digital science and technology in order to (i) compensate for the lack of data at a regional level and on systems about which there is little knowledge, (ii) improve the temporal and spatial modelling and representation of these systems and the visualisation of models' outputs, (iii) promote mediation between stakeholders, and (iv) secure systems and information channels.

4.4 Supporting the transition: sharing data, information and knowledge

Farmers and sectors must be supported in the agroecological transition, as it brings with it a significant amount of risk. This support must be compatible with the agroecological approach, which promotes *"individual and collective learning [as] a source of innovation"* (*Meynard,* 2017), drawing upon: (i) modelling, combined with indications regarding uncertainty in order to identify bottlenecks, risks and capacity for resilience; (ii) collective learning; (iii) risk identification and socio-economic and the relevant support (*Caquet et al.,* 2020). This chapter outlines the response from digital technologies when it comes to sharing and learning.

Digital technology: an asset for sharing knowledge

With regard to the deployment of the principles of agroecology, traditional knowledge – often specific to regions (*Altieri et al.,* 2012) – must be protected: this will involve strengthening human capital through training and participatory initiatives which take into consideration the needs, expectations and circumstances of small farmers (*Calvet-Mir et al.,* 2018). Knowledge-sharing platforms, featuring different levels of mediation, facilitate the gathering, exchange and distribution of knowledge: videos on agroecological practices produced by mediators linked to farmers (*AccesAgriculture, DigitalGreen,*[58] *Osea,* etc.) (*Bentley et al.,* 2019), knowledge gathered from farmers (like with CONECT-e, which created digital commons on traditional varieties for preventing the erosion of knowledge and hoarding by commercial companies) (*Calvet-Mir et al.,* 2018), social media platforms without mediation (YouTube), etc. *Wyckhuys et al.* (2018) identified two points which are important for the success of digital technology in the adoption of new practices: (i) guaranteed access to digital technology, overcoming technical, psychological and organisational obstacles, and (ii) using the knowledge and practices employed by farmers as a basis for devising digital-based training courses. Digital technology also makes it easier for parties to work together to create knowledge, an appropriate strategy for agroecology given the way in which it "combines different types of knowledge: traditional knowledge, indigenous knowledge and scientific knowledge, in addition to knowledge from farmers" (*Milgroom et al.,* 2016). According to *Wyckhuys, et al.* (2018), this social learning is well-suited to dealing with agricultural problems in that it opens up a space for different points of view, recognising diversity and local knowledge. For this reason, these authors recommended drawing on participatory experiments employing the use of digital devices (tablets): the Digital Farmer Field Schools.

58. More than 5,000 videos, in 50 languages, produced over 10 years with support from DigitalGreen (www.digitalgreen.org)

However, there remain obstacles to exchanges between peers and individual learning, whether technological (identifying technology for capitalising on and promoting exchanges) or sociological (identifying which modes of learning to promote).

A participatory approach and open innovation

The participatory approach is the cornerstone of open innovation and living labs, open innovation initiatives in which citizens, residents and users are given a key role in research and innovation processes. In agriculture, living labs can be supported by research initiatives around experiments involving agroecological systems or implemented within regional innovation projects. Open innovation is vital to agroecology: devising "pathways" (plausible future scenarios) and transition scenarios (instantiation of the model in accordance with the pathways identified) (*Antle et al.,* 2017), the best way of representing phenomena occurring at different levels (biological processes, farm management, optimisation) (*Groot et al.,* 2012). Digital tools are extremely useful for these participatory processes, in that they can be used to (i) store information from participatory workshops; (ii) show and visualise data (current, future, dynamic views... of the region); (iii) equip participatory processes (modelling and scenario-building tools, serious games, etc.); (iv) share and disseminate knowledge; (v) create new knowledge, drawing on the diversity of knowledge, discussions and interactions; (vi) create links between farmers, between farmers and researchers, between farmers and wider society, etc. (*Bergez et al.,* 2016; *Enkel et al.,* 2020; *Leveau et al.,* 2019). Some tools, such as boundary objects, make it easier to analyse compromises and multi-criteria representations during participatory workshops (*Duru et al.,* 2015). This includes companion models (*Barreteau,* 2003). To deal with any issues stakeholders may have in understanding models and in order to stimulate interactivity (*Bécu et al.,* 2008), these are implemented in the form of serious games, what is known as gamification (*Seaborn and Fels,* 2015); the past five or six years have seen the emergence of games on digital platforms, making it easier for people to express their points of view or preferences, facilitating co-construction (*Speelman et al.,* 2014), helping to raise awareness among stakeholders (*Prada et al.,* 2014), stimulating learning (the GATES[59] project, *Speelman et al.,* 2014), etc. To this we can now add augmented reality, which could assist stakeholders in visualising future diversified landscapes at the time of crop systems being designed.[60]

