Agriculture and Digital Technology

Getting the most out of digital technology to contribute to the transition to sustainable agriculture and food systems

Inria INRAE | WHITE BOOK | N°06

Agriculture and Digital Technology

Foreword

This white paper is an initiative of the executive boards of INRAE and Inria, who brought us together, tasked us and gave us carte blanche in coordinating and writing this work on digital technology in agriculture from a research perspective. Our reflections have been carried out in the context of the principal observed and foreseeable dynamics of agriculture in countries around the world that aim to support the development of more sustainable agricultural and food systems. In constructing the analysis and proposals presented in this publication, based on an inventory of the challenges, opportunities and risks associated with digital technology in agriculture, we have not aimed to simply focus on the consensus of opinion, but to express the diversity of the groups involved, in particular in terms of prioritising the challenges or scope of the dangers for agriculture and food systems of the future. This white paper is a collective work that aims to address the question of digital technology in agriculture as a balanced whole and its chapters are sequenced and interconnected in a way that allows all aspects to be covered. Each section should therefore be considered in perspective of the others, and using them in isolation without referring to the whole could present an unbalanced view.

Veronique Bellon-Maurel, INRAE, Ludovic Brossard, INRAE, Frédérick Garcia, INRAE, Nathalie Mitton Inria, Alexandre Termier, Université de Rennes 1 / Inria.

Design: Françoise Perret
Art direction: Sophie Barbier

Publication February 2022
ISSN in progress – ISBN 978-2-7261-1310-3.

Cover illustration: © Smart Farm by SBTS from NounProject.com

Table of contents

Executive summary 5

The challenges facing agriculture require a reconsideration of food production and supply methods 6

Foundations and the state of the art in technologies and methodologies 8

Digital technology offers opportunities for agroecology and sustainable food 10

Risks identified to be avoided 12

Challenges in the development of digital technology for the agriculture of tomorrow 14

General conclusion 16

1. Introduction 17

2. What are the challenges facing agriculture? 21

2.1 World food security under strain 22

2.2 There is an urgent need to reduce the negative environmental impacts of agriculture 23

2.3 Agricultural dynamics have favoured intensification and specialisation 24

2.4 What are the agricultural models of the future? 25

2.5 The territorial nature of agriculture 27

Conclusion 28

3. Foundations and state of the art 30

3.1 Data 31

Data capture (what, why, where and how) 31

Data collection and transmission (What data to send, when and how) 33

Data storage and exchange, traceability 36

3.2 Modelling, simulation and optimisation 38

What to model, for what purposes and with which tools 39

Representation frameworks 41

Modelling and simulation 45

Modelling and optimisation 46

3.3 Multi-scale learning and knowledge extraction 48
Massive data in agriculture 48
Data pre-processing 49
Supervised approaches 52
Unsupervised approaches 53
Reinforcement learning 55
Data warehouses and OLAP analysis 56
3.4 Knowledge management and engineering for decision support in agriculture 58
Knowledge-based systems in agriculture 59
Knowledge restitution, visualisation and human-machine interaction in agriculture 66
Decision Support Systems (DSS) 69
3.5 Automation, control and robotics 71
Structured environments: allies of robots 72
From adaptation to reconfiguration 74
Conclusion 75

4. Digital technology and agroecology: opportunities to explore, challenges to overcome 76
4.1 Improving production: creating knowledge to support the transition towards agroecology. 78
Representing complex systems within agroecology 79
Large scale data collection for new agroecosystems 79
Data-based modelling: a step towards new knowledge 80
4.2 Improving production: using digital technology to assist farmers with the running of their farms 80
Adapting the principles of precision agriculture to agroecology: observing and taking decisions. 81
Multi-objective decision-making in agroecology 83
Co-designing innovative agricultural equipment and agroecosystems 83
4.3 Improving integration within the agricultural regional or economic ecosystem 85
Agricultural services reshaped by digital technology 85
Reshaping value chains with greater market connectivity 86
Managing resources at a regional level 89

4.4 Supporting the transition: sharing data, information and knowledge 91
Digital technology: an asset for sharing knowledge 91
A participatory approach and open innovation 92
Farmers as data producers 93
4.5 Specific challenges facing the Global South 94
Conclusion 97

5. Risks 98
5.1 Compromising the ecological transition in agriculture 100
The agroecological transition and technological lock-in 100
Taking humans further away from nature 101
Contributing to digital's growing environmental imprint 102
5.2 Widening inequality and power imbalance 103
Risks of exclusion 103
A loss of autonomy for farmers 104
Upstream and downstream control 104
Accessing information and training - what role can advice play? 105
5.3 Loss of sovereignty 106
A loss of autonomy over food supplies 106
Seizure of agricultural data 107
A loss of control over production equipment 108
A challenge for cybersecurity 108
5.4 Accentuating vulnerabilities and negative yields 109
The vulnerabilities of the agrifood system 109
Increasing complexity, diminishing returns and associated risks 109
Conclusion 111

6. Challenges for the future 112
6.1 Providing digital tools for collective management at a regional level 113
Monitoring and measurement at a regional level 113
Visualisation 115
Digital devices for participation, mediation and governance 116
6.2 Helping farmers to manage their technical journey 118
Acquisition and diagnostic systems 118
The challenges posed by robotisation and the digital transformation of agricultural labour 120

Modelling to incorporate systemic effects and build practical, usable decision-support tools 122
6.3 Transforming relationships between stakeholders within sectors 125
Service: advice and insurance 125
Traceability, full supply chain transparency, data life-cycle 126
Platformisation and reconfiguration of channels 128
6.4 Creating and sharing data and knowledge 129
Conclusion 131

Conclusion **135**

Contributions and acknowledgements **144**

Bibilographic references **146**

Glossary **184**

Executive summary

All over the world, food systems are undergoing profound changes caused by external pressures (climate change, organisation of value chains, etc.) and intrinsic factors (innovation, reduction in the number of farmers, etc.). Food security is the number one concern at the global level and is today accompanied by a strong demand for production methods to become more sustainable and for the protection of a living rural structure based on attractive family farming. This is why, as the FAO reminds us,[1] agroecology is a vital issue in a growing number of countries, including France. In parallel to these changes, agriculture, like all economic sectors, is seeing an upsurge in digital technology. Since the mid-2010s, the concept of "digital agriculture" has emerged. It defines both a form of agriculture and a food system that uses digital science and technology such as data science and technologies for acquisition (satellites, sensors, connected objects, smartphones, etc.), transfer and storage (3G/4G/5G coverage, low-speed terrestrial or satellite networks, clouds) and on-board or remote processing (supercomputers

1. FAO (2018b), Initiative de passage à l'échelle supérieure de l'agroécologie, available at http://www.fao.org/3/I9049FR/i9049fr.pdf

accessible *via* very high-speed communication networks, artificial intelligence) at all levels of agricultural production and its ecosystem: farms, support services, territories, value chains.[2]

Digital technology is often seen by governments and experts as an opportunity to contribute to the development of agriculture for the benefit of farmers, consumers and society in general. But what does this mean? What digital tools should be developed?

This white paper aims to shed light on these issues and present research perspectives to better understand, master, prepare, equip and support the deployment of digital technology in agriculture and the food chain, while taking into account the way in which it will transform sectors and their ecosystems, with the aim of using it to support the agroecological transition (AET) and the territorialisation of food and rebalanced supply chains. It is structured in six chapters. After the introduction, Chapter 2 presents the challenges of transforming agriculture and food systems. An overview of the state of the art then presents existing digital technologies (Chapter 3). The possibilities offered by digital technology for the agroecological transition and better inclusion in society are then inventoried (Chapter 4). Identification of the risks linked with the uncontrolled development of digital agriculture is just as necessary to avoid or minimise the pitfalls (Chapter 5). Chapter 6 presents the technical issues and challenges identified that could mobilise our two institutes, INRAE and Inria, but also the French research ecosystem, in particular to develop responsible digital technology for agriculture.

The challenges facing agriculture require a reconsideration of food production and supply methods

Today, a series of global changes are placing the agri-food system under strain. On the one hand, the growing population (9.5 billion people in 2050 according to the UN's median scenario) with a changing diet (as in China for example), must be fed while adapting to a context of increasing devastation: climate change, collapse of biodiversity, reduction of resources (soil, fresh water, phosphorus). On the other hand, agriculture must accelerate changes to implement livestock production systems that are more respectful of animal welfare and reduce its impact on the environment (reduction of the use of inputs such as antimicrobials, fertilisers,

2. Bellon-Maurel V., Huyghe C. (2016) *L'innovation technologique en agriculture. Géoéconomie,* 80 - May/June 2016, pp. 159-180

pesticides, reasoned use of natural resources such as water, reduction of soil compaction and greenhouse gas emissions, better use of biological regulations) and contribute to CO_2 storage[3] and the preservation of biodiversity. In the last 70 years, agricultural dynamics have favoured intensification and specialisation. Farm sectors are based on competitive pricing, a phenomenon that is exacerbated by globalisation. Essentially, they are subject to unbalanced power relations between actors with diverse and even divergent interests. In addition, farming is carried out in territories that have, in many cases, become specialised, leading to imbalances. This leads to great complexity (in terms of specialisation and interdependence of these elements) that amplifies instabilities, multiplies the risks of failure and is ultimately a major hindrance to change. It is therefore crucial to very quickly implement strategies to improve production techniques and ways of organising the agrifood system to increase their resilience.

According to the FAO, production can evolve towards two models:[4] either sustainable intensification (improvement of process efficiency and integration into long supply chains), agroecology,[5] which is based on natural production processes and uses local and sovereign food systems. This second model is now supported by the French EGAlim law[6] and many local authorities and citizens. Farm structure is also a point of attention: it is important to provide the conditions for decent work for farmers and protect family farming, which is in the majority in the world.

In this context, digital technology could contribute to the virtuous transition toward agroecology in territorialised food systems and the protection of family farming by providing information to better understand these complex systems and individual or collective decision-making support as well as supporting concrete action, exchange, the reconfiguration of value chains, the development of strategies and policies, etc. It is precisely this path of placing digital technology at the service of the transition to agroecology and the renewal of food systems that we have chosen to explore in this white paper.

3. https://www.4p1000.org/fr/linitiative-4-pour-1000-en-quelques-mots

4. HLPE (2016). Sustainable agricultural development for food security and nutrition: what roles for livestock? A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome, Italy. http://www.fao.org/3/a-i5795e.pdf

5. Agroecology is a set of practices that aim to improve agricultural systems by «mimicking» natural processes, thus creating beneficial biological interactions between the components of the agroecosystem.

6. Law No. 2018-938 of 30 October 2018 for balanced trade relations in the agricultural and food sector and healthy, sustainable food accessible to all (1), https://www.legifrance.gouv.fr/loda/id/JORFTEXT000037547946/

Foundations and the state of the art in technologies and methodologies

Before reflecting on digital technology designed to assist this transformative ambition, the first step is to see what can be offered by current research advances. Digital agriculture is based on three levers for action which, when mobilised together, lead to innovations: (1) the abundance of data due to the development of sensors (from nanosensors to satellites) and facilitated communication and storage, (2) computing capacities, which make it possible to implement artificial intelligence and new modelling methods and (3) connectivity and information exchange interfaces. In addition to these three levers, there is a fourth one which already existed but is being renewed by measurement and computing capacities: automation and robotisation. In this paper, we will focus in particular on the following technology and methodologies.

DATA[7]

Sensors, which provide data acquired on the ground, present hardware and software challenges. It is important to define the nature and scope of what needs to be measured and which measurement technology(ies) should be prioritised and how to implement it (or them) to obtain useful information at the lowest cost. Free satellite images (such as from Sentinel-2), connected objects and collaborative applications on mobile phones are all massive data sources. By processing this data, we can quantify the desired property either directly or indirectly by merging data from multiple sources. This latter approach is a strategy to improve the accuracy of the assessed value but raises multiple aggregation issues due to the nature of the sources and their granularity and precision. Data access is also an issue: the use of FAIR data facilitates its reuse while blockchains allow data to be shared in an unfalsifiable way between actors with divergent interests (as in value chains).

7. It is important to bear in mind that digital agriculture originated in precision farming and livestock production, which explains why, in the current consensus, digital agriculture uses data collected on the ground, initially in the context of precision agriculture, but not genomic data. A convergence between the two communities will certainly develop in the coming years, in particular through phenotyping.

MODELLING

This is the key element in representing agroecosystems, which are inherently complex, in order to simulate, optimise and manage them. Different levels are involved, from plants and animals to the human population, the territory or the value chain, with an additional challenge associated with the coupling of levels and models representing subsystems. Modelling is a relatively old approach in agronomy but it is today being renewed by digital technology. On the one hand, the profusion of data leads us to supplement traditional mechanistic approaches based on human analysis with empirical models from data processing (linear or non-linear multivariate methods, artificial intelligence). On the other hand, modelled systems are becoming more complex and now include humans. Decision modelling therefore involves additional concepts (bounded rationality) and mobilises specific frameworks to take account of the human agent: discrete event systems, agent-based systems, constraint-based models, etc. Simulation is used to represent agrosystems or even socioecosystems with behaviours that are difficult to analyse; it provides a description of the possible states and can be used for many purposes such as individual or collective decision support (guidance models) and training. Optimisation goes further in decision support (prescription), because it searches for solutions to a given problem according to one or several criteria. It is used in automatic control (managing greenhouses or agrivoltaic devices), robotics, individual decision making (food formulation, crop planning, etc.) and collective decision making (land or water management, economic decisions, etc.). It relies on a range of methods to integrate more and more complexity (deterministic methods, metaheuristic stochastic methods, etc.). It raises numerous research questions linked to uncertainty, temporality, the complexity of the processes to be modelled, etc.

KNOWLEDGE EXTRACTION

In addition to these analytical modelling methods, new families of methods are emerging with models that are directly inferred from the data, when there is sufficient data to cover the parameter space. This is particularly the case for data from remote sensing or time series (such as those collected *via* connected objects). After a necessary pre-processing phase to improve the reliability of the data ("cleaning", comparison with expert data), it is processed using different formalisms to extract intelligible information. Supervised approaches consist in predicting values (that are impossible to measure directly) or classifying data into different categories using linear or non-linear methods (e.g. neural networks), which implies having sets of measured and reference data (the desired value). If reference data is not available, non-supervised approaches are used (clustering, pattern mining). Specific methods are implemented to improve the performance of learning systems (reinforcement learning) or data aggregation (OLAP processing).

New knowledge is extracted or generated by the models and is formalised and organised to make it available to different users through decision support systems adapted to each activity, whether cropping or livestock production, and at all levels. New ontologies are needed to create ergonomic interfaces that will allow this knowledge to be shared, linked and used, in particular by targeting the new opportunities offered by the Semantic Web.

ROBOTICS

Automated and/or robotic systems are another aspect of digital technology that are becoming increasingly accurate and reliable. Robotics initially developed in the livestock sector (fixed milking robots, cleaning robots in closed environments), but it faces additional challenges in crop production (changing and uncontrolled outdoor environment). Current issues include the use of GPS, the question of precise, secure and low-cost localisation, the safety of mobile robots (avoiding collisions, being able to negotiate obstacles) and modes of cooperation between humans and robots, animals and robots and even ground robots and drones.

Digital technology offers opportunities for agroecology and sustainable food

Steered in the right direction, digital technology has the potential to open up many opportunities to respond to the challenges of the agroecological transition (AET), improve integration into agriculture's vertical (upstream-downstream) and horizontal (territorial) ecosystems and increase farmers' capacity for action.

IMPROVING PRODUCTION

Devices to assist the farmer at the sensory (sensors), cognitive (DSS for "decision support systems") and physical (machines) levels could improve production methods. Today, the concept of precision agriculture or precision livestock production is generally associated with intensive farming, but it is nonetheless valid in agroecology, in particular for monitoring plant and animal health using automated observations from sensors and models and for implementing more complex cultivation processes (mixed cropping, selective harvesting, etc.) on a large scale. This requires sensors and models capable of analysing the signal received to give either a description of the state, a prediction of the future state or a prescription. Beyond the tactical decision behind the intervention, some models could help in strategic decision making for production organisation, a phase that is particularly delicate in transition processes (AET, climate change) and multi-objective decision making. As physical assistants to reduce arduousness, robots could provide solutions to the very specific requirements of new cropping

systems (mixed cropping, agroforestry) and livestock systems (milking robots for pastoral farming). However, improving production also requires building knowledge beforehand about these new, diverse and complex systems. The construction of essential knowledge for AET could benefit from three interconnected digital levers: (i) representation of these complex systems, (ii) massive (and potentially participative) data collection on new methods in cropping and livestock production (on-farm phenotyping) and (iii) inference of new models from the data.

IMPROVING INTEGRATION INTO THE ECOSYSTEM

Digital technology could help renew the agricultural ecosystem including agricultural services (insurance, advice), the organisation of value chains and the management of agricultural territories. Value chains are being transformed by disintermediation - encouraged by the Internet – and the possibility for product transparency, which is increasingly desired among consumers today. Blockchains, which are often evoked as a way of guaranteeing this transparency, still pose multiple technical and governance issues. Territorial management is another aspect of the agricultural ecosystem that is impacted by digital technology. The territorial level concerns both agroecology (landscape ecology, closing cycles *via* the circular economy) and agriculture, which plays a central role in territories and is the subject of tensions linked to the use of resources (land, water) and the role it plays in ecological services. Digital technology could offer tools for better identifying material flows and facilitating mediation and collective decision-making (support models, etc.).

IMPROVING SHARING AND LEARNING

The connectivity offered by digital science and technology facilitates individual and collective sharing and learning, both sources of innovation in agroecology. Knowledge (including traditional knowledge) is capitalised and exchanged between peers, either directly (social networks), or through participatory collective processes in which digital technology plays an increasing role (Digital Farmers Field School[8]). Participatory approaches with an innovative aim (open innovation, living labs) could be enhanced by technologies that facilitate the capitalisation, representation, expression and processing of data and trace the contribution of each individual. Lastly, the farmer could become a data supplier to private or public actors (research through on-farm experimentation, territorial documentation, etc.), which could change their status for better integration and recognition.

8. Witteveen, L., Lie, R., Goris, M., Jane Ingram,V. (2017) *Design and development of a Digital Farmer Field School. Experiences with a digital learning environment for cocoa production and certification in Sierra Leone.* Telematics and Informatics 34(8), DOI: 10.1016/j.tele.2017.07.013

OPPORTUNITIES IN THE GLOBAL SOUTH

Most international organisations and backers see digital technology as a major source of transformation in the Global South, particularly in Africa. Digital technology could help diversify the service economy, accelerate the structural transformation of agriculture and make it more attractive to young people, improve value chains at local (building territorial food systems) and long-distance (guaranteeing product traceability) levels and help build the information capital of territories. However, technical issues persist -related to the weakness of the network coverage, the lack of infrastructures, the weakness of information systems, and the taking into account of the diversity of languages or even illiteracy in the Human-Machine interfaces. Digital technology also raises political, economic and social issues.

Risks identified to be avoided

The development of digital technology in society and the changes it brings are naturally accompanied by inherent risks. The agricultural sector is no exception and many questions are being raised about whether digital agriculture can meet expectations, what difficulties may be encountered and what vulnerabilities it could accentuate.

The first risk identified is that of failing to respond to the demand for a more ecological form of agriculture. While the development of digital technology in agriculture offers solutions for reducing inputs, this benefit could be accompanied by a technological lock-in that would hinder the implementation of alternative practices that are more radical and systemic, or of the set up of alternative organisational methods that could offer greater environmental and socioeconomic benefits. Furthermore, the widespread introduction of digital interfaces between farmers and animals or plants, in a context of the increasing technologisation of agricultural production, could also weaken connections to nature (particularly the human-animal connection), but society today is clearly looking for a type of agriculture that is more strongly connected to the living world around us. Lastly, digital technology has a definite ecological footprint, which is still poorly understood in agriculture, and the increase in equipment and operations for data capture, transfer, storage and calculation could worsen the environmental impact.

Another group of risks to be considered concerns the social consequences of reinforcing, through digital technology, a trajectory of industrialisation and the concentration of production in ever larger units and farms that are geared towards productivity. This movement would risk excluding minority forms of agriculture, mainly farms operating at a smaller economic scale. The development of robotics

could contribute to precarious employment in agriculture, especially for poor migrant worker populations. Difficulties in access to digital technology could also be a factor of exclusion in agriculture, whether at the individual (lack of skills) or territorial level (underdeveloped digital infrastructure). Digitalisation could affect farmers' decision-making autonomy (use of DSS) or even the meaning of their profession, with the fear of becoming mere "data workers". Another question concerning digitalisation is the change in power relationships between farming and its upstream and downstream sectors. Upstream, digital technologies could affect the understanding and use of production tools due to their increasing complexity, making maintenance and training increasingly difficult and potentially leading to dependence on certain specific inputs[9] Downstream, new data technologies could change the role of certain actors (such as companies in the digital sector) in value chains, with consequences in terms of sharing and governance and the risk of forms of subsidiary creation driven by downstream actors. Lastly, it is important to consider the concerns raised by digital technology for agricultural advising and its actors, methods, content and legitimacy.

The third group of risks identified concerns digital and food sovereignty. Growing digitalisation in the food chain could later also include agriculture with the emergence of monopolistic players and tools. In addition, digital sovereignty involves data control and there is a risk of agricultural data being seized by suppliers of digital technology or services (agri-equipment, AgTech companies, digital giants, etc.) The sharing of agricultural data, which is a priority for innovation, must therefore be structured and the governance of this data clarified. Lastly, cybersecurity risks must also be taken into account, such as potential attacks *via* connected objects (sensors, robots, etc.), the availability of geolocation systems and the challenge of preventing piracy (theft, damage, destruction) of agricultural data. Our food systems, which have remained relatively unimpacted until now, are of vital importance, which could make them potential targets in the future.

Lastly, the digitalisation of the agrifood system may increase dependence on resources among the different actors in the system and create new dependences with those who produce and own these technologies. This may accentuate the vulnerabilities of the system in the face of the many upheavals that will inevitably strongly impact on the functioning of our societies in the coming decades. More generally, it should be noted that agriculture and its upstream and downstream sectors form a complex sociotechnical system of which the overall energy cost is rising; it is important that this does not outweigh the anticipated benefits of digitalisation. The development of digital technology can also amplify the dynamic

9. An interesting parallel is that of the "printer/ink" lock-in: printers are sold very cheaply but require ink of the same brand to be used, which itself is sold at a very high price.

of growing complexity, and must not be allowed to spark a headlong technological rush that would lock us in a spiral of uncontrolled complexity.

Challenges in the development of digital technology for the agriculture of tomorrow

Seizing the opportunities offered by digital technology for agroecology and rebalanced value chains, while identifying and anticipating the risks, also poses scientific, technical, economic, organisational and political challenges. We will focus in detail on the scientific and technical challenges and the associated human challenges in order to respond to four main types of issues for the sustainable food system: (i) improving collective management and incorporating the territorial level, (ii) improving farm management, (iii) rebalancing the value chain between upstream and downstream and (iv) creating and sharing data and knowledge.

COLLECTIVE MANAGEMENT

This generates new needs: (i) collecting data at the territorial level (while managing the balance between specificity, scope of measurement, resolution and heterogeneity of multisource data), (ii) visualising this data and the post-processing results for non-specialist audiences (by elucidating complex concepts like uncertainty, incompleteness), (iii) enriching territorial engineering methods to facilitate participation and open innovation (need for support models, gamification, analysis tools for participatory sessions), collective decision making (digital tools for deliberation, negotiation and voting processes) and mediation (creation of digital "boundary objects" such as support models to encourage dialogue between stakeholders).

INDIVIDUAL FARM MANAGEMENT

The aim is to increase the farmer's perceptive, cognitive and physical capacities. For perception, there is a need for highly accurate and secure geolocation, early warning systems for plant or animal problems, frugal, inexpensive and non-invasive sensors, distributed data processing to limit transfer, fusion of heterogeneous data to construct relevant indicators and uncertainty reduction strategies. With regard to decision making, research challenges concern several aspects of model construction: representing complex and extensive socio-agroecosystems (multiscale and multi-temporal modelling, integration of interactions, digital twin concept), incorporating expert knowledge into models (knowledge of the environment, strategic choices), building user-centred DSS (personalising inferred information, creating evolving models, ensuring the correct functioning of the recommendation made, adapting the user interface to the specific aspects of

agricultural work), managing uncertainty and its spread. In robotics, there are still challenges to be met in scene perception and interpretation in a dynamic environment (i.e. the analysis of images and other "perceptions" by the robot), mobile manipulation and coordination with a moving carrier, human-machine interaction and shared autonomy, soundness of operation and adaptation to new production systems and, besides these technical aspects, questions in the field of humanities about the link between robotics and the transformation of work.

THE AGRICULTURAL ECOSYSTEM AND STAKEHOLDER RELATIONS

Upstream, services could be improved through digital technology by developing more personalised "digital" advice, which would require incorporating the farm's characteristics and potential as well as the farmer's preferences and underlying models. Insurance policies could be improved by creating new and fairer indicators based on automatically collected data (remote sensing, connected objects). Downstream, reconnecting farmers with consumers could be assisted through simple digital solutions that increase transparency (information on the products) and by improving platformisation. Blockchains could be a solution in response to the demand for transparency, bringing with them even more technical challenges (link between the flow of information and physical flows, coupling between private and public blockchains, environmental impact of public blockchains, integration of data for reuse) and institutional challenges (how should blockchains be governed?). Platformisation and disintermediation pose other challenges: production planning between multiple farmers (to supply catering or urban needs); coordinating actors within "food hubs" grouping different products; developing logistics solutions for peri-urban production. In the Global South, these issues are crucial in avoiding post-harvest losses, aggravated by specific weather conditions.

TOOLS FOR SHARING DATA AND KNOWLEDGE

Data and knowledge will be core to any digital system designed to promote agroecology, if the scientific, technological, regulatory, organisational and institutional challenges associated with their sharing can be met. Participatory data (from professionals or not) will be available in greater volume, raising questions about data quality, estimation and calculation of the value produced and recognition of the role of actors in the resultant innovation. What forms of governance should be used for this data in the context of reuse? How can virtuous and secure data circulation that avoids power appropriation by a single actor be supported? As for knowledge – which needs to be co-constructed (participatory, serious games, etc.) and formalised – it raises the question of digital commons and the collection and connection of expertise *via* ontologies that will require pooling and alignment..

IN CONCLUSION, ALL RESEARCH IN DIGITAL AGRICULTURE WILL BE UNDERPINNED BY CROSS-CUTTING CHALLENGES

Research aimed at building responsible digital technology for sustainable agriculture must absolutely incorporate (i) a systemic vision for agriculture and digital technology (taking account of the impacts of technology), (ii) the search for frugality (to reduce environmental impact and economic cost), (iii) the search for resilience rather than economic optimisation in food systems and protection of farmers' autonomy and (iv) cybersecurity (attacks *via* the IoT, data hijacking, geolocation jamming, etc.), a topic that is all the more essential as it affects food sovereignty.

General conclusion

The transition of food systems and agriculture towards more sustainable methods (agroecology, territorialized food systems, rebalanced long chains etc.) in a context of climate change is one of the biggest challenges for the years to come. Digital technology is being deployed rapidly in agriculture and, while it can provide solutions, it can also contribute to damaging fragile balances. It can accompany and accelerate virtuous transitions but it is essential to anticipate and avoid the pitfalls of misuse. The most pertinent research challenges concern: data acquisition at different levels and associated governance issues; devices to assist farmers at the cognitive (decision support), sensory (acquisition and transmission of information) and physical levels (tools, robots and cobots);[10] the modelling of these complex systems and management of the associated uncertainty; digital tools for encouraging participatory processes (essential in AET); traceability and use of data among consumers and, lastly, the key issue of cybersecurity due to the fact that agricultural production concerns food sovereignty. The adopted approach will play a fundamental role in building responsible digital technology for farmers: the priority research position could use the responsible research and innovation (RRI) framework, which is starting to emerge in digital agriculture and requires a degree of inter- and cross-disciplinary work. Lastly, it is important to remember that several agricultural models exist and the future will bring even more diversity, leading to the development of digital offers adapted to each model and its needs.

10. Robotic elements that work collaboratively with humans

1

Introduction

All over the world, food systems, i.e. *"the ways in which humans organise themselves, in space and time, to obtain and consume their food"* (*Malassis,* 1994) are undergoing profound changes caused by external pressures (climate change, value chain organisation, etc.) and intrinsic factors (innovation, reduction in the number of farmers, etc.). Consumption patterns are changing under the pressure of five types of factors: (i) demographic and lifestyle factors, (ii) economic factors, (iii) cultural and value factors, (iv) technological factors and (v) regulatory factors (*Blezat consulting et al.,* 2017). At a worldwide level, *"the primary concern about the future of food and agriculture is knowing whether these systems will be able to feed everyone sustainably and efficiently by 2050 and beyond, while meeting the additional demand for agricultural products due to non-food uses"* (*FAO,* 2018a). But while food security is the primary concern at the global level, agroecology,[11] and particularly its large-scale deployment – including small farms – are also highlighted by the FAO (*FAO,* 2018b). Preserving family farming and lively rural structures is instrumental to the attractiveness of agricultural professions, another issue found worldwide. In France, agriculture is turning to the agroecological transition to increase its resilience (adapting to climate change), reduce its environmental impact (fewer pesticides, antibiotics, fertilisers, etc.), respect animal welfare and ensure a decent income for farmers.

In parallel to these major changes in food production and consumption patterns, another phenomenon is emerging in food systems, as in all sectors of the economy: the deployment of digital technology offering *"versatile technology that is transforming processes and life in all areas across the planet"* (*Scholz et al.,* 2018). This is known as digital agriculture.

"Digital agriculture" refers to a form of agriculture and, beyond that, a food system *"that uses information and communication technology (ICT): technologies for data acquisition (satellites, sensors, connected objects, smartphones, etc.), data transfer and storage (3G/4G coverage, low-speed terrestrial or satellite networks, clouds) and on-board or remote processing (supercomputers accessible* via *very high-speed communication) [...] at every level of agricultural production and its ecosystem, whether on the farm (optimisation of cropping operations, herd management, etc.), in support services (new agricultural advisory services based on automatically collected data), or more widely at territorial level (water*

11. We use here the definition of (*Caquet et al.* 2020): *"Agroecology is at once a scientific field, a practice and a social movement. [...] Agroecology is above all a new paradigm that aims to utilise biological processes to respond to the demands for both agricultural production and other agroecosystem services: protecting resources, contributing to climate change mitigation, preserving habitats and cultural heritage."*

management) or in the value chain (enhancing inputs such as seeds,[12] *improving harmony between production and the market, etc.)"* (*Bellon-Maurel and Huyghe,* 2016). It is important to specify that there is now a global consensus on the definition of digital agriculture, which is essentially based on the multiplication of data collected "in the field", the role of artificial intelligence, as well as connectivity and automation. Today, this consensus does not include genomics, where data is collected in the laboratory. We therefore deliberately do not address this field in this paper. Connections will be drawn between these two topics in the conclusion (in particular in terms of the advantages of collecting very precise data to characterise the environment).

Digital technology was first used in agriculture about 50 years ago (satellites, then computing capacities, GPS, etc.) and has become more widespread with new data acquisition systems (*Sentinel* satellites, connected objects and the Internet of Things (IoT), high-speed phenotyping, supply-chain traceability) and the explosion of processing capacities. The term "digital agriculture" was coined in the early 2000s, while the concept of precision agriculture has existed in the literature since the mid-1990s. The number of articles (journals and conferences) on digital agriculture (with "Digital Agriculture" in the title, keywords and abstract) stagnated at fewer than ten per year until 2017, when it began to rise exponentially with 59 publications in 2019 (compared with 1000 publications on Precision Agriculture), including 6 in a special issue of NJAS (*Wageningen Journal of Life Sciences*), and 94 publications in 2020. The concept is therefore still in its infancy, even in research. In the political sphere it began to draw attention between 2010 and 2015, with expert reports and political positions in favour of the development of digital technology in agriculture, whether in the USA (*The Hale Group & LSC,* 2014), France (the "Agriculture innovation 2025" report in 2015),[13] Europe (the "A smart and sustainable digital future for European agriculture and rural areas" declaration in 2019),[14] or elsewhere in the world (*Dinash et al.,* 2017; *FAO,* 2019; *OECD,* 2019). In France, digital technology, connected objects, precision agriculture and the use of data have been identified as key technologies in the field of agriculture and agrifood (*DGE,* 2019).

12. Seed enhancement is a vast field that encompasses genomics (knowledge of genetic potential), phenotyping (measurement of the expression of this potential) and the relationships between the two. Digital agriculture takes an approach to genetic improvement based on phenotyping due to the enhanced possibilities of characterising plants or animals, brought about by new sensors; it does not include genomic research, which is carried out upstream.

13. https://agriculture.gouv.fr/sites/minagri/files/rapport-agriculture-innovation2025.pdf

14. Available at https://ec.europa.eu/digital-single-market/en/news/eu-member-states-join-forces-digitalisation-european-agriculture-and-rural-areas

The development of digital technology in the agrifood chain is proving to be inevitable and is often seen by governments and experts as an opportunity to contribute to changes in agriculture for the benefit of farmers, consumers and society in general. What is at the heart of the matter? How can research institutes like INRAE and Inria accompany this change?

This white paper aims to address these questions. They have already been covered in numerous publications in recent years, but they are still few white papers (the most extensive examples are *Isaac and Pouyat,* 2015 and *Scandurra et al.,* 2020, among others). The originality of this white paper will be to study to what extent digital technology can contribute to agroecology and how research can be oriented in this direction. It will also attempt to answer the following question: what research questions must be addressed in order to understand, master, prepare and support the deployment of digital technology in agriculture and the food chain while taking account of the way in which it will transform sectors and their ecosystems, with the aim of placing it at the service of agriculture, farmers and the common good? We have chosen to concentrate on research needs and not to cover the field of innovation, which is very dynamic with numerous start-ups and therefore very fluid, meaning that the paper would quickly become outdated. In particular, we will study the role that digital technology can play in the development of agroecology and sustainable food systems. With this paper, we aim to provide an overview of the state of play and propose paths which, we hope, will lead us collectively towards responsible research and innovation in digital agriculture (*Owen et al.,* 2012).

The white paper is structured as follows: first of all, it presents the challenges of the transformation of agricultural and food chains, then provides an overview of the state of the art and existing technology. Lastly, it explores the opportunities offered by digital technology in broad terms and the risks linked with an uncontrolled development of digital agriculture. Finally, core reflections highlight the technical issues and challenges that arise in developing the digital agriculture of the future, and in particular those that could mobilise the research teams of our two institutes.

2

What are the challenges facing agriculture?

Authors – *Benoît Dedieu, Emmanuel Prados.*

Acknowledgements (contribution, proofreading, editing) – *Véronique Bellon-Maurel, Ludovic Brossard, Frédérick Garcia, Nathalie Mitton, Alexandre Termier.*

Agriculture is already facing multiple challenges. These concern food security, the environmental impact of agriculture and the organisation of the sector. Can digital technology help build a desirable future to respond to these issues?

2.1 World food security under strain

The world's population is growing at an annual rate of 1.1% and is expected to reach around 9.5 billion people in 2050, according to the UN's median scenario. This population growth generates a considerable increase in global food demand, which is also accelerated by rapid development and the changing diet in China (*Bai et al.,* 2020). The world's agrifood system is increasingly subject to constraints, especially since it relies on a number of non-renewable resources that are becoming scarcer or more and more damaged (fresh water, phosphorus, oil, cultivable soil, etc.). This system will soon feel the full force of the impact of climate change, both directly (extreme weather events, drought, etc.) and indirectly (melting glaciers, proliferation and spread of harmful species of organisms and diseases, rising sea levels) (*IPCC,* 2014; *UNESCO,* 2019). It is also under threat from the current collapse of biodiversity in seeds, pollinators, crop auxiliaries, etc., which endangers many ecosystem services necessary for its proper functioning (*FAO,* 2019a). Conflicts over the use of products, land and water will also increase with, for example, the use of biomass for energy and the implementation of afforestation/reforestation programmes to capture CO_2 (also known as "negative emissions" techniques, which now underpin all IPCC scenarios limiting the temperature increase to 2°C). Moreover, for a number of cereals deemed critical[15] for food security, agricultural yields seem to have reached their limits in developed countries.[16] Lastly, the current agrifood system is not very resilient. It depends, for example, on globalised resources that are unevenly distributed around the world (phosphorus, oil, etc.) and a whole range of potentially fragile exogenous systems such as just-in-time transport and logistics systems, global markets and finance (speculation, price volatility, etc.) and flows of seasonal migrant workers. The Covid-19 health crisis has highlighted some of these vulnerabilities. [17]

The growing tension between supply and demand leads to a risk of worldwide food shortage in the medium term with multiple geopolitical consequences (*Brown,* 2012). The latest statistics from the FAO show that hunger is on the rise

15. i.e. which form the basis of diets.

16. For example, see analyses of the French Academy of Agriculture on the evolution of the average annual yield of wheat in France from 1815 to 2018 and on that of maize from 1960 to 2017.

17. See for example the Cirad press release of 29/04/2020 (https://www.cirad.fr/actualites/toutes-les-actualites/communiques-de-presse/2020/pandemie-coronavirus-menace-agriculture-alimentation) and the analysis by the association *les Greniers d'Abondance* of 16/04/2020 (https://resiliencealimentaire.org/covid-19-qui-veille-au-grain-pour-demain-lanalyse).

again (*FAO,* 2017). However, certain levers and opportunities could potentially have a positive impact such as changing eating habits in developed countries, drastic reduction of losses and waste (*FAO,* 2019b), capacities for recycling and use of by-products/co-products and the improvement of production techniques and organisations in the agrifood system to increase its resilience and adaptive capacities. While these levers are probably within our reach, it is crucial to move forward on these issues very quickly.

Alongside these food security issues, the WHO has observed that 13% of adults worldwide are obese. This aspect of malnutrition is another critical issue for the agrifood system alongside the development of related chronic diseases (cancer, diabetes, cardiovascular events) through the production of ultra-processed foods that often have a very high sugar content. The same is true of the use of antibiotics as growth promoters in certain livestock farming models. These food-related health issues are the focus of growing attention (see, in France, the *États généraux de l'alimentation* and the Égalim Law[18] in 2017-2018) and prompt a demand for healthy and sustainable food that is accessible to all and preferably local, agroecological and minimally processed.

2.2 There is an urgent need to reduce the negative environmental impacts of agriculture

The agricultural production system based on intensive farming has strongly contributed to the current collapse of biodiversity (*Sánchez-Bayo and Wyckhuys,* 2019)[19] and the reduction of soil fertility and water quality (*Caquet et al.,* 2020). There is an urgent need to drastically reduce the use of phytosanitary products and mineral fertilisers and reconcile agriculture and the environment generally. In addition, we must rethink our interactions with "natural" ecosystems (wildlife, forest and pastoral biodiversity reserves), bearing in mind that "natural" does not mean excluding all human intervention and activity. It is just as essential to improve livestock welfare: animals should be considered as subjects that are both sentient and conscious, working in cooperation with the farmer, and no longer as mere objects with biological functions. Farm systems that respect the animal and ensure a good life and an acceptable death must be designed (*Porcher,* 2011).