59. https://www.gates-game.eu/en/project/overview
The H2020 project "Applying GAming TEchnologies for training professionals in Smart Farming — GATES" (Grant Agreement number: 732358 — GATES — H2020-ICT-2016-1)

60. See #DigitAg PhD thesis "The use of digital technology in agroecology: Designing agroforestry systems using augmented reality" on www.hdigitag.fr

At a sociological level, there are a number of obstacles to implementing a participatory approach: willingness on the part of farmers to head into uncharted territory, the capacity for collectively bringing about change, the capacity to gather and represent tacit knowledge, and the capacity to open up sources of information that will support change.

Farmers as data producers

Although "multifunctional agriculture" has always existed (*Renting et al.,* 2008, 2009), a new function has emerged thanks to digital data collection tools: data production.

Farmers can be committed to contribute to the digital capital at a regional level. Information – related e.g. to biodiversity, soil fertility, etc. – will be crucial when it comes to documenting, evaluating and paying for ecosystem services. Such information would be useful for the PES but the cost of gathering it is now such that payments for ecosystem services (PES) are distributed in a uniform way depending on the resources implemented (*OCDE,* 2011). In order to move from a resource-driven approach to a results-driven approach, it will be necessary to better characterise the environment, and to identify and quantify simple, measurable parameters representing how it works (*Caquet et al.,* 2020). Looking beyond PES, farmers will contribute towards the creation of information commons, which *Antle et al.* (2017) view as a public good when it comes to public investment and political decision-making. Initiatives are already in place relating to data on soil quality (*Della Chiesa et al.,* 2019) and biodiversity.[61] *Van der Burg et al.* (2019) identified the capacity of digital agriculture to generate other services as a result of the data produced; research must be prioritised in order to clarify the social role played by farms, to stimulate imagination among stakeholders with regard to the other possible objectives which smart agriculture could serve, and to improve the way in which their relative values are understood.

Farmers are also producing data alongside – and for – research, the goal being to analyse and understand the biological processes underlying the provision of ecosystem services within new agroecological systems. *Caquet et al.* (2020) advocate new strategies "combining experiments carried out by researchers and the deployment of other data sources [...]", including experiments on farms (*Cook et al.,* 2013). A number of authors see this field as a new avenue for research in agronomics (***Reckling et al.,*** 2020) for re-designing crop systems by understanding processes (*Falconnier et al.,* 2016), carrying out variety testing in real-life

61. http://observatoire-agricole-biodiversite.fr/

conditions (*Schmidt et al.,* 2018) and demonstrating new production systems (*Leclère et al.,* 2018). Conducting experiments on farms has been made easier by automatic monitoring and measurement systems (*Piepho et al.,* 2011) and precision agriculture (*Adams and Cook,* 1997; *Panten et al.,* 2010), both of which reduce uncertainties linked to sampling and manual measurement.

These strategies, employed by farmers for collecting data for use in research or environmental documentation, have encountered a number of scientific and technical obstacles (e.g. what variables to measure? Where? At what frequency? What data- and knowledge-sharing infrastructure should be employed?) and socio-economic obstacles (motivation to share data, the value of data, changes to the profession, data governance, etc.).

4.5 Specific challenges facing the Global South

The majority of international organisations (FAO, 2020) and development funds (*World Bank,* 2019) see digital agriculture as something that will significantly transform and improve the agriculture sector, food systems and trade for countries in the Global South (*Lixi nd Dahan,* 2014). In Africa, the reasons for developing digital agriculture are as follows:

- digital technology will help to diversify the service economy, with the right conditions for creating jobs: a good level of IT training, applied research in data science and geomatics, and a population familiar with mobile phones (72% of the population in 2014)[62];
- this could impact many categories of agriculture and agricultural households; by promoting the inclusion of women and young people (*El Hassane Abdellaoui et al.,* 2015) digital agriculture will counteract the rural exodus;
- Africa is a land of opportunity for agriculture, with vast tracts of land and the potential for the agribusiness sector to provide jobs within a range of agricultural sectors (*Pesche et al.,* 2016).