18. See issue 1566 (2017) of the Alim'agri magazine by the Ministry for Agriculture and Food, which summarises the various projects underway https://agriculture.gouv.fr/alimagri-les-etats-generaux-de-lalimentation. The Égalim Law (agriculture and food), which follows on from this work, was enacted in 2018.

19. In thirty years, almost 80% of insects have disappeared in Europe.

The circulation of zoonoses (Covid-19 and other recent zoonoses such as H1N1) remind us of the porosity with regard to certain diseases between the animal – both wild and domestic – and human worlds. According to the OIE (International Organisation for Animal Health), more than 60% of human infectious diseases are zoonotic. This figure increases if we consider emerging infectious diseases (70%)[20] interactions between animal, human and ecosystem health are leading to the concept of "One Health" (*Gibbs,* 2014; *Zinsstag et al.,* 2015).

Lastly, agriculture is the third largest source of greenhouse gas (GHG) emissions in France (19% of the national total in 2018) (*CITEPA,* 2018). Agricultural and forestry machinery only account for 12% of these emissions, while livestock farming accounts for 48% (mainly *via* methane emissions) and crops for 40% (mainly *via* nitrous oxide emissions during soil fertilisation). Between 1990 and 2018, agricultural emissions decreased by 8% (national GHG emissions increased by 6% in the same period). Transformations and efforts must therefore increase if the country is to meet France's low-carbon strategy objectives[21] and its commitments in the framework of the Paris Agreements. In this context, crops, forests, grasslands and pastoral land and corridors could be of great help as they play an important role in carbon storage.[22] For example, the *"4 pour 1000"* (4 for 1000) project launched by INRAE aims to increase carbon storage in all the world's agricultural soils by 0.4% every year (i.e. the equivalent of the world's annual CO_2 emissions linked to human activities)[23] by developing alternative cropping practices such as intermediate crops, intra-plot agroforestry and temporary grasslands in crop rotation.

2.3 Agricultural dynamics have favoured intensification and specialisation

Farming is part of sector chains in which agricultural production and processing models are designed and locked, but also transformed and invented. At all levels of the chain, the agrifood model imposes costly requirements for competitiveness and sanitary standards linked with processes and product logistics. These chains

20. See https://www.oie.int/fr/pour-les-medias/une-seule-sante/

21. The 2018-2019 SNBC strategy aims to reduce emissions from the agricultural sector by 18% compared with 2015 by 2030 and by 46% by 2050. It aims for a global reduction of greenhouse gas emissions by 40% by 2030 (compared with 1990) and carbon neutrality, i.e. zero net emissions, by 2050.

22. For example, according to the ONF, forests store the equivalent of 15% of national GHG emissions.

23. The *"4% sur les sols pour la sécurité alimentaire et le climat"* initiative (4% on soils for food security and the climate) launched by France on the occasion of the Paris Climate Conference (COP-21), proposes to increase the carbon stock in the world's soils by 0.4% per year. This figure is the result of a simple initial calculation, considering that total annual CO_2 emissions from human activity currently account for the equivalent of 0.4% of the carbon stock (C) of the planet's soils (approximately 2,400 gigatonnes of C). An annual storage of 4 per 1000 (4% or 0.4%) in the full depth of the soil would therefore compensate for these emissions.

are part of sociotechnical regimes[24] focused on competitiveness through pricing (as low as possible). This has been made possible by greater productivity of labour through the substitution of the latter by capital (in the form of increasingly efficient machines and automated, climate-controlled buildings) and workforce competition, exacerbated by globalisation. This system is underpinned by the intensive use of increasingly sophisticated technology, which many users gradually rely on (agricultural machinery, biotechnology, pesticides, etc.). Among other things, this has led to a steady fall in agricultural employment in all OECD countries, including France[25], and to the specialisation of a growing number of farms in a single type of production. Through the CAP (Common Agricultural Policy), purchasing organisations and oligopolistic multinationals, the organisation of this system, from the individual farm to the consumer, is driven by tensions and unbalanced power relations between actors with different and sometimes divergent interests, contributing to lock-ins. Moreover, agricultural activity takes place in territories that have, in many cases, become specialised, leading for example to the spatial dissociation of livestock and crop production and the geographical concentration of sectors. All this forms a highly complex system characterised by the specialisation and interdependence of each element at the different levels, which demands very high levels of resources. This amplifies instabilities and multiplies the risk of failure. It is also an obstacle to change.

2.4 What are the agricultural models of the future?

The debate on which agricultural models would best respond to the present challenges is wide open, particularly since the rise in organic farming in France (which now accounts for 8% of the agricultural area) and the promotion of agroecology. These debates are not limited to the national framework but have taken on an international dimension. In 2016, the HLPE (High Level Panel of Experts) of the FAO proposed to address the future of agriculture (including livestock farming) according to two standard models: sustainable intensification and agroecology (*HLPE,* 2016). The first matches current trends to improve process efficiency and integration into long-chain systems. It is based on cutting-edge scientific knowledge and technological advances made possible by precision agriculture

24. According to *Geels* (2002) and the "multi-level perspective" model: a regime is a network formed of different economic and social actors around a product, service or, in our case, an agricultural model. The stakeholders are private and cooperative actors from the chains, but the system can be strengthened by teaching, research, the farm advisory system, national or European policies, etc., whether deliberately or not.

25. In some areas of the world, particularly Africa, demographic dynamics and the limited opportunities offered by the industrial and service sectors mean that the creation of jobs in rural and peri-urban areas must be considered as part of the challenges facing agriculture. This also applies to some hinterland areas in France.

and livestock production and genomics. The second standard model promotes agriculture based on natural processes and integration into local and sovereign food systems. It prioritises all forms of diversity (biodiversity, farming diversity and integration of cropping and livestock production), peer learning and the search for coherent systems that promote autonomy with regard to inputs and cost savings. Organic farming is one such approach (see insert on the Métabio metaprogram by INRAE). This model is increasingly supported by associations and local authorities who are developing territorial food projects and are strongly committed to promoting short supply chains. More detailed modelling has also been proposed. In particular, *Therond et al.* (2017) identify eight agricultural models positioned along two axes: dependence on inputs versus the implementation of ecosystem services; the territorial anchoring of food products versus long supply chains.

For example...

The "**INRAE METABIO**" metaprogram launched in 2019 proposing the "change in scale of organic farming" looks to explore the hypothesis in which the majority of the national supply of products comes from organic farming, in a context of strong demand and agroecological transition. It studies the challenges, levers and consequences of the change in scale of organic farming throughout the agrifood system. The aim is to explore scientifically supported proposals to anticipate consequences and inform the deployment of organic agrifood systems.

Another debate on models revolves around the structural characteristics of farms that could provide a response to the challenges outlined above. Here, there is a marked difference between family farming and more capitalistic models, such as the corporate agriculture described by *Gasselin et al.* (2015) and *Hervieu and Purseigle* (2013). In the first case, capital and labour are in the hands of the family whereas in the second, capital is held by non-agricultural actors and all workers are employees. The latter situation prefigures the megafarm,[26] which is underpinned by very high productivity made possible by extremely large-scale operations, mechanisation and, increasingly, adapted automation.

There is some contrast between these two types of models, because agroecology is more family-based while sustainable intensification is more capital-based. However, the diversity of systems cannot be reduced to these archetypes. There

26. The largest farm in the world is located in China with approximately 40,000 dairy cows; an even larger one (100,000 cows) is under construction... way beyond our controversial 1,000-cow farm!

are also many hybrid situations of what is known as "agriculture of the middle". In addition, the opposition between these two types in the societal or professional debate does not exclude forms of coexistence in the territories – which may be spatial or work-based (exchanges) – and the urban food supply chain. Whatever the model, farmers want a decent income and working conditions (*Ghai,* 2003), that is, conditions that protect their health, offer social protection and preserve their ability to influence their future. They also want work that is meaningful, useful, attractive and maintains relationships with others.

2.5 The territorial nature of agriculture

Another element to be positioned in the debate on agricultural models is the territorial nature of agriculture. The question of the territorial inclusion of the models addresses certain needs: the economic and social development of these territories, their increased resilience, their environmental quality and the availability of opportunities to integrate activities that use by-products in local applications. How can agricultural models reduce material and energy flows? At what scales should production and activities be relocated and rediversified? How can city-countryside relations, short chains and agriculture near cities meet these needs? What strategies and tools should be mobilised (geographical quality indications such as PDO, AOC[27], etc.)? How can employment be promoted and sufficient economic value be ensured? These questions all position the territory (composed of its spaces, activities and actors) as an essential entity in addressing the challenges that agriculture must face, in particular through:

- the analysis of modes of coexistence and border sharing between agricultural models (*Gasselin et al.,* 2021) in food systems;
- the design of processes for the agroecological transition at the territorial level (*Bergez et al.,* 2019);
- the provision of information and decision-making tools for stakeholders, local authorities and government services concerned with the environmental and health dimensions that link agriculture to the other components of ecosystems, hydrosystems and pathosystems.

27. *Appellation d'Origine Contrôlée.*

Conclusion

Agriculture is currently facing critical challenges in terms of food security, pollution and resources that call into question the productive dimensions of the activity and profession of the farmer. They raise questions about which agricultural models could provide a response and about the territories themselves in which the concrete variations of these new models interact, contrast or coexist. It should be noted that they are subject to different dynamics, depending on the socio-technical regimes to which they are attached. Sustainable intensification is often associated with large farms with a small workforce and is linked to the evolution of the predominant regime inherited which relies on (large) private upstream and downstream companies, large cooperatives, advisory services from chambers of agriculture, the CAP and research leading to the prescription of technical solutions applicable in most environments. Agroecology is still a socio-technical niche, but a real change in priorities has been observed among multiple actors, including in research, public policy making and education. Agroecology is also associated with the idea of transition and radical transformation. It calls for the development of knowledge, methods and tools exploring levers to enhance the coherence and performance of agroecological systems. It also accompanies processes of change and facilitates the exploration of desirable situations, learning, adapted mechanisations. It supports the step-by-step reconfiguration of systems in a context of incomplete knowledge and uncertainty about the impact of actions.

In this context, digital technologies are considered above all from the perspective, for the precision of the information they provides and the new decision support regimes that they support. In this way, they can reverse the dynamics of simplified reasoning and actions brought about by the increase in farm's size. By providing tools for observing and managing increasingly large areas, digital technology acts as a lever for sustainable intensification and the expansion of structures, which becomes compatible with precision and individualisation. At the same time, digital technologies could also contribute to the development of the agroecological model on family farms. Indeed, part of this model is based on dialogue and learning among peers and on direct links with consumers: forums, online stores and social networks could become effective tools. More digital technology could help understand and manage the biotechnical, ecological and socioeconomic complexity of systems based on agroecological farming, although this remains to be confirmed. It could also "equip" the farmer to detect malfunctions sooner and help decision making (decision "support" information).

The territorial level is also of interest from the digital perspective, due to the ability of digital technology to deal with complex processes connecting spaces, activities and actors and to explore useful scenarios for multi-actor decision making, whether this concerns food systems, environmental issues or, increasingly, health issues (infectious animal or zoonotic diseases) (*Charrier et al.,* 2019).

Ultimately, to allow a quick transformation capable of meeting the challenges, it is necessary to question the capacity of digital technologies to respond to the demands of the different actors and stakeholders (public or private) and their urgent needs for:

- information, understanding of the complexity of the systems, risks and uncertainties;
- support for the development of strategies and policies and the multi-criteria assessment of agricultural production/food system scenarios at different levels (European, national, regional and territorial);
- support for decision making and managing compromises in single and multi-actor situations;
- and lastly, support for the components of concrete action that link humans, machines and tasks on the one hand and experiential dialogue between peers on the other.

Foundations and state of play

Authors – *Nathalie Mitton, Ludovic Brossard, Tassadit Bouadi, Frédérick Garcia, Romain Gautron, Nadine Hilgert, Dino Ienco, Christine Largouët, Evelyne Lutton, Véronique Masson, Roger Martin-Clouaire, Marie-Laure Mugnier, Pascal Neveu, Philippe Preux, Hélène Raynal, Catherine Rousset, Alexandre Termier, Véronique Bellon-Maurel.*

Acknowledgements (contribution, proofreading, editing) – *Isabelle Piot-Lepetit.*

Having described the different challenges facing agriculture in the previous chapter, in particular those of agroecology and sustainable food systems, which will be the "target" of our reflections, in this chapter we will address the foundational aspects of digital technology, their use in agriculture and current research. In the Introduction, we reviewed the pillars of digital agriculture, which can be summarised as data, processing capacities, connectivity to allow data and information exchange and, finally, automation. The challenges facing agriculture concern all levels of the data cycle, from capture to use *via* collection, traceability, processing, storage, interpretation, provision and application in automatic and robotic systems.

3.1 Data

The use of digital technology in agriculture produces large volumes of highly heterogeneous data that can be qualified as "big data" (*Bellon-Maurel et al.,* 2018). It is uniquely complex because it includes observations of complex objects and environments of different natures and operating at very different spatio-temporal levels (for example from the gene to the field), with strong intra- and inter-level interactions and involving numerous actors. This complexity leads to questions about what data to collect (nature, frequency, objective, etc.) to guide the deployment of a technical solution at all levels (hardware, software, interface, etc.).

Data capture (what, why, where and how)

The challenges of data capture are both hardware- and software-related. Knowing what the data is intended for helps to determine the choice of measurement equipment.

First, the nature of the measurement (temperature, air or soil humidity, condition of a plant's leaves, weight of an animal, etc.) and the accuracy required must be specified. These requirements, which depend on the needs defined, vary greatly from one use to another. The second issue is how to capture the data. The nature, size, weight, bulk and robustness of the sensor will also depend on the nature of the measurement, the object to which it is applied and the environment in which it will be placed: a sensor worn by an animal will be chosen according to the weight and bulk of the equipment and the size of the animal. Similarly, a sensor for field measurements on soil or plants will require protection to make it resistant to the surrounding environment (humidity, temperature variations, shock resistance, etc.). Finally, how the data will be used will define the sampling method, in particular the collection location and spatial and temporal resolution (*Brun-Laguna et al.,* 2018). For example, should the sensors be positioned per m²

or per km²? If the aim is to monitor animals, should all or just a few of the animals in the herd be equipped (*Jabbar et al.,* 2017)? What time frequency is required and should it be constant? Some applications require high spatial and temporal frequency, offered by satellite remote sensing. Others need less frequent measurements, such as those obtained from participatory data (*Minet et al.,* 2017).

The decision of which technology and equipment to use and which methodologies to implement for the deployment of sensors has been the subject of numerous studies in recent decades, with applications in both cropping and livestock production: identification and geolocation using RFID (*Ruiz-Garcia and Lunadei,* 2011) or GPS; imagery (2D, 3D, infrared, hyperspectral), accelerometery, acoustics, biochemical measurements on fluids (including biomarkers), measurement robots such as weighing scales, water or milk meters, feed dispensers, etc. (*Chastant-Maillard and Saint-Dizier,* 2016; *Halachmi et al.,* 2019). In most cases, trade-offs must be made between cost, resolution, precision and practicality (*Foubert and Mitton,* 2019). Research aims to limit these concessions, either by developing sensors that are increasingly precise, energy-efficient, smaller, less intrusive and less costly, or by designing massive data acquisition devices (using satellite images, drones, etc.). The deployment of new satellite constellations (*Sentinel-2*),[28] which produce high-resolution images (both spatial and temporal) made available free of charge, offers new monitoring opportunities.

In conclusion, the work to develop acquisition systems is inherently multidisciplinary and requires collaboration between agronomists, biologists, zootechnicians, geneticists, computer scientists, electronic engineers and end users to ensure that the requirements of users (who are sometimes researchers themselves in another field) are met and to combine knowledge of the objects of study, their specificities and their constraints with knowledge of digital technology.

28. https://sentinel.esa.int/web/sentinel/missions/sentinel-2

For example...

Several INRAE units are developing such acquisition devices for phenotyping or monitoring animals or crops. Examples include: a high-speed 3D image acquisition device and its associated processing methods to measure the physical condition and morphology of dairy cows, developed by the **PEGASE** Mixed Research Unit (UMR) in collaboration with the Agricultural Technical Institute **IDELE** and the company **3D Ouest**. An automatic feeder has been developed by the **PEAT** Experimental Unit (UE) and the **BOA** UMR for studying the feed intake and individual feeding behaviour of poultry reared in groups. The electronic mounting detector "ALPHA" (the company Wallace), based on an automatic RFID reader worn by a ram, was designed by the **SELMET** UMR to automatically detect heat in sheep, particularly in large-scale farming. In the plant field, the **ITAP** UMR and the **CAPTE** Mixed Technology Unit (UMT) are developing optical sensors for phenotyping or early detection of plant diseases. The **TETIS** UMR uses satellite remote sensing to detect plot defects. The acquisition of phenotypic data using sensors is being addressed by large-scale programmes and infrastructures such as **PHENOME** on the characterisation of crops grown in greenhouses and in the field and **IN SYLVA** on forests. The resulting data can be used to improve the predictive capacities of models and how they take into account interactions between genotypes and the environment. More broadly, high-speed phenotyping systems are also being developed in plant and animal experimental units at INRAE.

Data collection and transmission (What data to send, when and how)

Once the data has been acquired, it must be transmitted. Some systems use wired communication (Ethernet, serial, etc.), but this is not always possible and sensors have to be equipped for wireless communication, which poses different challenges. Data capture and transmission in agriculture increasingly use Internet of Things technology (*Zhao et al.,* 2010), especially RFID and wireless sensor networks with specific features for agriculture.

Monitoring of animals in extensive breeding. © Selmet – CIRAD.

Most wireless sensors rely on energy sources that are either limited (e.g. batteries) and/or variable (e.g. *via* a solar collector) and must therefore be preserved. Data transmission is often the most energy-consuming factor and presents a major challenge, so the aim is to limit the amount of data sent while maintaining the data accuracy required for the application to function. Research therefore focuses on data processing in the sensor, which itself is limited in computing and memory capacity, using spatial and/or temporal data aggregation (*Salim et al.,* 2020) and simplified artificial intelligence methods. For example, researchers use the correlation between two quantities (such as temperature and humidity) to transmit just one of the two values and interpret the second. Another option is to locally predict the next value to be measured and only transmit the data if it does not match the predicted value. The more demanding an application is in terms of temporal resolution or accuracy, the more data transfer is required. This also requires a trade-off between efficiency, accuracy and cost.

For example...

The **FUN** and **EVA** project-teams at Inria are working on data collection for agriculture using wireless sensor networks. Their work concerns both specific network protocols and the question of which data to transmit to avoid saturating the communication media and reduce the energy consumption of transmissions. The **FUN** project-team is installing sensors in vineyards in South Africa to improve watering and water management. They also collaborate with Sencrop, which uses sensors in cereal and potato farming. **EVA** installs sensors on peach trees in Argentina to protect against frost.

The choice of communication technology depends on the quantity of data to be retrieved as well as the distance to cover and location of the sensors. For data to be collected over long distance and requiring greater intervals between transmission (such as once-a-day temperature readings) one would uses long-range technology with low data rate and power consumption, whereas high-frequency readings (such as animal video tracking) require high data rate. The measurement points may be located in areas not covered by cellular technology (such as 3G/4G/5G or LPWAN – Low Power Wide Area Network), which would require specific network mechanisms to be put in place such as routing (relaying information to the destination station). This must take account of the constraints and requirements of the applications and the material limitations and characteristics of existing radio technology (*Foubert and Mitton,* 2021) and the environment in which the sensors are deployed (*Ferreira et al.,* 2020). An additional difficulty is the heterogeneity of technologies required that must to coexist and sometimes cooperate, as well as the more general challenges of the Internet of Things (IoT), addressed in the Inria *White Paper on the Internet of Things.*[29]

Lastly, mobile data collection solutions are emerging for blackspots, ranging from simplified solutions (portable data devices that can be carried in a rucksack, as in the case of the *COWSHED* project in Africa[30]) to high-tech solutions with "aerial" devices (drones or nanosatellites). The latter can collect data from thousands of connected objects at a low data rate (LoRa protocol) or high data rate (i.e. 100 kB per transmission) using a smaller number of terminals on the

29. Scientific challenges of the Internet of Things. Inria White Paper. https://www.inria.fr/en/inria-white-paper-internet-things-iot
30. https://hal.archives-ouvertes.fr/hal-03102190/document

ground (around 100) (UHF protocol). Applications are developing in the field of agriculture, such as in Australia where farmers remotely monitor the level of irrigation tanks using nanosatellites.[31]

Definition

The Internet of Things (IoT) is the interconnection of the Internet with things, places and physical environments. The term refers to a growing number of objects that are connected to the Internet, allowing communication between the physical and digital aspects of our possessions. The IoT combines a wide range of technologies from simple RFID tags to mobile phone applications and wireless sensor networks. Radio communication technologies are diverse with different characteristics with regard to data rate, consumption, range, etc. Sensors can be equipped with microcontrollers with varying levels of power and energy consumption.

Data storage and exchange, traceability

Once the data has been captured and transmitted, it can be used for a variety of purposes. Firstly, it can be stored and processed to extract knowledge, anticipate malfunctions, etc. This data can be very heterogeneous and of varying levels of quality. It can also have very different sampling rates due to it coming from different sources (physical sensors, "human" sensors or even simulation results) and can be very large in volume (many capture points, potentially high temporal frequency). Methods derived from multivariate data management and now big data offer a response to the challenges of volume, processing speed and the diversity of formats and sources (*Bellon-Maurel et al.,* 2018). The prerequisite for successfully using this data is that it meets the guiding principles of "FAIR", which are Findability, Accessibility, Interoperability and Reusability,[32] with minimal human intervention. There is therefore a demand for a new generation of information systems adapted to agriculture in order to manage and structure this complex mass of data using the FAIR principles. Metadata and data must be well described using semantic resources (ontology, taxonomy, thesaurus) to make them understandable and facilitate access *via* standardised protocols..

31. https://which-50.com/world-first-australian-iot-uses-satellites-to-monitor-farmers-tanks-rain-levels/
32. Wilkinson et al. *The FAIR Guiding Principles for scientific data management and stewardship.* Scientific Data 3, 160018. doi:10.1038/sdata.2016.18.

For example...

At INRAE, automated data processing centres (**CATI**), federate and structure skills, methodologies and technologies to facilitate the reuse of data, such as the **CATI SICPA** (Information Systems and Computation for Animal Phenotyping), the **CATI** Codex (plant phenotyping) and the **CATI GEDEOP** (Management of Experimentation, Observation and Practice Data on Agro-socioecosystems).

Finally, the question of data validation is becoming a central issue with the increase in the quantities of data collected: is the measured value correct, for what applications and under what conditions?

A variety of DBMS (Database Management Systems) exist depending on the data model used, with the relational model currently being the most common. *Benchini et al.* (2007), for example, coupled a dynamic cropping system simulation model with a relational database to achieve efficient storage and analysis of model data at farm level. But when it comes to dealing with very large volumes (of the order of petabytes) or complex and heterogeneous data (graphs, documents, etc.) in highly distributed contexts (remote servers, Internet of Things, etc.), NoSQL-type databases using a different data model – which has fewer conceptual constraints than the relational model – are more pertinent.

In some cases, the primary aim is to share the data among multiple actors, for example to limit fraud or validate certain processes (correctly following a given route, compliance with the cold chain, local production or insecticide-free requirements). To achieve this, one of the most promising digital tools currently available is the blockchain (*Bermeo-Almeida et al.,* 2018). Blockchains, which use a distributed database that requires no control entity, date the components they contain and guarantee their unalterability. In agriculture, this technology makes it possible to record the life stages of a product and thus ensure traceability (*Kamilaris et al.,* 2019). It offers multiple advantages (see Chapter 4: Opportunities) including transparency and records of transactions between farmers, suppliers, buyers, consumers etc. In some sectors, using blockchains makes it possible to avoid long and costly certification processes (*Lin et al.,* 2017).

However, blockchains also pose new digital and organisational challenges. In any information system, there is always an inherent risk of hacking. Also, blockchain technology was initially designed for transferring and sharing intangible goods

(funds, certificates, diplomas) and is not infallible in cases where information flows must be coupled with physical flows, such as in agriculture and agrifood where the digital data must be an exact representation of the physical flow. Furthermore, the perceived security of a blockchain is based on a mechanism known as "proof of work" (of computer operations), which validates the new blocks to be incorporated. Public blockchains rely on large numbers of "proofs of work", which is very energy intensive, and research currently focuses on reducing the complexity of these cryptographic algorithms to reduce their energy consumption.

3.2 Modelling, simulation and optimisation

If data is one of the driving forces of digital agriculture, modelling is also essential for linking measurements and observations to interpretations and recommendations to help actors in the agricultural sector better understand, manage and improve their production systems.

In the field of agriculture and agronomic research, the scientific approach of modelling to predict harvests emerged as early on as the reign of Egyptian Pharaoh Sesostris I, when river levels were used to make crop forecasts (*Gros de Beler,* 1998), or among Inca farmers who knew several months in advance what agricultural cycles to expect by observing nature (*Gutiérrez,* 2008). Much later, the pioneering work of Mendel (*Mendel,* 1907) and then Fisher (*Street,* 1990) definitively legitimised the use of statistical models in the fields of genetics and agronomy. In the latter half of the 20th century, agricultural modelling developed in particular in rural economies to rationalise and optimise production, agronomy and zootechnics, crop management, animal nutrition and genetic selection in plants or animals. With the development of computers and the first calculators, modelling gradually went beyond statistics and operations research and increasingly used symbolic and algorithmic formalisms to produce models expressed in mathematical and computer terms and in which simulation plays a key role.

The general function of a model is often called a mediation function: *"to an observer B, an object A* is a model of an object A to the extent that B can use A* to answer questions that interest him about A"* (*Minsky,* 1965). This mediation can help meet different cognitive objectives: facilitating experience, intelligible formulation, theorisation, communication and the coconstruction of knowledge, decision and action (*Varenne and Silberstein,* 2013). Today, agricultural modelling concerns a very broad spectrum of objects and has four main purposes: analysis, communication, predicting and controlling the evolution of various components in an agricultural system and designing and optimising the system under consideration. In the rest of this section, we will present a few of the major types of models and how they can be used in digital agriculture thanks to simulation and optimisation.

What to model, for what purposes and with which tools

What to model? – In agriculture, the objects of study – or subjects of the model – are anthropised natural systems that can involve multiple scales and levels of organisation. Modelling focuses on the components of these systems as well as the processes that govern their dynamics, the events that activate or inhibit these processes and the exogenous factors that influence them (such as weather conditions) (*Martin et al.,* 2011). Some of the components are biophysical (such as crops with growth processes, diseases) (*Kumar and Sinhg,* 2003) while others are centred on the roles played by human actors. In the latter case, modelling can concern either a single individual (*Martin-Clouaire and Rellier,* 2004; 2009) or a group of individuals (such as the members of a cooperative) and the social processes of activity coordination carried out by different individuals in the collective (*Drewniak et al.,* 2013; *Manson et al.,* 2016).

For example...

Models of processes, flows and interactions are being developed by many teams and units. Below are a few examples at different scales.
At INRAE, several teams are working on crop or livestock modelling, whether on a plot-by plot basis (multispecies crop models such as **STICS**, which describe growth according to climate and environmental variables), at the individual level (animal growth models according to their diet and environment), or at larger scales (plant epidemiology models including inter-plot dispersal and animal epidemiology models describing inter-herd transmissions, etc.). These models are hosted by modelling platforms such as **RECORD**, **OPEN ALEA** and **OPEN FLUID** and form the basis of simulations run according to different climate and contextual scenarios.

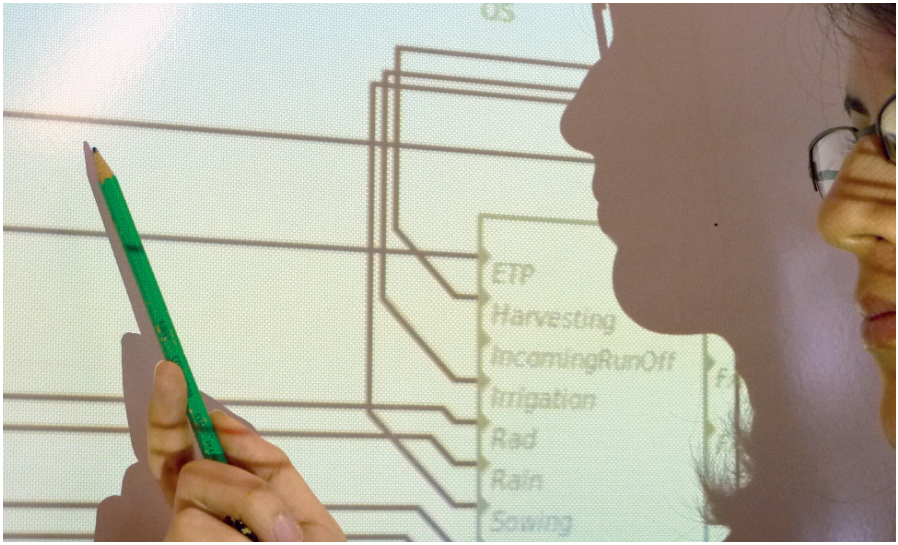
The **STEEP** project-team (Inria, CNRS, Université Grenoble Alpes) develops mathematical models for analysing material flows (production, transformation, exchanges, consumption, waste) in agriculture and the forestry-wood sector in order to 1) understand the upstream/downstream vulnerabilities in the sectors, 2) question the use of natural resources and potential problems caused by competition for use and, finally, 3) assess environmental impacts. The tools developed are based on the modelling of chains in terms of products and sectors and the existing flows between them. One of the major difficulties is the particularly patchy and inconsistent nature of the data.

The **EASE** project-team (Inria, Ecole Nationale Supérieure Mines-Télécom Atlantique Bretagne Pays de la Loire, Université de Rennes 1) is developing a complete series of new interaction models, offering tools for augmenting and describing information from complex systems. The work has been applied to energy management in agriculture. In particular, the model helps define how to reduce the environmental impact of energy consumption when optimising an existing site or installing new facilities. It has shown that the optimisation of a single parameter alone (local production, storage or process transfer) is not enough to maximise self-consumption and minimise energy requirements.

What purposes to model for? – The level of detail of the modelling systems at the heart of a study is defined by the purpose of the study and the tool under consideration. The most commonly applied objectives range from identifying the aims and means of managing agroecosystems to predicting performance (*Rio et al.,* 2019) in the light of different scenarios going through the identification of risks and the critical analysis of the functioning and conduct of agricultural production systems (*Li et al.,* 2019). Modelling can also allow the design of new systems such as the configuration and sizing of a logistics chain (*Taghikhah et al.,* 2021).

For example...

Many models concern agroecosystem management. The joint **INRIA** / **INRAE** project-team **BIOCORE** (CNRS, Sorbonne Université-UPMC) focuses on modelling and control in epidemiology for tropical agriculture. At INRAE, the **MIAT** UR and **MISTEA** UMR develop simulation models and optimisation methods for managing agroecosystems at farm level. For animals, UMRs such as **BIOEPAR**, **SELMET**, **MoSAR**, **UMRH** and **PEGASE** are developing models on animal health and epidemiology, dynamic ingestive, digestive and metabolic phenomena and livestock farming systems. For example, the **PEGASE** UMR has developed new models for adjusting daily feed according to the nutritional needs of each animal for individualised feeding for pregnant and lactating sows (*Gauthier et al.,* 2019).



Building an agronomic model. © INRAE.

How to model? – Computer modelling to support the analysis, design and management of agroecosystems is combined with approaches using either simulation or optimisation (*Li et al.,* 2020). In dynamic simulation, the modelling of phenomena considered important for the objectives of the study is centred on realism (*Kaghazchi et al.,* 2021), whereas optimisation involves algorithmic exploration of the space of alternatives that efficiently searches for an optimal solution according to one or more explicitly formulated criteria using reductionist mathematical models (*Ezanno et al.,* 2020; *Casagli et al.,* 2020). The two methods have relatively antagonistic objectives (modelling realism versus computational efficiency) and therefore generally use different modelling approaches.

Representation frameworks

Agroecosystems are complex objects of which the models concern, on the one hand, the functioning of the biophysical entities that compose them (soil, plants, animals, mineral and water flows, etc.) and, on the other hand, human decision making and action on these biophysical entities (*Zabala et al.,* 2021). Models convey knowledge that mainly comes from scientific disciplines such as agronomy, zootechnics, environmental science, management science and the humanities.

Biophysical models can be classified into three main fields: mechanistic, empirical and hybrid (*Reyniers,* 1996). Mechanistic modelling focuses on events, causal relationships and processes, whereas empirical models treat systems as

"black boxes" and only generally describe the underlying biophysical phenomena. These models represent the input-output dynamics of a system component in terms of observation data. In reality, there are few truly mechanistic or empirical models. Models are generally hybrids or classified in one or the other category according to whether they possess mainly mechanistic or empirical components. The overall understanding and level of information required to build these models increases as we move from empirical to mechanistic models. By making causality explicit, mechanistic models can be more complex, while empirical models are generally simpler but have a more limited scope of application due to statistical data availability issues.

Decision modelling varies depending on the modeller's hypothesis about the decision maker. In a first type of hypothesis, the decision maker is assumed to be perfectly rational (in the economist's sense) and, when making a decision, determines the mathematically optimal choice according to theoretically defined functions of utility. In a second type of hypothesis, known as a bounded rationality hypothesis, the agent makes a decision that leads to an outcome that they consider satisfactory given the information available and their level of aspiration. Mental models of varying levels of sophistication are often used, including models based on decision rules that associate situations with decisions or actions (*Martin-Clouaire,* 2017). To facilitate and standardise the development of these models, ontologies can be used to define the concepts, relationships and other distinctions relevant to the areas concerned (major crops, livestock production, etc.) (*Roussey et al.,* 2011). An ontology (see Section 3.4) is an abstract model (metamodel) of the area and provides the representation primitives allowing the instantiation of models for specific systems in the form of knowledge bases (*Martin-Clouaire and Rellier,* 2004; *Fishwick*, 2007).

Definition

An ontology defines a vocabulary and the semantic links between the elements of the vocabulary. The vocabulary is composed of names of concepts (or "classes"), which are types of entities known by the system and names of possible relationships (or "roles") between these entities (for example, the relationship of "pest" links two "living organism"-type entities). The ontology is described in a logical computer language that expresses the representation of knowledge to different degrees of expression. It can range from a simple taxonomy (a set of concepts structured by progressive specialisation) to complex descriptions of vocabulary elements and their semantic links. The language used allows the implementation of automatic reasoning.

Discrete event, discrete time and continuous time systems – A discrete event simulation model allows the representation of a dynamic system using variables whose evolution depends entirely on the occurrence of asynchronous events over time. One particular case is when the time progression is in fixed increments. The discrete event approach contrasts with (but does not oppose) the "system dynamics" approach in which the state of the system is modified continuously over time based on a set of differential equations defining the rates of change and state variables. In each of these different cases, researchers are interested in the representation of causal relations (i.e., for the biophysical aspect, mechanistic models). One of the best known formalisms is Discrete Event System Specification – DEVS (*Zeigler et al.,* 2000), which is based on a generic framework allowing different adaptations to specific formalisms such as Petri nets, cellular automata and, more generally, models with fixed time intervals. Petri nets are a particularly popular mathematical formalism because of their ability to represent the synchronisation of processes running in parallel and offer possibilities for rigorous model analysis. A cellular automaton is built using a network of discrete cells and is well suited to representing spatial dynamics (such as the propagation of an infestation) and self-organising phenomena (such as the landscape dynamics of natural reforestation). Some formalisms such as statecharts (*Léger and Naud,* 2009), timed automata (*Hélias et al.,* 2008) and Petri nets (*Guan et al.,* 2008) can also suit processes for verifying the behaviour of the model (e.g. to ensure that it cannot lock up) or its temporal properties.

Automatic detection of mangoes by artificial intelligence from a smartphone photo. Hortsys.
© Hortsys – CIRAD.

Individual- or agent-based models – These models focus on systems that can be broken down into a set of entities (such as plants, animals, zones) that act or interact (*Daudé,* 2004; *DeAngelis and Diaz,* 2019). When combined with a cellular automaton-based approach, the individual-based approach allows the spatial representation and simulation of biophysical processes on a territory divided into plots. When the modelled entities acquire more elaborate cognitive and decision-making capacities (*Bahri et al.,* 2020), we speak of agent models that allow, for example, simulation of the decision-making behaviour of a group of agents (such as farmers) operating in a given territory (*Huber et al.,* 2018). Farm management has often been modelled using simple mechanisms for triggering decision-making rules associated with possible situations. With this approach, however, it has proved difficult to control the order in which rules are used and to maintain the rule base once it reaches a certain size. An improvement was introduced by the BDI (Belief, Desire, Intention) approach (*Georgeff et al.,* 1970; *Bratman,* 1987), which makes it possible to model the process by which an agent makes decisions based on a perception of the current situation (Belief), the declared objectives (Desire) and decisions on how to proceed toward the objectives (Intention).

For example...

The **INRAE-MIAT** UR has developed several formalisms to represent and simulate the decision-making behaviour of farmers when managing their farms using the BDI approach, temporal planning and uncertainty in artificial intelligence. For example, Martin-Clouaire and Rellier address the problem of production management as one of coordinating a set of activities organised in flexible plans for which it is possible to simulate the implementation in a particular context (*Martin-Clouaire and Rellier,* 2009). For application examples in dairy farming see *Martin et al.* (2011) and *Martin-Clouaire et al.* (2016) in viticulture.

Constraint-based models – Constraint-based models use varied range of formalisms that are mainly based on the concept of graphs modelling binary relationships between variables (*Hurley et al.,* 2016). These relationships can model correlations and causal influences, whether deterministic or probabilistic, as in the case of Bayesian networks and Markov chains. These networks can also describe constraints between variables in terms of combinations of acceptable or unacceptable values, leading to a Constraint Satisfaction Problem (CSP)

(*Moummadi et al.,* 2011). In a similar vein, linear programming methods are based on the optimisation of a linear combination of multiple variables connected by linear relationships called constraints (*Maqrot et al.,* 2017).

For example...

At INRAE, the **BAGAP** UMR works on modelling the problem of dynamic crop allocation on a farm, based on the use of spatial and temporal constraints and the toolbar2 solver (*Akplogan et al.,* 2013). For example, the team analysed the wooded countryside of the Charolais-Brionnais region to show the uniqueness of this landscape and its suitability for the different structures and functions of hedges. Thanks to this analysis, the countryside was added to the list of potential sites for submission to UNESCO for heritage protection.

Modelling and simulation

The primary advantage of modelling approaches is no doubt the ability to model and simulate complex behaviours in agricultural systems and, more broadly, socioecological systems such as agroecosystems (*Peart and Curry,* 1998). Models, especially agent-based ones, are often complex due to the number and heterogeneity of components and interactions and their sensitivity to variations affecting the systems. Their behaviour is difficult to study because the phenomena involved are non-linear with multiple discontinuities and feedback between levels of organisation and scales. Some of these models represent cognitive agents with bounded rationality behaviour. Numerous agricultural applications have been developed based on the CORMAS (*Bommel et al.,* 2015) and GAMA (*Taillandier et al.,* 2010) platforms, such as for studying water management, the reform of the Common Agricultural Policy, reducing the use of pesticides and developing organic farming.