The specific context of agriculture in Africa must be covered by digitalization:

- production systems are far more diverse than they are in temperate countries: inter- and intra-country diversity; diversity between agroclimatic zones, resulting in significant contrasts between agroecosystems (tropical and Mediterranean, arid and wet regions); the wide variety of contexts in rural regions, structures and land tenure systems; the coexistence of varied socioeconomic structures,

62. https://donnees.banquemondiale.org/indicator/IT.NET.USER.ZS?end=2016&start=1960&view=chart

with a high prevalence of families engaged in subsistence farming –, either commercially or in conjunction with other forms of work (75% of arable land in the world; *Lowder et al.,* 2016), linked to a range of methods and practices and specialist structures for monoculture, often for export purposes;

- – production systems are also more complex: the high prevalence of integrated and multifunctional multi-species systems, such as agropastoral systems (in dry regions) or agroforestry systems (cocoa and coffee in wet regions) generates complex landscapes and organisational frameworks, with multiple rules and governing bodies for shared regional resources (pastureland for mobile pastoral systems, tropical forests), in circumstances in which regional information is sorely lacking and, when available, is rarely shared;
- distribution channels are highly varied (short, local distribution chains primarily for food production; regional and national sectors for supplying towns and cities; and international sectors, which take in products from small producers) and can be fragile (lack of infrastructure, fragmentation of the offer, difficulties adapting to standards, etc.);
- as has been the case in the North, there has been a significant change to food systems, accelerated by the emergence of new stakeholders and investors in agricultural supplies, production and agricultural marketing – generating tension as a result of the co-existence of different agricultural models – and by digital tools, with e-commerce platforms and the revolution in decision support and regional information systems (the use of drones for proxy detection, information systems on markets, enterprise resource planning, etc); it is also worth noting that digital technology is boosting the participation of women and young people;
- there is a distinct lack of organisation with regard to agricultural data: no metrics (measurement data), no pooling and archiving of data, weaknesses on the part of certain public information systems – in terms of property (property deeds, land registers), resources (soil quality, water availability), the quantities of inputs used, the quantities produced and origin (traceability);
- intermediation, communication and modes or levels of interaction (information exchange) between stakeholders within the agricultural sector are made more complex by low levels of training among users, illiteracy and the number of different dialects, paving the way for the development of ad-hoc digital solutions (farming advice using voice assistants speaking regional dialects).

When we are targeting the needs of “intermediary” and multifunctional farms engaged in multiple activities, as well as their production ecosystems, i.e. logistics channels and regional information, we have to thrown up a number of obstacles. Therefore, the objective will be to develop digital technology capable of tackling the following priorities:

- promoting the development of “local and regional food systems” centred around alternative production models (agroecology, biomass recycling, etc.)
- contributing towards the structuring of information capital in regions in which data is sorely lacking, benefiting everyone (individual holdings, intermediary organisations, institutions, etc.);
- facilitating communication with farmers, overcoming issues such as poor network coverage, inequality in terms of access to energy, illiteracy, multiple languages and dialects, etc.;
- improving supplies in distribution channels.

Both on farms and in the supply chain, the scientific and technical obstacles are broadly the same as those encountered in the Global North: a need for technology capable of anticipating risks (early detection of errors, customised decision making support, etc.), collective management of rare resources such as water or organic matter, access to markets (information, logistics). However, these are exacerbated by the specific challenges facing the Global South: diversity in terms of systems, solvency, the technical aptitude of farmers, illiteracy, lack of communication infrastructure (networks, data centres, etc.) and energy distribution infrastructure. Over and above these technical aspects, political, social and economic considerations must also be explored in order to anticipate the impact digital technology will have on businesses, agricultural households engaged in multiple activities, markets, local sectors and global value chains, companies and regions (*Tsan et al.,* 2019), given the number of unanswered questions regarding the use of digital technology in agriculture in the Global South (*Bonnet et al.,* 2019; *Deichmann et al.,* 2016; *Pingali,* 2012). The conditions for innovation and the transition towards digital agriculture will need to be studied at both an institutional level (exploring the political, socio-technical and socio-economic context required in order to develop digital agriculture and, more generally, the digital economy) and a process level (identifying innovation processes that will lead to applications with a proven impact on family agriculture), with questions regarding the research methods employed in digital agriculture and the innovation systems that will need to be put in place.

Conclusion

This chapter presented an overview of the fields in which digital technology could contribute towards the scaling up and development of agriculture, to meet the principles of agroecology with regard to production and integration into its social and economic environment (value chains, regions, etc.). This overview revealed technological and methodological needs in terms of observation, data science, modelling, knowledge extraction, data storage and exchange and specialist agricultural equipment for assisting humans, highly sought after in agroecology. But although there could be many opportunities, there are also risks to developing digital technology in agriculture. These must be identified and analysed (Chapter 5) in the interests of guiding future research (Chapter 6), the goal being to develop responsible digital technology for sustainable food systems that are compatible with planetary limits.