For example...

At INRAE, the **AGROECOLOGIE** UMR coordinates the development of the MAELIA platform for the integrated modelling and evaluation of socio-agroecological systems. It aims to produce knowledge on the structure, functioning and performance of these forms of agriculture at plot, countryside and/or territorial level.

In practice, modelling-simulation approaches offer a variety of uses, ranging from laboratory analysis by scientists, decision support (*Huber et al.,* 2018), real-time decision making by farmers or agricultural advisors and support for negotiations between stakeholders (e.g. support models for joint water management in a territory) to the co-design of new production systems by a group of farmers and training. Individual or groups of farmers can thus improve their understanding of biophysical functioning and obtain ideas for improving the system studied in terms of product quality, system vulnerability, environmental consequences of the practices implemented, reduction of work overload and drudgery and, finally, economic performance linked to the application of agroecological principles.

For example...

At INRAE, skills are grouped in **CATIs** for modelling large-scale systems, such as the **IMOTEP CATI** (Information, Models and Data Processing in Epidemiology and Population Dynamics) and the **IUMAN CATI** (Computerisation and Use of Models for Digital Agroecosystems). The work covers both modelling of the spread of epidemics in plants or animals and software development for platforms and proofs of concept allowing the sharing and computerisation of these new models at multiple scales.

Modelling and optimisation

By definition, optimisation explores possible solutions to a given problem using different methods to find an optimum or optima according to a criterion or set of criteria (*Zelinka et al.,* 2013). It is used in different areas of agriculture and at different scales (*Plà-Aragonés,* 2015). At the farm level, optimisation is implemented either explicitly or implicitly, whether in feed formulation, herd management, animal slaughter planning, crop and land use planning or water management. It is also used at different scales, including groups of farms, territories, regions and countries, for managing land use, water and economic trade and market issues (*Carpentier et al.,* 2015). In these cases, bioeconomic models are employed according to an analytical approach, in which the primary objective is to evaluate the impact of the applying constraints and criteria to optimal solutions.

Due to the complexity of agricultural systems and changes in questions relating to agriculture, optimisation has also evolved in agriculture (*Jones et al.,* 2016). The early economic models of the 1950s focussed above all on maximising income.

Today, the formulation of low-cost feed still primarily aims to obtain the cheapest feed possible while meeting nutritional criteria. Optimisation has gradually become multi-objective to combine different aims: productive (e.g. animal or plant production, working time), economic (e.g. income, cost) or environmental (nutrient levels, environmental impact calculated by life cycle analysis, ecosystem services, etc.). In "constrained" optimisations, the constraints are also varied and can be biological, structural, regulatory, environmental or linked to decision-making.

Model optimisation in agriculture has also benefited from developments in optimisation methods, using a diverse range of methods. Deterministic linear programming methods are still very common, with adaptations to solve multi-objective problems. Stochastic metaheuristic methods are applied alone or in combination with the previous ones. These metaheuristic methods make it possible to address multicriteria optimisation and obtain a set of optimal solutions considered admissible in the context (called Pareto Front); they include, for example, evolutionary algorithms (such as genetic algorithms or differential evolution) that work on a population of solutions, particle swarm optimisation, taboo search, simulated annealing, etc.(*Kaim et al., 2018; Memmah et al.,* 2015).

Current issues surrounding optimisation concern, in particular, how to adapt methods to increasingly complex models, and in particular how to take account of uncertainty (*Crespo et al.,* 2010) and the temporal aspect in the formulation of the optimisation problem (*Akplogan et al.,* 2013). These issues echo those traditionally addressed in the automatic control and optimal control community. Another major topic of research is the coupling between optimisation and simulation (*Borodin,* 2014), in particular in connection with reinforcement learning methods (*Gosavi,* 2015). Despite technological advances in computing power, the processing time of optimisation processes is still an important factor to be considered due to the increasing complexity of the models in question. Recent developments in metamodelling offer a possible simplification strategy to reduce these processing times.

For example...

At INRAE, the **PEGASE** and **SMART-LERECO** UMRs develop multi-criteria optimisation approaches (zootechnical and economic performance, environmental impact) for feeding strategies in pig farming, based on a pig farm model.
At Inria, there are more than twenty project-teams working on the development of optimisation, operational research or control algorithms.

3.3 Multi-scale learning and knowledge extraction

The two previous subchapters presented the approaches used to collect data, followed by modelling techniques based mainly on human analysis. In this subchapter, we will focus on the main families of approaches to building models directly from data and thereby automatically extracting knowledge. The resultant knowledge can either be presented to human experts or remain within a learning context for prediction or identification tasks, for example.

We will first show that the "raw" data sent by the sensors cannot generally be used in its initial state and that its pre-processing represents a challenge in itself. Let's start by presenting the types of data frequently used in digital agriculture, and which could constitute a Big Data.

Massive data in agriculture

In agriculture, the most "massive" data comes from sensors with high temporal or spatial resolution, such as time series and remote sensing or mapping data from embedded sensors.

Time series – A time series is a sequence of numerical values representing the evolution of a variable measured on an individual over time. Such sequences of variables can be modelled individually to understand their past evolution and predict future behaviour using ARMA-type models (*Box et al.,* 2015). Today, experiments in agronomy make it possible to observe the same variable on thousands of individuals (e.g. leaf area on thousands of plants in a greenhouse, the temperature of livestock) over long periods. The aim of analysing these time series has therefore evolved toward the search for common characteristics between series, major differences or the acquisition of more detailed knowledge about the internal (e.g. effect of genotypes) or external (e.g. linked to environmental variables) mechanisms that influence the observed variables. Time series are thus studied more generally as functions of time. Their data is also known as "functional" or "longitudinal" data.

Remote sensing data – Remote sensing data can be images of a given area, taken by satellite or by drones. Satellite images – which we will focus on next – can be recorded at different periods, these sequences constituting time series. They can also, for the same period, be taken from different satellites, each with a different radiometric content (i.e. radar information, optical information). Thanks to recent

space missions such as *Copernicus*, plant dynamics can now be monitored with a spatial resolution compatible with the size of the objects of interest and short revisit time intervals. The *Sentinel-1* satellite mission acquires radar information (two bands) every five or six days over the same area at a spatial resolution of ten metres. This source of data provides access to information on the structure of objects (i.e. forest or agricultural biomass) and makes it possible to monitor and assess wetland areas and the area of land that has been irrigated over a certain period. Another equally interesting satellite mission is *Sentinel-2*, which provides multispectral imaging information (thirteen bands), again delivered every five or six days and at a spatial resolution of ten metres. This optical sensor is particularly suitable for mapping land cover and land use, monitoring the biodiversity of natural states and for large-scale yield estimation over large areas (*Lambert et al.,* 2018).

At the other end of the scale, at the microscopic level, metabarcoding[33] metaomic data allows a better characterisation of the biological environment of crops or animals. This metadata is constructed by assembling the "fingerprints" of the genomes present or of their expressions (RNA, proteins), making it possible to analyse new dimensions of ecosystems, which can better explain the behaviour of crops or animals. We are still only at the beginning of exploring these new data sources, some of which remaining difficult to access (proteomics, metabolomics, etc.).

Data pre-processing

The major challenges in data pre-processing are: i) identifying outliers or unreliable data: data collected during experiments or in the field is voluminous, very noisy and can be affected by errors from a variety of causes, such as a faulty sensor. Specific tools are therefore needed to annotate this data, rapidly detect faulty sensors and diagnose heterogeneity in the field or greenhouse to improve the quality of the data sets for future analyses; ii) linking data with expert knowledge, such as mimicking an expert's reasoning by an automaton when validating a "small" data set, or using the expert's knowledge to adjust curves (alignment of phenological stage dates).

One particular challenge is data fusion. Information that is difficult to obtain directly can be retrieved by combining data, whether of the same type (for example, the leaf area of a plant can be predicted from the analysis of

33. Metabarcoding is a method of identifying species from DNA or RNA segments. Instead of targeting different species, metabarcoding determines the composition of species in a sample, thereby allowing the identification of many taxa in an assembly of populations (of bacteria or other microorganisms) within an environmental sample (e.g. soil sample, sediment, excrements, etc.). It is thus one of the fastest methods for the environmental assessment of the biodiversity of ecological systems with a high number of unknown or difficult-to-identify species.

fifteen images of this plant taken from different angles), or of different types. To do so, i.e. to monitor the same phenomenon or the same study area, an ever greater volume of heterogenous data of various types (called "multisource" data) is collected. The knowledge contained within this data is a real opportunity for improving our understanding of the complex phenomena associated with modern agricultural practices in order to better monitor and manage them. Within this general framework, one of the main challenges today is knowing how to make the best use of these heterogeneous and complementary sources of information to obtain the maximum amount of information (because, in the science of complexity, "the whole is greater than the sum of its parts"[34]). Depending on the typology of the sources involved in the process, two merging strategies can be used: early and late merging. In the first case, the data is combined at the beginning of the process to form a single new homogeneous dataset. This can be done, for example, by bringing all the available information to the same spatial or temporal resolution or unit of analysis. In this context, once the new dataset has been built, standard single-source analysis techniques can be used. In the second case (late merging), an analysis process is set up by each source specifically and the merge is carried out at the descriptor or decision-making level. For example, specific descriptors can be extracted from each source and then combined to exploit higher-level interactions between the different sources considered. Lastly, the different sources can be combined in what is known as an "end-to-end" process, in which the standard processing stages are replaced by a single system (usually a deep neural network) that takes the raw sources as input and returns the required decisions as output (*Charvat et al.,* 2018; *Plaisant,* 2004; *Tonda et al.,* 2018).

In the case of time series, merging series with different temporal resolutions is a major challenge, for example if the activity sensor in a collar worn by an animal sends information every five minutes, but the animal is only weighed once a day. In order to compare individuals, it may be necessary to interpolate the time series for the same time period (using linear or polynomial smoothing methods), possibly by matching similarities (dates of phenological stages, growth peaks, etc.). Dynamic Time Warping (*Sakoe et al.,* 1978) is one of the well-known techniques for measuring similarities between two series. However, this technique does not provide answers to all the curve alignment issues encountered when dealing with living beings, when it is essential to take phenological time into account. These questions present challenges that are still largely unresolved in biology.

34. http://www.scilogs.fr/complexites/le-tout-est-il-plus-que-la-somme-des-parties/

There are also methods able to extract several models from time series at different time scales and then select the most relevant ones using information theory approaches (principle of Minimum Description Length – MDL) (*Vespier et al.,* 2012). The advantage of these approaches is that they allow us to focus on the temporal scale of the observed phenomena instead of the technical sampling value.

In the case of remote-sensing, with the explosion in the number of satellite missions (*Sentinel, Spot, Pleiades* and *PleiadesNeo, PlanetScope,* etc.), it is now possible to collect information describing a single study area at a lower cost in different spectral ranges (optical and radar) and at different spatiotemporal scales. This massive volume of multisource information requires new data management and analysis tools to be developed (*Schmitt and Zhu,* 2016). Typically, in a classical multisource fusion process for Earth observation data, sources are exploited through an early fusion process. For example, in the case of imagery at different spatial scales, a resampling stage is incorporated to bring all the images to the same spatial scale beforehand. Unfortunately, this type of process can introduce bias or error by generating new synthetic information. This is why late fusion approaches are now preferred wherever possible. Early examples in the context of land use mapping are starting to appear but we are still far from a generic solution that can be deployed systematically across different territories and adapted to different agricultural practices.

For example...

At INRAE, the **MISCA** team of the **TETIS** UMR develop information management methods to meet the major societal challenges related to the environment, whether storing, managing, sharing or analysing large volumes of data. In particular, it contributes to soil mapping by applying Deep Learning techniques on very large datasets.

At Inria, several project-teams (**GEOSTAT**, **TITANE**, **FLUMINANCE** (Inria, INRAE, Université de Rennes 1), etc.) and the exploratory action **AYANA** are working on the analysis of satellite images.

In addition to purely satellite-based multisource information, other types of information are now combined with Earth observation data. For example, "spontaneous" geolocation information or information from citizen science (*Ienco et al.,* 2019) have much to offer to improve calibration and complement the purely physical information from satellite sensors.

Supervised approaches

Supervised analysis consists mainly of two tasks: supervised classification and prediction of future values. Supervised classification consists in assigning, for a given time series and set of predetermined classes (e.g. "sick animal" and "healthy animal"), one of these classes to the time series. In practical terms, this can help determine the condition of an animal or plant from sensor data and information on the different conditions possible. Supervised classification methods need to be "trained"; to do this, they must be provided with a large number of correctly labelled examples indicating their class. Using these examples, the classification algorithm builds one (or more) model(s), to assign a class to an unlabelled time series according to its characteristics. The main differences between the major families of supervised classification approaches lie in the way the models are built. The simplest approaches, known as k-Nearest Neighbor (kNN), do not build a model but search for the k examples of the training set closest to the individual to be labelled, and return the majority label. The difficulty lies in choosing a suitable similarity method (*Karlsson et al.,* 2016).

Finally, the very popular deep neural network methods can also be used to classify such data. The most successful method of this type is currently MLSTM-FCN (*Karim et al.,* 2019), which combines a convolutional CNN (Convolutional Neural Network) block with a LSTM (Long Short Term Memory) block. The CNN block, widely used in image analysis, serves as a filter that traverses the time series or spectrum and extracts characteristic attributes at time t. It is combined with the LSTM block, which is widely used in the analysis of sequential data (especially text), and allows connections between past and present values to be made. This type of approach can produce excellent results (*Kamilaris and Prenafeta-Boldú,* 2018). However, it requires an even greater volume of labelled training data (which can be difficult to acquire in some agronomic contexts), and its parameters can be tricky to define (*Zhu et al.,* 2017)..

For example...

At Inria, the **STATIFY** project-team (Inria, CNRS, Institut Polytechnique de Grenoble) focuses on the statistical modelling of systems involving complex-structure data. The team develops statistical methods for capturing the variability of the systems studied while ensuring a good level of precision and taking into account extreme values that generally reflect rare phenomena. In particular, they model weather events for agroecology.

An example of the use of supervised classification methods in agriculture can be found in *Fauvel et al.* (2019), in which the authors work with precision breeding sensor data from dairy cows. The cows are equipped with thermometers and collars with an accelerometer. The time series of temperature and physical activity are analysed to allow more accurate oestrus detection than with existing methods or visual observation, even in the frequent cases where cows do not express any particular behaviour in the pre-oestrus phase (30%).

Unsupervised approaches

Unsupervised approaches are used to reveal certain structures in data, whether groupings with clustering or recurring patterns with pattern mining.

Clustering – The aim of the clustering (or unsupervised classification) learning method is to identify relevant classes in the data. Data is grouped by similarity or proximity within each class. To achieve a good classification, it is necessary to minimise the intra-class inertia (to obtain homogeneous classes) and maximise the inter-class inertia (to obtain well differentiated classes). Two main families of methods are commonly used: i) hierarchical ascending classification (HAC), which seeks to group individuals iteratively, starting at the bottom (the two closest) and gradually building a tree, or dendrogram, to finally group all the individuals into a single class, at the root; ii) classification by dynamic reallocation (the k-means algorithm is a well-known example of this). The number k of classes is fixed a priori. After initialising k class centres, all individuals are assigned to the class whose centre is closest in the sense of the chosen distance. The algorithm then calculates the barycenters of these classes which become the new centres. The process (assignment of each individual to a centre, determination of the centres) is iterated until convergence to a fixed (local) minimum or maximum number of iterations.

The main issues to overcome when clustering multivariate data are identifying the "right" number of classes and defining a distance that is adapted to the data, sometimes implying the need to reduce the dimension. One common technique involves performing principal component analysis on the data and then apply clustering on the coordinates of the data in the eigenbasis, with all the difficulties of choosing dimensions that this entails. Clustering by combining Dirichlet processes (*Coquet et al.,* 2002) offers a way to get around these difficulties.

Patterns mining – Patterns correspond to implied regularities/irregularities or specificities of the data or subparts of the data. In agronomic applications, an individual can be described through a sequence of characteristics or events. For example, a plot can be described by a sequence of cultivation operations, a plant can be described by a DNA sequence, etc. one of the major challenges with this type of data is the extraction of frequent or rare subsequences.

For example...

At INRAE, the **TETIS** UMR focuses on extracting frequent/rare subsequences in this type of data and frequent patterns in the form of items and sequences (sequences of events ordered in time) in order to characterise the difference in vegetation growth between different spatial areas. Their work is particularly relevant for wetland area estimation and biodiversity monitoring.

Other approaches aim to highlight sub-parts of the data with very different characteristics to the rest of the data (distribution differences for certain attributes, etc.). For example, in *Millot et al.* (2020), the authors use the notion of discriminating patterns to characterise, from simulation data, sub-families of crop protocols in urban farms where part of the attributes (temperature, light, CO_2, etc.) show an interesting distribution with respect to a given measure of interest.

Unfortunately, these methods are often faced with a number of patterns that prove to be too large to be easily used by experts. A promising and currently much studied avenue is the selection of the most relevant pattern subset. Patterns can be extracted from time series after a pre-processing phase in which the sequence of numerical values is transformed into a sequence of symbolic values, allowing classical pattern discovery methods to then be applied. When the numerical data is kept, methods for extracting representative subsets, called "shapelets", can be used..

For example...

INRAE units such as the **PEGASE** UMR, **UMRH**, the **Toxalim** UMR and the **GenPhyse** UMR use these different learning approaches for precision feeding, early detection of anomalies in the activity of dairy cows in a herd, detection of pathologies in piglets or analysis of sow behaviour respectively.

Reinforcement learning

Like many types of data, agricultural data is often uncertain (see 3.1). Reinforcement Learning (RL) is concerned with learning to operate in an uncertain environment. One example of a modern use of RL for crop management planning is *Déciblé* (*Chatelin et al.,* 2005), originating from *Garcia* (1999) and based on interaction using a decision rule model for wheat cultivation. This empirical crop simulator is used to evaluate policies expressed as sets of decision rules. In *Ndiaye* (1999), model-free methods – namely Q-learning and R-learning – are mixed with genetic algorithms, decision trees and fuzzy logic to find optimal decision rules for crop management coupled with *Déciblé*. The result was considered to be not as good as the decisions that an expert would expect to see. These early approaches were interesting in that they introduced modern RL techniques for crop management while considering a range of actions. They also expressed an optimised policy in a natural way, i.e. in the form of a set of simple decision rules corresponding to farmers' reasoning. However, the solutions in Garcia (1999) and *Ndiaye* (1999) are limited in that learning is offline, using an empirical decision model simulator with its own biases and field of validity. Because learning is not in real time, the systems do not use farmers' feedback to improve the policy learned from the simulator.

These methods were later applied in a more complex context, incorporating an economic model for oilseed rape management and a pest and disease component in crop modelling (*Trépos et al.,* 2014). RL methods have been successfully applied in irrigation planning when water availability is limited (*Bergez et al.,* 2001). Nevertheless, each management decision must take into account the whole sequence of choices. Different crop varieties have different water requirements, so there will be different irrigation costs. *Bu and Wang* (2019), proposed a general computer architecture for intelligent decision making in agriculture based on deep Q-Learning. In practice, deep Q-Learning requires billions of instances of trial and error. Furthermore, no proposal has been made to integrate specialist knowledge (e.g. knowledge of plant physiology) into this system; approaches using expert knowledge could therefore be considered (model-based learning), allowing the amount of examples needed for training to be reduced by several orders of magnitude.

For example...

The **SCOOL** project-team (Inria, CNRS, Université de Lille) specialises in reinforcement learning and is studying the recommendation of practices in agriculture for very small farms, especially in developing countries, and in gardening. The research is carried out with a focus on sustainable development.

Different machine learning and data science methods are implemented in the scikit-learn library, which was principally developed at Inria and is one of the three most downloaded artificial intelligence libraries in the world.

The INRAE **MIAT** unit is also working on the development of methods based on Markov decision processes and reinforcement learning applied to the management of agroecological systems, with particular focus on issues related to the spatial dimension of problems.

Data warehouses and OLAP analysis

Data warehouses (DWs) were designed to handle very large volumes of data from heterogeneous sources (*Chandra and Gupta,* 2018). Multidimensional modelling (where data is characterised across multiple axes of analysis) and hierarchical modelling (where an axis of analysis can be associated with different levels of granularity) form the basis of DWs and multidimensional analysis. For example, the analysis of the amount of pesticides or nitrogen used by farmers can be characterised according to several dimensions (or axes of analysis): temporal, spatial and at crop level (*Bouadi et al.,* 2017). This allows quantities to be represented by crop type, season and plot. These dimensions can be expressed in different levels of detail. For example, spatial information can be defined at the scale of a single plot or at a larger scale such as the watershed, region, etc., since each plot belongs to a watershed, which in turn belongs to a region, which in turn belongs to a country.

Multidimensional analysis uses OLAP (On-Line Analytical Processing) to aggregate, visualise and interactively explore data. If we take the previous example, we could analyse the quantity of pesticides or nitrogen at plot level or at a more aggregated level of spatial dimension such as the watershed. OLAP processing is used to navigate between different granularities of one or more dimensions in a very efficient way (i .e. navigation is instantaneous).

Users can use the data warehouse by combining the different dimensions and different levels of granularity of the corresponding hierarchies. To select the appropriate data at the right scale, users express and submit queries to the data warehouse.

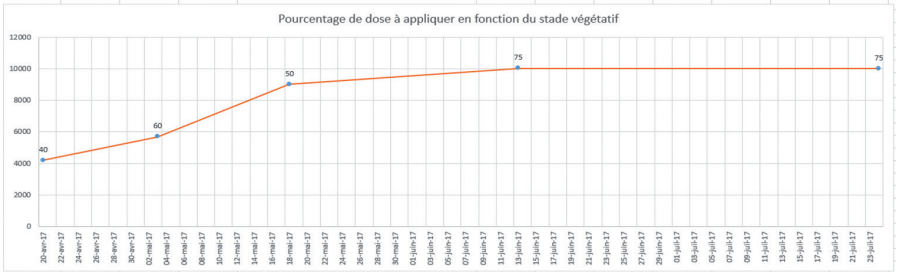
Other works (*Palpanas,* 2000) describe the coupling of multidimensional analysis with data mining methods (e.g. pattern mining), with the aim of proposing hybrid methods that combine the exploratory and analytical capacities of OLAP with the descriptive capacities of data mining. For example, the ADSS-OLAP tool (*Abdullah and Hussain,* 2006) combines OLAP and data mining (clustering) and was developed to analyse the impact of mealy bug on cotton crops. To further enhance OLAP analysis and allow geographic data mining, the idea emerged to couple OLAP and GIS (Geographic Information System) technologies. Thus, the new concept of Spatial-OLAP (SOLAP) (*Bédard et al.,* 2007) was introduced to jointly exploit OLAP tools (decision, graphs, etc.) and geographic tools (cartographic representation, geographic aggregators, etc.).

For example...

At Inria, the **LACODAM** project-team (Inria, Institut national des sciences appliquées de Rennes, Institut national supérieur des sciences agronomiques, agroalimentaires, horticoles et du paysage, Université de Rennes 1) has modelled and built a data warehouse to analyse/explore, in space and time, the effects of agricultural practices on nitrogen emissions to water and the air (*Bouadi et al.,* 2017). The team is also studying the use of machine learning to improve animal welfare (dairy cow health and sow feeding).

At INRAE, the **TSCF** unit focuses on spatial OLAP. Among other things, it contributes to storing and analysing biodiversity data online, in particular through the VGI4BIO project (www.vgi4bio.fr) which proposes methods for analysing biodiversity indicators in an agricultural context centred around data and VGI users.

Ilot	Parcelle	Cépage	Date_photo	Nom_fichier	Stade_BBCH	H	L	LWA	TRV		dose optidose Oïdium (%)
Larzat	Aranel	Aranel	20-avr-17	2017_T1_Chapitre_Larzat_Aranel_1.JPG	54	52	37	4200	723		40
Larzat	Aranel	Aranel	03-mai-17	IMG_20170503_090132777 aranel larzat chapitre.jpg	57	71	43	5680	1193		60
Larzat	Aranel	Aranel	18-mai-17	2017_T2_Chapitre_Larzat_Aranel_1.JPG	60	113	64	9016	2766		50
Larzat	Aranel	Aranel	13-juin-17	2017_T3_Chapitre_Larzat_Aranel_1.JPG	75	125,2	66,11667	10016	3310		75
Larzat	Aranel	Aranel	24-juil-17	2017_T4_Chapitre_Aranel_IR.JPG	81	125,125	69,65625	10010	3494		75



Optidose® a tool to adapt the dose according to the parameters of the crop and the epidemic risk.
© Le Mas Numérique.

3.4 Knowledge management and engineering for decision support in agriculture

The previous sections provided an overview of the state of the art in data collection, management and processing; we also saw how modelling makes it possible to manage and represent knowledge in a mathematical way using measurements and observations to help with interpretation and recommendation. Another important facet of digital agriculture is knowledge management, i.e. higher-level information including both general scientific knowledge (e.g. plant or animal physiological processes) and methods specific to certain actors in the agricultural sector (e.g. a livestock farmer's herd management, methodology for making certain cheeses, etc.). In recent years, significant effort has been made to formalise this knowledge and organise it in ontologies that provide a structured access. Ontologies are a component of computer systems that help users accomplish a task. This assistance can take many forms, from automating an irrigation decision to finding information to help make a decision. Knowledge can also be generated by the analyses presented above. In this case, the difficulty lies in presenting these analyses to human actors in the most intelligible way. Again, recent developments in data analysis are of particular interest to agriculture, whether *via* visualisation approaches or methods for interpreting learning models. Lastly, the aim of

everything presented in this section is to enable human actors to make better decisions. Specific tools known as DSS (Decision Support Systems) that use all or some of the techniques presented in this chapter are available to these actors and are constantly evolving. This section will conclude with an overview of these tools.

For example...

The **BIOEPAR** UMR contributed to the development of **EMULSION**, an open source program and DSS based on artificial intelligence. **EMULSION** allows modellers to develop stochastic mechanistic models of complex systems in epidemiology at different scales and using different paradigms, while reducing the amount of computer code that has to be written (*Picault et al.,* 2019). Based on this, the **ATOM** (Automation of decision support Tools based On epidemiological Models) project aims to develop a process for industrialising the DSS generation using mechanistic epidemiological models (https://www6.angers-nantes.inrae.fr/bioepar/Recherche/Projets-en-cours/ATOM).

Knowledge-based systems in agriculture

From the first expert systems to knowledge-based systems – The first expert systems emerged in the 1970s as a result of research in artificial intelligence. These systems were dedicated to resolving a specific problem by using the knowledge of one or more experts and mimicking their reasoning, with the ultimate aim of replacing them. In one approach, called the symbolic approach, expert knowledge is formalised using a knowledge representation language based on logical reasoning. This is in contrast to the connectionist approach, which mimics the functioning of the human brain using neural networks.

One particularity of the agricultural sector is that the inherent problems in crop or herd management require expert knowledge in several fields (soil science, meteorology, chemistry, biology, etc.). To meet this demand for multidisciplinary expertise, some expert systems incorporate simulation models as components, such as those described in Section 3.2. Such an example is the expert system *"CrOp MAnagement EXpert"* (COMAX), dedicated to cotton cultivation, which aims to maximise yields while minimising inputs (*McKinion and Lemmon,* 1985) and encapsulates a simulation model of cotton development (GOSSYM). Because the acquisition of expert knowledge is crucial for the development of expert systems, knowledge engineering has focused on methods for acquiring such knowledge. These methods have been used to guide cognitive scientists through the complex

tasks of identifying, extracting and formalising expert knowledge from a variety of sources (expert interviews or other documents describing the task of solving the problem).

Very popular in the 1980s, expert systems have also been severely criticised for not being adaptable to applications other than the one they were designed for and for offering poor potential for development. In the 1990s, expert systems gradually evolved into knowledge-based systems. The notion of ontology then appeared in computer science. Ontologies are designed to formalise consensual and relatively stable knowledge in a given domain to allow it to be reused in other knowledge-based systems.

A knowledge-based system is composed of two distinct parts: firstly, a knowledge base including an ontology that structures the knowledge from the domain, with a fact base that instantiates the ontology to describe specific situations and sometimes a rule base that enriches the ontology; secondly, a reasoning engine associated with the knowledge representation language but independent of any particular knowledge base.

Evolution of knowledge acquisition and capitalisation methods – The shift toward knowledge-based systems was accompanied by a change in the conception of the relationship between humans and machines. Knowledge-based systems and their associated intelligent computer system aim to cooperate with the user to help them perform a task requiring different types of knowledge by supplementing the user's knowledge, revealing the consequences of their choices and proposing alternative options to those they would have imagined. Knowledge engineering then evolved into a form of knowledge modelling mediation, producing "knowledge models" – a model here taking on a different and more global meaning than in Section 3.2 since it no longer represents phenomena but knowledge. These models allow the cognitive scientist, in charge of implementation in a computer system, to dialogue with experts to enrich and validate the knowledge to be represented. To help this mediation, several methods have been developed, the best known being "Knowledge Acquisition and Documentation Structuring" (KADS, from which commonKADS was later developed). For example, a system for recommending irrigation dates for mango trees was developed using the commonKADS method (*Nada et al.,* 2014).

For example...

The **GRAPHIK** project-team (Inria, INRAE, CNRS and Université de Montpellier) studies knowledge representation. Among other things, the team is working on a method for collecting, modelling and formalising knowledge to improve the quality of local cheeses. Data collection is carried out through questionnaires; modelling is done by creating mind maps to facilitate validation by experts and formalisation is carried out using conceptual graph language.

Knowledge models were deployed in other computer systems such as information (source) search systems. This development led to the creation of "organisational memories". An organisational memory is the set of human and material resources – knowledge carriers – which allow an organisation to carry out its tasks. A memory can be composed of a set of text documents, videos, lists of employee skills and one or more knowledge models. The formalisation of these models allows them to be used automatically to help the circulation of resources and knowledge among the members of the organisation. This formalisation often takes the form of a thesaurus: a structured list of standardised terms organised into three types of relationship (equivalence, hierarchy, association), with the aim of indexing and helping to search for different content.

Find out more

The FAO (Food and Agriculture Organisation of the United Nations) has been instrumental in producing organisational memories in the agricultural field (*O'Leary,* 2008). Its bibliographic database AGRIS offers different types of resources (scientific documents, data sets, etc.) in several languages. These resources are indexed using the *AGROVOC* thesaurus, which is now one of the most important tools in the agricultural field (*Sini et al.,* 2008). This thesaurus encompasses many aspects of the agricultural domain and can be adapted to the needs of a new organisation. An example of an organisational memory is the Agropedia project, led by a number of Indian agricultural institutes in collaboration with the FAO (*Pappu et al.,* 2010) to transform scientific knowledge from universities into practical knowledge of use to farmers. Agropedia uses Topic Map knowledge models, which aggregate all the knowledge needed for a given crop.

Semantic access to information sources – The birth of the Semantic Web in the early 2000s had a strong impact on the field of knowledge representation. Semantic Web technology is a set of standardised languages, protocols and tools under the aegis of the W3C to enable the automated exploitation of Web resources according to their content. Web resources (such as HTML documents or, more broadly, any data available on the Web) are annotated with metadata describing their content in a formal language, constituting a fact base that can be enriched with a thesaurus or ontology that specifies its semantics.

Definition

The main formal languages of the Semantic Web are:

- Resource Description Framework (RDF): the language for describing Web resources in the form of a graph made up of triples (subject, predicate, object);
- RDF Schema (RDFS): an extension of RDF that allows a vocabulary to be defined in terms of classes and properties (or binary predicates) organised by specialisation;
- SPARQL Protocol and RDF Query Language (SPARQL): the RDF(S) description query language;
- Ontology Web Language (OWL): the most commonly used language for describing Semantic Web ontologies;
- Semantic Web Rule Language (SWRL): a rule language that can be used to enrich OWL descriptions;
- Simple Knowledge Organization System (SKOS): RDFS specification for formalising terminologies, thesauri, classifications and other vocabularies used in information retrieval systems.

Web ontologies are modular and focus on a specific need to facilitate their reuse and combined use. By making them available on the web, the interoperability between knowledge-based systems can be improved. Of particular interest is the RDA *Agrisemantics* working group initiative which has been exploring the use of this technology and associated resources to improve the exchange and sharing of agricultural data (*Aubin et al.,* 2017). This technology has allowed organisational memories to be transferred to the Web.

For example...

INRAE is also developing organisational memories on the impact of climate change on agricultural practices and agroecology. An archive of French agricultural information bulletins, the Plant Health Bulletins (BSV), was compiled during the VESPAproject, which studied epidemiosurveillance networks (*Roussey et al.,* 2017).

The GECO collaborative web portal (https://geco.ecophytopic.fr/) was developed to improve knowledge sharing around integrated crop protection and agroecology. This portal manages a set of explanatory text sheets to propose means of controlling pests (*Soulignac et al.,* 2017). GECO allows users to perform searches regardless of their level of expertise.

Web ontologies and SKOS thesauri have become reusable resources. Specific portals have been developed for searching for all these resources..

For example...

At INRAE, the computer science department of the **MISTEA** UMR has, among other things, developed the AgroPortal (http://agroportal.lirmm.fr/) which lists ontologies and thesauri related to agronomy and agriculture and makes them openly available. AgroPortal also provides services to help annotate text documents and detect links between concepts in two ontologies (ontology alignment). It also contributes to advances in high-throughput plant phenotyping.

Semantic integration of structured data – Linked Data refers to a network of linked sets of resources. It was developed in the 2010s and marked a new stage in data sharing using Semantic Web technology by considering a network of interconnected sets of resources. This network is based on the use of shared vocabularies (thesauri, ontologies, etc.), used to describe the data. This development goes hand in hand with the generalisation of the concept of data and encompasses all data, including structured data from different databases.

For example...

Examples of structured data include:
Weather data from an INRAE station is available as Linked Data (http://meteo.clermont.cemagref.fr/). A central Semantic Sensor Network (SSN) ontology provides a design pattern for describing the measurements.

The European project SmartOpenData (http://www.smartopendata.eu/) proposed an infrastructure (and a SmartOpenData (SMOD) schema) for managing Open and Linked Data in the field of biodiversity and the environment (e.g. in agroforestry data management).

The Agronomic Linked Data project (AgroLD – http://www.agrold.org) integrates 50 databases into a single RDF database. Its objective is to jointly question and link different points of view on cultivated plants (genomic, proteomic and phenomenic) formalised by at least one of the ten Web ontologies used (Gene Ontology, Plant Trait Ontology, etc.).

Hybrid architectures such as *OpenSilex* (http://www.opensilex.org/) that incorporate ontologies, an inference engine and different formats of databases (relational, NoSQL, RDF) are used to develop multiple information systems for high-throughput phenotyping. In this architecture, a scientific object (plant, pot, field, etc.) is identified by a web identifier (URI) and typed by an element of one of the associated ontologies. The RDF database stores the static descriptive metadata while the NoSQL database stores the raw data streams: drone photos, time series from field sensors, etc.

For example...

The GnpIS information system stores all the structured data from experiments carried out on plant phenotyping (*Pommier et al.,* 2019). The ontologies proposed by the Crop Ontology network (https://www.cropontology.org/) are used as dictionaries for all observable traits in the experiments.
For animals, the descriptions of animal experiments carried out in different research centres can be made compatible using a web ontology network developed at INRAE. The network currently consists of three web ontologies (*Salaun et al.,* 2018): Animal Trait Ontology for Livestock (ATOL, on phenotypic traits in livestock), Environment Ontology for Livestock (EOL, on environmental parameters in livestock farming), and AHOL (for livestock animal health).

Emerging architectures – Beyond the Web of Data, the problem of the intelligent exploitation of increasingly large and heterogeneous data has led to very active research combining knowledge representation, data management, the Semantic Web, data mining and learning, etc. It is in this context that a new architecture has been proposed called Ontology-Based Data Access (OBDA) (*Xiao et al.,* 2018), which combines a specific approach to data integration, called mediation, with the concept of the knowledge-based system. OBDA systems are structured in three levels: the conceptual level, organised around an ontology (described for example in RDFS or OWL); the data level, composed of various pre-existing and independent databases; and the mapping level, which translates the data relevant to the target application into a fact base using the ontology vocabulary. Queries to the system (e.g. in SPARQL) use this vocabulary, with the user expressing himself at a conceptual level with no knowledge of the data storage system (for example, a query such as "*"what auxiliaries can control pest X and what are the associated techniques that would limit competition with the main crop?"* would be completely dissociated from the underlying database schemas).

For example...

At INRAE, the Ecology of Mediterranean Forests URFM unit of the **ECODIV** department conducts multidisciplinary research in ecology. In particular, it implements mature OBDA systems such as Ontop (https://ontop-vkg.org/) and MASTRO (https://www.obdasystems.com/mastro) for the sustainable management of Mediterranean forest ecosystems.

In the context of the Internet of Things, some of these systems also use Semantic Web technologies (OWL ontology, SWRL rules, RDF annotation base).

Standardisation bodies such as W3C and ETSI are currently working on the validation of new standards and ontologies to combine the Internet of Things and the Semantic Web: these are the SAREF ontology by ETSI and the Web of Things (WoT) ontology by W3C. These ontologies have not yet reached a sufficient level of maturity to be used in real-life applications..

For example...

At INRAE, the **TSCF** unit has proposed a translation of the IRRINOV manual irrigation method into SWRL rules and a web ontology network to represent knowledge for automating irrigation.

Questions remain about the compatibility of ontologies built on different principles: different uses, different authors, different foundational ontologies etc. Some web ontologies propose data schemas corresponding to reusable patterns (design patterns) centred on a specific need. Other ontologies offer reference classifications to qualify data. Data managers must therefore build a network of ontologies to structure their data, checking that these ontologies remain compatible with each other. Are they based on the same patterns? Do they allow correct inferences to be made? Lastly, current research topics focus on questions concerning the distribution of reasoning over all the components of an "Internet of Things"-type system.

Knowledge restitution, visualisation and human-machine interaction in agriculture

Data-driven knowledge production methods (section 3.3) have produced results that are not only increasingly accurate and reliable but also increasingly difficult to understand, to the extent that most of these approaches are now described as "black boxes", of which the user is unable to understand the determinants of the result produced (e.g. a decision on the technical process). One solution to this problem consists in using local interpretability approaches such as LIME (*Ribeiro et al.,* 2016) or SHAP (*Lundberg and Lee,* 2017). Instead of aiming to explain the learned model as a whole, which is too complex, these approaches explain the reasons that led the model to produce such a decision in the specific case provided by the user, such as the attributes that contributed most (positively or

negatively) to the decision. For example, SHAP, used in oestrus detection as seen above (*Fauvel et al.,* 2019), provides explanations of the type: *"an oestrus was predicted today based on temperature changes over the last three days and a significant rest period three days ago."*

In parallel to the issue of interpretability, the visual representation of data and information is essential for any computer system designed with user interaction in mind. "Visualising" consists in producing visual elements (graphs, curves, maps, images) to help users understand, explore and analyse to make sense of data, models and information, sometimes present in large quantities and often complex (*Kubicek et al.,* 2013). Smooth and efficient human-machine interfaces and visualisations are often essential to the success of digital systems intended for the general public. The field of agriculture is no exception to the rule.

There is a high demand for visualisation in this sector due to a combination of several factors: significant growth in the masses of data collected, the existence of users who are not computer scientists but are often technophiles, and the need for visibility on private and public data at different spatial and temporal scales. Visualisation is sometimes even seen as a strategic matter, because mastering these techniques can offer a competitive advantage or afford a certain power to some actors in the agrifood chain. Private players (equipment manufacturers) are heavily involved in the field, but there are also initiatives by universities and institutes, including INRAE and Inria, available under free (e.g. *AQUAPONY,*[35] *GeoVisage,*[36] *PARCHEMIN*)[37] or participatory licenses (*I-EKbase*)[38] (*Wachowiak et al.,* 2017).

For example...

At INRAE, the Ecology and Evolution of Zoonoses group of the **CBGP** UMR analyses the viral diversity of hantaviruses and the evolutionary processes that shape it. Among other things, they piloted the development of AQUAPONY, a web-based viewer that allows interactive navigation through a phylogenetic tree and facilitates the objective interpretation of evolutionary scenarios.

35. http://www.atgc-montpellier.fr/aquapony/
36. http://geovisage.nipissingu.ca/
37. http://www.parchemins.bzh/index.php/outil-de-visualisation-donnees-lagriculture-littorale-bretagne/
38. http://iekbase.com/hot-spots-monitoring

The tools currently deployed for the agricultural world are based on traditional visualisation paradigms: cartography (GIS, or Geographical Information Systems), sensor data visualisation interfaces, collections of linked visualisations (multi-faceted) and reactive tools (dynamic queries). Semantic interfaces and related visualisation strategies (linking views) are major topics of interest, as well as 3D visualisation, which provides a view of the topology of geographical areas (down to field profiles), and the use of image synthesis or even augmented reality.

For example...

At INRAE, the **SAS** UMR supports the agroecological transition of livestock systems and territories. In particular, it participated in the *PARCHEMINS* project on the visualisation of coastal agricultural data in Brittany, completed in March 2021. This project developed a map viewer, a web-based map consultation tool that allows the user to interact with geographical data. Designed for users who are not geomatics experts or computer scientists, it allows spatial information to be represented and analysed in an intuitive and easy-to-use way.

The interactivity and speed of response of visualisation tools are key in agriculture (and elsewhere!) as these visualisations must be adapted to lightweight devices (smartphones, tablets) or on-board terminals (connected tractors). The fluidity of data visualisation is closely linked with technical solutions, data exchange protocols and system architecture. Adaptive visualisation, which is currently a major research topic, makes it possible to adapt the visualisation to the context, such as the user's profession, the visualisation terminals or the nature of the data available.

The issue of visualisation and knowledge sharing is not widely addressed in practice and thus remains more in the field of research than application for the time being. In agriculture, however, human expertise traditionally plays a very important role, creating a particularly favourable context for the development of interactive techniques: it is indeed tempting to combine human expert capacities with learning, optimisation or modelling algorithms (*Boukhelifa et al.,* 2018). Depending on the strategy and the system, Human-Computer Interaction (HCI) can be either explicit (the user is regularly asked questions *via* an interface or visualisation system) or implicit (unbeknownst to the user or non-verbal, with the machine capturing information and using it as a learning base). Current research in visualization and HCI focuses primarily on questions concerning the interpretability, explicability, causality and transparency of interactions.

The HCI/visualisation tandem is also a factor in frameworks in which human expertise is required to manage data uncertainty and decision-making on multi-criteria issues: qualitative approaches are complementary to automatic/statistical approaches (e.g. choice of criteria) for managing ambiguities, knowledge gaps or extrapolations to different crop types. Examples include uses in agroecological zoning – based on clustering and segmentation techniques – or the Crop-GIS web application combining modelling and visualisation for maize crop management.[39] However, interactive systems can be difficult to evaluate because while the algorithm learns and adapts to the human, the reverse is also true: the user learns to use a system. Understanding these subtle mechanisms of co-adaptation and co-evolution requires the use of experimental science approaches (test plans, reliability of results, biases) and testing on cohorts of volunteers.

In conclusion, the topics of visualization and HCI applied to agriculture are relatively rarely addressed in both agronomic and visualization scientific literature. And yet, the issue is a key factor in the adoption of technology because farmers prefer tools that are less accurate but easy to use to high-performance ones that are difficult to use (*Pierpaoli et al.,* 2013).

Decision Support Systems (DSS)

In the 1980s, computer programs and electronics began to be used to improve efficiency in agriculture and reasoning in agricultural activities. This saw the emergence of the first digital DSS (Decision Support Systems). This revolutionary development has been fairly well received both by farmers (79% of farmers who use new technologies recognise their usefulness, source: *Rapport agriculture et innovation 2025*)[40] and in society where there is a demand for digital innovations for the protection of the environment (47% of those questioned, *OpinionWay survey,* 2016). Digital DSS are based on "simple" computer programming combined with a relatively small body of reference data, and can be installed on personal computers or used in a web interface that allows access to the application. They are most often developed by research or technical institutes. This generation of DSS includes software such as *INRAtion*[41] and *InraPorc*.[42] These programs, designed by INRA, are French benchmark tool in terms of assistance for defining feed rations for ruminants and pigs. Many software programs have also been developed in the plant sector to help farmers plan and manage crop fertilisation, pest control or irrigation. Today, with the upsurge in digital technology, a new generation of DSS

39. https://www.cropgis.com/
40. https://agriculture.gouv.fr/sites/minagri/files/rapport-agriculture-innovation2025.pdf
41. https://www.inration-ruminal.fr/
42. https://inraporc.inra.fr/inraporc/

has emerged that uses contemporary digital technology such as remote sensing, GPS, the Internet of Things, artificial intelligence, etc. These DSS are designed and produced by the AgriTech sector, which involves major agribusinesses and numerous start-ups (*Padhy and Satapathy,* 2020).

Definition

Agritech is a generic term for agricultural technology. It includes four main areas: 1/ biocontrol, 2/ agricultural big data , 3/ robotics and 4/ plant genetics and biotechnology. These four elements are often closely linked and many agricultural technologies are derived from them.

The integration of new technologies into DSS allows the range of services offered by these tools to be expanded as farmers seek to make the most appropriate farm management decisions (*Spanaki et al,* 2021). Precise knowledge of the state of agricultural plots or herds is essential for the farmer, who can now use data (images, biophysical measurements, etc.) from connected sensors to obtain more information than can be perceived by the naked eye. After various digital processes, the farmer can access this information *via* a dedicated application online or on a smartphone. In the livestock sector, these new digital tools are readily adopted by farmers if they promise technical and economic gains and can reduce the arduousness of work. First of all, there are DSS based on sensors worn by the animals (externally or internally), which provide real-time measurements of the physiological characteristics of the animal and its activity (temperature, abdominal pressure sensors, movement, etc.). In dairy farming, the farmer can use these tools to monitor the animal's reproductive cycle and reliably detect heat or parturition or health problems, even before any external signs can be detected by a professional. We are also seeing the emergence of DSS prototypes based on image recognition (from cameras installed on the farm) using artificial intelligence methods (deep learning). These allow animals' behaviour and health to be monitored and can even go so far as facial recognition. If an anomaly is detected in a group or animal, an alert can be sent to the farmer's smartphone. Despite the number of initiatives underway, certain issues, which are crucial for making a DSS used and usable by professionals, are still the subject of research carried out in collaboration with the latter. In particular, these concern precision, pertinence (a DSS that provides too many false alerts, for example, risks being rejected), the adequacy and form of the information made available to the farmer according to his expertise and needs, and the ergonomics of the tool, in connection with the notions seen in the visualisation and HCI section (*Li et al.,* 2020). The way in which user knowledge is used is also the topic of ethical questions raised in connection with open innovation more generally.

3.5 Automation, control and robotics

As highlighted above, digital farming is far from being limited to data acquisition and processing. The aim is to use this data in decision making and determine actions to be taken, both spatially and temporally, to optimise cultivation techniques capable of reconciling high levels of production, crop quality and environmental conservation. In this sense, precise and potentially frequent work will be required in order to meet such specifications, which is not always possible in terms of human resources and capacities. This is especially true since agricultural tasks are often tedious and sometimes dangerous. Exploiting the full potential of the principles of digital farming could therefore lead to task automation. Today, robotics technology is taking the developments already implemented in the context of automated tools or driver assistance systems for agricultural machinery even further. But, beyond the automation of certain tasks, advances in the field of robotics in the agricultural world must pave the way for a change in practices to accompany the ecological transition.

Farmstar is a DSS based on subcellular spatial images. It was developed by Airbus in collaboration with agricultural technical institutes. The complex processing chain combines the use of spatial images and other data sources such as climatic data, and uses computer simulation for agronomic models. The result can be accessed via APIs (Application Programming Interfaces) which are queried by the user application. The farmer can thus obtain useful information in the form of maps and "dashboard" indicators via an integrated web application that hides the complex computer architecture and data flows involved..

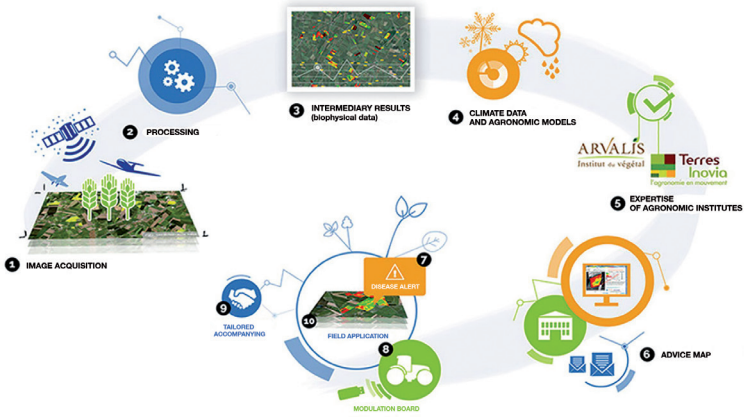


Figure 1: Farmstar, from high-resolution spatial imagery to advice maps.

For example...

The **VALSE** project-team (Inria, Ecole Centrale de Lille, Université de Lille) studies problems arising from the analysis of distributed, uncertain and interconnected dynamic systems. Its aim is to design estimation and control algorithms for different fields. In particular, in the field of oyster farming, these algorithms have enabled the design of a biosensor based on the measurement and interpretation of bivalve mollusc behaviour, for the remote detection of coastal water pollution and the consequences of climate change.

Structured environments: allies of robots

The rise of robotics has historically been rooted in industrial applications, especially automotive, for the automation of production lines (*Bahrin et al.,* 2016). From this, it is possible to design infrastructures that allow robots to be referenced and operate in perfectly known and unchanged environments, as well as to control the conditions of interaction (lighting conditions, handling known objects, creation of specific zones). This greatly helps the design of robust perception and control algorithms based on robot operation models that require strong assumptions (rolling without slipping, object or scene recognition, accurate localisation, etc.). As a result, robotics applications in agriculture have primarily focused on the indoor environment, particularly for livestock production (*Bergerman et al.,* 2016). In this sense, the biggest market for robotics in agriculture is currently in the livestock sector, with feeding and milking robots. These are able to operate using a number of reference points and benefit from special arrangements to maintain high repeatability. They can thus perform demanding tasks (such as milking or feeding animals) and free up the farmer's time. Such developments are increasingly common in agricultural practices, and today half of new French dairy farm facilities are equipped with milking robots (*Tse et al.,* 2018).

In cropping, such infrastructures are more difficult to put in place, with the structure of crop production being inherently changeable and posing detection and referencing issues. Nevertheless, the automation of certain tasks, particularly driving farm machinery, has greatly benefited from the advent of GPS, especially centimetre-precision models which offer absolute referencing. Many devices aimed at automating machine operation under the supervision of a "driver" have thus emerged, sharing a certain number of research challenges with advances in driverless vehicles.

However, the use of GPS sensors alone remains limited for the production of fully autonomous robots (i.e. without on-board human supervision) for several reasons. Firstly, the potential loss of satellite signals near buildings, in greenhouses or near tall vegetation, would require manual intervention Secondly, farming requires referencing and interaction with plants and not absolute references, even if planting is carried out using GPS referencing. Lastly, the absence of an on-board supervisor means that autonomous machines must be equipped with a means of perception to ensure their safety (avoiding obstacles, traversability management).

Study of a robotized electric tractor for agroecology. © INRAE.

Thus, several other strategies including vision (*Stefas et al.,* 2019) and laser technology (*Tourrette et al.,* 2017) are substituting or complementing absolute referencing to achieve autonomous navigation. This is already being used commercially in robots, mainly for mechanical weeding, mowing and surveillance. However, the task efficiency of these robots is currently limited and performance is closely correlated to detectability conditions.

Before envisaging more complex work (pruning, harvesting in the field) performed in a fully autonomous way, there are several scientific and technological obstacles that must be overcome in order to deal with the variability of the environments and the diversity and complexity of the tasks to be carried out while preventing any damage to the robot(s).

From adaptation to reconfiguration

Unlike mobile robotics in industrial environments or road traffic, mobile robots in natural environments require specific adaptive abilities to deal with the diversity of interaction conditions and their variability (*Bergerman et al,* 2016). This involves the online modification of perception and control parameters (such as modifying response times as a function of speed (*Hill et al.,* 2020) or adapting detection thresholds to light conditions. Several adaptation and anticipation or robust control mechanisms have been proposed to deal with the variation in these environments and maintain a high level of accuracy, while protecting the robot from damage (*Krid et al.,* 2017, *Yandun et al.,* 2017). This last functionality is defined in a relatively binary way in structured environments: avoid collisions with geometric obstacles, do not operate in out-of-bounds areas, etc. In natural environments, the notion of "obstacle" is less well defined and solutions are more complex. Firstly, encountering an obstacle is not necessarily a failure, as robots do not have to be stopped when passing over vegetation or if they have to push aside a branch. Secondly, some areas can be traversed under certain conditions (speed or load limitation) and the crossing also depends on the ground conditions (especially adhesion) and the properties of the robot (*Guastella,* 2018). Lastly, operating in some areas may lead to a loss of control or physical stability of the robot (*Wolf et al.,* 2019).

For example...

At INRAE, the TSCF UR designs reconfigurable and shared autonomy systems to enhance the performance and safety of machines operating in natural environments, particularly those found in agriculture. For example, the team designs adaptation mechanisms to deal with the diversity of interaction conditions and their variability.

Several approaches allow this complexity to be taken into account through the concept of traversability (the set of conditions allowing a given area in front of the robot to be crossed). Nevertheless, work on this concept illustrates the difficulty of defining a single perception and control approach to allow a robot to perform complex agricultural tasks. Many studies currently focus on the real-time selection or fusion of typical behaviour (see the INRAE *Adap2E* project[43]), which addresses the problem of scene interpretation and behaviour evaluation.

43. https://adap2e.inrae.fr/

In addition, many strategies in agricultural robotics are based on cooperation between less complex robots able to work together or in the same area. This reduces the risks in terms of the operation of each robot (limited kinetic energy in the case of impact) and their cost, but shifts the issue of complexity to the association and synchronisation of the group (*Blender et al.,* 2016).

Conclusion

In this chapter, we have browsed at the different areas of research addressing the use of digital technology in agriculture. They mainly concentrate on data at all levels of the data cycle, from capture to exploitation *via* collection, traceability, processing, storage, interpretation, restitution and use in automated or robotic systems. Different skills involving networking, modelling, learning, knowledge management, control and security are used to provide efficient, safe and secure solutions. The key aims are to assist farmers in difficult tasks, allow better management of our resources and promote exchanges and expert knowledge, all while respecting the environment as much as possible.

4

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

Authors – *Véronique Bellon-Maurel, Pascal Bonnet, Isabelle Piot-Lepetit, Ludovic Brossard, Pierre Labarthe, Pierre Maurel, Jean-Yves Courtonne.*

Acknowledgements (contributions, proofreading, editing) – *Frédérick Garcia, Nathalie Mitton, Alexandre Termier.*

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.

5

Risks

Authors – *Frédérick Garcia, Pierre Labarthe, Emmanuel Prados, Véronique Bellon-Maurel, Grégoire Chambaz.*

Acknowledgements (contributions, proofreading, editing) – *Ludovic Brossard, Nathalie Gandon, Aurélie Javelle, Nathalie Mitton, Alexandre Termier.*

The ongoing digital revolution has had a significant impact on the world we live in. Chapter 4 explored the opportunities opened up by this new technology, which could help to make agriculture more agroecological, more sustainable and more productive. More broadly, the disruptive potential of digital technology seems boundless, and the digital revolution could be seen as a revolution of empowerment, bringing about a considerable increase in the capacity of stakeholders to efficiently transform all areas of society – not just agriculture, but also health, transport, culture, the environment, etc. Observing, predicting, anticipating and controlling the natural and social processes at play on Earth could soon be possible through digital technology.

The growing development of digital technology in the agricultural sector has raised a number of questions with regard to delivering on promises made and the social acceptability of the accompanying transformations. This awareness of the risks inherent to the digital revolution is not specific to agriculture. Analysis conducted on issues linked to democracy, the economy, the environment, work, education, information, etc. have confirmed the extent of the changes that are taking place, stressing how important it is for society to tackle challenges linked to digital, incorporating the fact that technology is not neutral (*Stiegler,* 2015; *Boullier,* 2019).

Despite the wide range of opportunities it opens up, we feel that the development of digital technology in agriculture brings with it a number of risks: not living up to expectations in terms of agriculture and food systems being made more environmentally-friendly; exacerbating the negative impact of digital technology on society in terms of a loss of autonomy and widening inequality; sliding towards a loss of digital and food sovereignty; and aggravating vulnerability and weakening the governance of an overly complex food system, aggravating vulnerability, weakening the governance and reducing the yields of an overly complex food system.

Exploring these risks will give citizens, farmers and researchers the opportunity to reflect on their practices, their choices and their priorities, guiding them and helping digital technology to become more responsible in order to minimise these risks. This chapter will present an overview of these risks.

5.1 Compromising the ecological transition in agriculture

There are a number of factors which could impact the capacity of digital technology to contribute towards the ecological transition. Some see digital technology as an "obstacle" in itself, in that it is deployed in an attempt to treat symptoms as opposed to correcting the causes of problems and hazards facing us, arguing that its widespread deployment is an evasion tactic preventing any possibility of more systemic, radical change. The use of digital technology in agriculture is also seen as stretching thin the ties still linking man and nature. Lastly, although little is known about it and it is rarely taken into consideration, digital has its own environmental footprint, which could call into question any environmental benefits.

The agroecological transition and technological lock-in

Technological or socio-technical lock-in, a concept taken from theories of innovation (*David,* 1985; *Arthur,* 1994), refers to such situations where an innovation is blocked as a result of the economic and technological strategies implemented by different stakeholders – known as the sociotechnical system – coming together in such a way as to prevent any destabilisation or change, even if the innovation could be widely beneficial.

This concept is often raised in relation to the agroecological transition (*Meynard,* 2018). It aims to guide production systems towards practices which use fewer chemical inputs. This is done with reference to two specific features of agriculture in developed countries: i) crop protection based primarily on the use of pesticides and ii) the increasing specialisation of production alongside the increasing scarcity of holdings which combine crops with livestock breeding. The systemic, integrated way in which the food supply chain is structured around these aspects is an obstacle for the agroecological transition in that all economic, technological and regional stakeholders must act in concert with each other.

This raises the question: could the development of digital technology in agriculture also carry the risk of further technological lock-in, thereby limiting the chances of success for the agroecological transition, in all its diversity? Digital would appear to be an excellent driver of integration between the different stakeholders within the agricultural supply chain, at all levels. It is also, broadly speaking, compatible with the current agricultural model's sociotechnical system, particularly in terms of its associations with agricultural machinery (tractor-GPS-modulated

application software) or satellite technology, highlighting the objective of greater control over the consumption of inputs (*Labarthe,* 2010). In this way digital technology could reinforce the technological lock-in of the current situation, further restricting the possible emergence of alternative innovations promoting agricultural practices which are radically more environmentally-friendly and less production-driven, and which could eventually help the current system to evolve. Digitalisation can thus be characterised by a sort of path dependence[63], excluding alternative forms of agriculture (*Clap and Ruder,* 2020). The concern is not, therefore, linked to digital agriculture "not being environmentally-friendly", but rather to the digitalisation of agriculture reinforcing the dominant, production-driven model, when in fact the goal is to make agriculture more agroecological.

Taking humans further away from nature

The digital revolution and the new technology it has brought with it have transformed our perception of the world, through interfaces designed to expand and enrich our physical and cognitive capacities.

In agriculture this has resulted in "augmented farming" through the use of smart robots and sensors, forming a new interface between farmers and the living world of their farms, animals or plants. Research has been carried out in the social sciences on the consequences of these new interfaces, particularly in livestock breeding, exploring whether or not *"machines separate humans from matter"* through data or if robots are *"a liberating or restricting force for animals and humans"* (*Lagneaux and Servais,* 2014). Although little consideration has been given to the world of plants, we have started to see some research into the way in which digital technology is transforming our relationship with plants (*Javelle et al.,* 2021).

Over and above the risk of losing our material connection to nature through an increase in digital interfaces, a number of authors have also tackled the issue of the reification of the living world brought about through precision agriculture, and the ethical questions this raises (*Bos et al.,* 2018). This is particularly true in livestock farming, some seeing the growing engineering and artificialisation of agricultural production as evidence of possible transanimalism[64], geared towards developing "augmented" animals in order to not only improve their well-being but also to boost productivity. What impact will this reductionist approach – which reinforces the perception of the animal machine (*Meuret et al.,* 2013) – have

63. Having first emerged in political science in the nineties, path dependence is a term used to describe how influential decisions made in the past and decisions taken by political bodies are on present decision-making.

64. Droit Animal Ethique & Sciences (2017). Trans-animalism, augmented animals and cyborg animals: towards the status of "sub-machine"? 93, https://www.fondation-droit-animal.org/documents/revue93.pdf

on human-animal relations (*Larrère and Larrère,* 1997) or the efficiency of the production system as a whole? How do citizens view this type of agriculture? These are all issues which have been explored in the humanities in conjunction with agronomy.

Contributing to digital's growing environmental imprint

Digital technology has an environmental impact which has been given little or no consideration in agriculture. As is the case with other areas of society, the development of digital technology in agriculture will involve an increase in the use of equipment for data capture, transfer (deploying wireless sensor networks, or even employing the use of 5G), storage and processing (see platforms offered by tractor manufacturers), requiring increasingly powerful and energy-intensive electronic components and systems, with all of the environmental consequences [65]that this entails (resource depletion, climate change, etc. (*Marquet et al.,* 2019))..

Find out more

The agricultural supply chain is currently responsible for 13% of overall energy consumption in France (particularly for maintaining the cold chain); across all sectors digital is responsible for 12% of electricity consumption and 3% of total energy consumption, the biggest contribution coming from video streaming. Although there does not seem to be anything particularly alarming about current statistics for agriculture, attention will need to be paid to the rising contribution made by digital agriculture.

The increase in the number of various different types of connected sensors will result in greater reliance on resources such as the precious metals (silver, gold, palladium) and rare-earth elements (neodymium, praseodymium, gallium, germanium, etc.) found within these electronic components, the extraction and separation of which uses up vast quantities of energy and water. The geographical distribution of production sites is also highly uneven, the majority currently found in China (*Pitron,* 2018). This will also pose challenges when it comes to end-of-life management for materials, with the not properly controlled risk of the spreading of technological waste, similar to what we have seen with the reprocessing of mobile phones in France: only 15% of handsets are collected out of more than 25 million phones sold every year, despite the existence of a specialist stream for the recycling of electronic waste (*Blandin,* 2016).

65. https://www.lemonde.fr/blog/binaire/2019/01/29/impacts-environnementaux-du-numerique-de-quoi-parle-t-on/

5.2 Widening inequality and power imbalance

One of the risks associated with the digitalisation of agriculture, first flagged up in the nineties (*Wolf and Buttel,* 1996), relates to the increasing industrialisation of agriculture, the social and environmental consequences of which are a source of controversy. It is argued that there will be a sort of co-evolution between the roll-out of digital technology and production becoming concentrated in ever greater production units, driven by a desire for greater efficiency and productivity at the expense of other types of agriculture or groups of agricultural workers. These risks have been discussed using strategies from different disciplines in the humanities, primarily sociology, political science and institutional economics (*Klerkx et al.,* 2019).

Risks of exclusion

There are a number of risks of exclusion associated with digital agriculture, linked to various different debates on the subject of the diversity and coexistence of agricultural production models.

The first risk relates to agricultural holdings with a small economic impact. The issue of small farms being excluded is not specific to digital technology: it has been shown how the modernisation of agriculture in France has excluded small agricultural holdings, chiefly through the economies of scale which are typical of technological development (*Deléage,* 2013). Digitalisation is part of this technological trajectory for agriculture, which is centred around increasing the size of agricultural holdings. It could even accelerate it given that, by its very nature, some digital technology (such as that based on satellite imaging) requires holdings of a minimum size in order for it to be profitable. This risk of exclusion can be compared to the incompatibility outlined in 5.1 between digital technology and certain ways of making agriculture more ecological, which require a more extensive overhaul of production systems.

The second risk is linked to aggravating the precarious nature of agricultural work, at a time when there is a growth in the percentage of salaried workers in agriculture and a desire to reduce labour costs in the interests of increased productivity. The development of robotics – which could either replace human labour or limit the human workforce to certain, more qualified positions – could further exacerbate precarity among certain groups, particularly the poor in society or immigrant workers.

The third risk is linked to the difficulty of accessing digital technology and/or the skills needed to use it, which could also drive exclusion in the agricultural sector. This debate is partly linked to the digital divide and the risk of excluding certain rural areas lacking in digital equipment at an infrastructure level.

A loss of autonomy for farmers

Research has been carried out in the field of rural sociology to assess the potential implications of digitalisation on the decision-making autonomy of farmers and the meaning they place in their work. This could have significant repercussions for the cultural fabric of rural areas and farmers in that it will alter what it means to be a farmer (*Burton and Riley,* 2018). Digitalisation may bring about a shift in agriculture from "practical", experience-based management towards a data-driven approach. It could "discipline" working routines for farmers, conditioning them through a new form of "algorithmic rationality" (*Miles,* 2019). As a result, digitalisation which is not controlled by farmers is a topic for debate.[66] Questions have also been raised regarding the effect of digitalisation on the autonomy of farmers, including a fear that farmers could become "data workers" (*Rotz et al.,* 2019).

Upstream and downstream control

Another issue relates to the imbalance between agriculture and its upstream and downstream sectors, which digitalisation could exacerbate. Agriculture has often been described as a sector that is dominated by upstream and downstream, and particularly by its upstream (mechanisation, the chemical industry, seeds/grains, etc.) when it comes to innovation dynamics. A number of authors have questioned the role played by digitalisation in transforming (or exacerbating) the balance of power between agriculture and other sectors.

Upstream, digital technology could increase farmers' dependency on certain inputs (pesticides, mineral fertiliser, etc.) while optimising and limiting their use. This paradox can chiefly be explained by the fact that digital technology takes the form of specialist equipment which embeds models, standardises decision-making and leads to asymmetry of knowledge. This is changing the way in which knowledge is controlled (*Bronson and Knezevic,* 2016).

66. https://www.amisdelaterre.org/communique-presse/nouveau-rapport-agriculture-et-numerique-vers-une-fuite-en-avant/

Downstream, new tools for sharing and controlling information (particularly blockchain and big data technology) have the capacity to change or strengthen the positions of different stakeholders in innovation ecosystems and value chains. Questions relate to the consequences on value sharing, how sectors are governed, the risk of forms of subsidiarisation within agriculture and control by agribusiness companies situated downstream from agriculture.

One new issue relates to the role which new stakeholders – firms in the digital technology sector, from startups to multinationals – could play; digital giants have, for example, made significant investments in agriculture, sometimes in conjunction with equipment manufacturers. Alongside this investment, a number of questions have been raised regarding data governance in agriculture, and the capacity of stakeholders in the agricultural sector to control knowledge integrated into digital technology and to grasp the value which it produces (*Carbonell,* 2016).

Digital technology is therefore associated with cross-sectoral dynamics, calling for multidisciplinary research to be carried out on the resulting institutional changes and the risk of potential lock-in (*Carolan,* 2020; *Labarthe,* 2010).

Accessing information and training - what role can advice play?

A fundamental feature of digital technology is that it is not neutral for innovation systems and agricultural knowledge: it has the capacity to completely overhaul the way in which knowledge and information within the sector is constructed and disseminated (*Busse et al.,* 2015).

Research carried out recently has revealed both the potential of digital technology and the threat it poses to certain stakeholders or roles within innovation systems. This is particularly true for farming advice – its participants, methods, content and even legitimacy are all called into question by digital technology (*Fielke et al.,* 2020).

However, there are a number of issues linked to the role advisors or other-intermediaries in innovation systems can play with the advent of digital technology: how can more and more information be integrated without generating excess stress or mental strain for farmers? Who will be in a position to evaluate the efficiency, durability and suitability of digital tools? Who will have the capacity to monitor the content of knowledge (agronomic models, validity testing, etc.) contained within these tools and applications?

The question of digital's impact on the dissemination of information and knowledge within the agricultural sector also takes us back to the issue of inequality, as discussed in the previous subsection. This inequality is linked to issues surrounding accessibility (financial, cognitive, connectivity) to digital technology. The issue of unequal access to advice and information is not a new one (*Mundler et al.,* 2006); the goal will be to determine whether digital helps to reduce or exacerbates this inequality. This refers us back to issues such as cost and the digital infrastructure of rural regions, but goes further than that; it will be necessary to train rural and agricultural communities, in all of their social diversity, giving them the opportunity to acquire the skills needed to use this technology in an effective and appropriate manner.

5.3 Loss of sovereignty

The final report from the 2019 French Senate inquiry "Digital Sovereignty" (*Longuet,* 2019) proved that the issue of digital sovereignty has never been more topical. The report was keen to stress that this is a threefold problem for France, relating to *"ethics, security and economic liberty"*, at a time when our societies are finding their values are being questioned and humans are *"increasingly collections of data to be exploited"*. Although agriculture is an area in which the question of national sovereignty – at both an individual and a collective level – may be thought of as a given (production is by nature rooted in regions, there are strong cultural ties to the land, public authorities have a track record of supporting and guiding agricultural production, the importance of public research into agronomy is recognised in France, the CAP is a cornerstone of the European project), the development of digital technology is bringing forth new challenges linked to digital sovereignty (*Klerkx et al.,* 2019).

A loss of autonomy over food supplies

The increasing digitalisation of the supply chain – from producers to processors to distributors to consumers –, the primary aim of which is to bring production into line with needs, to minimise logistics and processing costs and maximise customer satisfaction, could potentially lead towards ever greater integration of agriculture. Sovereignty becomes an issue when monopolies develop, as can be seen with the current offensive being led by digital giant Amazon in the food distribution industry[67] Also worthy of note is the rapid development and use of connected tools on smartphones for evaluating food and other consumer products (in terms of environmental impact, nutritional value, etc.), which could have a significant

67. https://siecledigital.fr/2020/08/31/amazon-ouverture-de-son-premier-supermarche-connecte-amazon-fresh/

long-term impact on modes of consumption[68] There is no guarantee of democratic control over these new tools, resulting in the risk of a monopoly developing. Lastly, the economic model for the digital transition is partly based on start-ups, some of which have designs on being bought over by major groups. This inevitably raises questions linked to national sovereignty with regard to the digital technology and services developed for agriculture and the data it produces (*Schneider,* 2020).

Seizure of agricultural data

Digital sovereignty entails control over data. Whether it is down to major manufacturers of agricultural equipment or digital giants, there is a risk of agricultural data being seized, either by access to data simply being restricted or by data being opened in formats which are not practical to use. Agricultural machinery could act as a Trojan horse for the collection of data in agriculture. This includes milking robots in livestock breeding, but also tractors and harvesting machines for field crops. These agricultural machines feature an increasing number of sensors, gathering data on tasks performed which is then shared with manufacturers. Purchase agreements govern their use in a way which benefits manufacturers (it is often stipulated that farmers must share all agricultural data). This helps to maintain a lack of transparency along the data chain (what does the data contain, where is it going, and for what purpose?), resulting in a near lock-in situation (it is sometimes very difficult for farmers to gain access to their data, and even harder to put it to any purpose) (*Carbonnel,* 2016). There is an awareness within the profession of this risk, farmers in France having come together *via* the Data Agri[69] charter put forward by two trades unions, the FNSEA and the JA. This is aimed at improving the handling, transparency and security of agricultural data in contracts. France would appear to be somewhat ahead of the game at a European level when it comes to reflecting on the use of agricultural data, building independently on the GDPR regulation on personal data.

The sharing of agricultural data is a priority both for the agricultural profession and for research in agronomy, the goal being to support the development of agronomic knowledge and digital technology and services in agriculture. This is a key issue in relation to digital sovereignty. Agdatahub[70], a data exchange platform for the agricultural sector developed by a number of agricultural organisations (chambers of agriculture, technical institutes, etc.) and businesses, is a good illustration of how a trusted system can be built around data (French companies *DAWEX* and *3DS OUTSCALE* were selected for the *Agdatahub* platform).

68. https://www.capital.fr/conso/peut-on-faire-confiance-a-yuka-pour-ses-courses-1319721
69. https://www.data-agri.fr/
70. https://agdatahub.eu/

A loss of control over production equipment

Sovereignty is also an issue when it comes to control over production equipment in agriculture. Digitalisation is resulting in this equipment becoming increasingly complex (*Bournigal,* 2014) and maintenance becoming more and more difficult, for both farmers and distributors, who are experiencing a loss of technical autonomy. The same is true when it comes to training: teachers at agricultural high schools have encountered difficulties training future professional users of agricultural equipment in what is a high-tech and constantly changing field (*Isaac and Pouyat,* 2015).

Another issue linked to sovereignty is the lack of French companies among the world leaders in agricultural machinery (*AGCO, John Deere, New Holland, Lely, De Laval*), although France does boast a number of pioneering companies when it comes to mobile agricultural robots (e.g. *Naïo Technologies*).

A challenge for cybersecurity

In the field of cybersecurity, the first challenge concerns the risk of attacks *via* connected objects and sensors (*Dhar*, 2021). This either involves the connected object itself becoming a source of a denial-of-service type attack, or it is hacked for malicious purposes. The latter example is the most troubling, particularly in the case of highly-integrated agricultural systems where farmers have granted significant autonomy to automatic control systems (automated greenhouses, milking robots, etc.). The fact that these devices are often manufactured outside of Europe and that we have no say over design (to ensure security by design), means we must be even more vigilant as to the risk of backdoors.

A second challenge relates more broadly to protection against the recovery and hacking (theft, modification, destruction) of agricultural data. The choices made in designing the platforms used to share this data clearly have a significant impact on the possible level of protection. Although the most notable examples of cyberattacks have targeted institutions of key strategic importance to society (hospitals, airports, banks, etc.), the crucial importance of our food production and consumption systems could see them becoming potential targets in the future (*Gupta et al.,* 2020).

5.4 Accentuating vulnerabilities and negative yields

The vulnerabilities of the agrifood system

As described in 2.3, modern agriculture interacts with a range of sectors and stakeholders of various types and sizes. This results in very "long" supply chains and decision-making systems. Agricultural activity has also expanded into increasingly specialist areas (*Bowler,* 1986). This system is centred around a large number of asymmetrical relationships of dependency between these stakeholders. It also centres around the intensive use of technology, which users are gradually becoming dependent on. The digitalization of this system could increase dependencies[71] between several of its elements and create new ones. These developments increase the risk that the partial or interrupted functioning of one element could paralyze the entire system. These changes are increasing the risk of an error affecting one element paralysing the entire system. These issues (blockages, interdependency) were highlighted during the Covid-19 crisis, with the emergence of a number of areas of tension in different parts of the agrifood system[72]. By disrupting supply chains, the Covid-19 crisis also resulted in a shortage of goods – including copper and microchips – in a number of sectors, highlighting the risks linked to dependency on such goods (*Bouissou and Albert,* 2021). This warning is all the more striking given that a number of crises expected over the next two decades (regional and systemic),[73] most notably peak oil (*Delannoy et al.,* 2021), are likely to have a far greater impact on society and the agrifood system in particular (*Servigne,* 2014). At a time when increasing the resilience of the agrifood system has become critical, its digitalisation runs the risk of making it more vulnerable.

Increasing complexity, diminishing returns and associated risks

As discussed earlier, the agrifood system is centred around a number of increasingly specialist regions, sectors and stakeholders, of various types and sizes. It is also centred around a number of regulatory mechanisms and various relationships of dependency. Agriculture and its upstream and downstream sectors can now be said to form a complex sociotechnical system in the sense understood by Tainter (*Allen et al.,* 1999).

71. See section 5.1 ("Technological lock-in and the agroecological transition") and section 5.2.
72. This includes risks linked to logistics and halting migratory flows, in addition to the instability generated by the introduction of non-collaborative, "every man for himself" national policies.
73. The probability and intensity of which are set to increase in the decades to come. See Chapter 2.

Tainter demonstrated that human societies have a tendency to become more complex as they solve the problems facing them – this is because the solutions deployed require the addition of new elements to the system and the introduction of new regulations (*Tainter,* 1990; *Chambaz,* 2019). Ultimately, this complexity is "paid for" through energy costs: the more complex a society becomes, the more energy is required for its basic functions (*Tainter,* 2016). This problem is exacerbated by the fact that this increasing complexity follows the law of diminishing returns: above a certain threshold, the benefits of a society increasing in complexity grow more slowly than the costs, until a critical situation is reached at which point costs may be higher than the benefits[74] (known as negative returns), as was the case prior to the collapse of a number of civilisations (*Tainter,* 2009). The challenge of complexity is keeping overall energy costs lower than the profits it brings in; otherwise there is a risk that the evolutionary trajectory of the system will get out of control and that any attempt to correct the system will only result in rendering it more volatile, vulnerable and uncontrollable.

The food and agricultural system is already a particularly complex sociotechnical system, the overall costs of which include indirect costs (sometimes very far removed) linked to negative externalities such as environmental, health and sociopolitical issues, which are either invisible or ignored by the vast majority of stakeholders (see 2.1). Our inability to evaluate these consolidated overall costs (energy, materials, pollution) and to fully grasp the aforementioned dynamic makes us liable to take major risks each time the system develops further complexity.

For this reason, it will be necessary to explore the impact of the development of digital technology in relation to this risk, particularly in agriculture. Indeed, as was discussed previously, the increasing digitalisation of the agrifood supply chain risks making this system more complex and strengthening or expanding ties and dependency. Uncontrolled use of AI and big data[75] could trap us further in a spiral of increasing complexity.

74. The phenomenon of diminishing returns followed by negative returns has been widely studied and documented, including in agriculture (*Brue,* 1993), in security (*Elhefnawy,* 2004), hydrocarbon extraction (*Tainter and Patzke,* 2012) and, more generally, in global macroeconomics (*Elhefnawy,* 2008).

75. With this technology the quantity and the complexity of the services and materials required will significantly increase (data generation, circulation, storage and processing – sensors, platforms, networks, etc.).

Conclusion

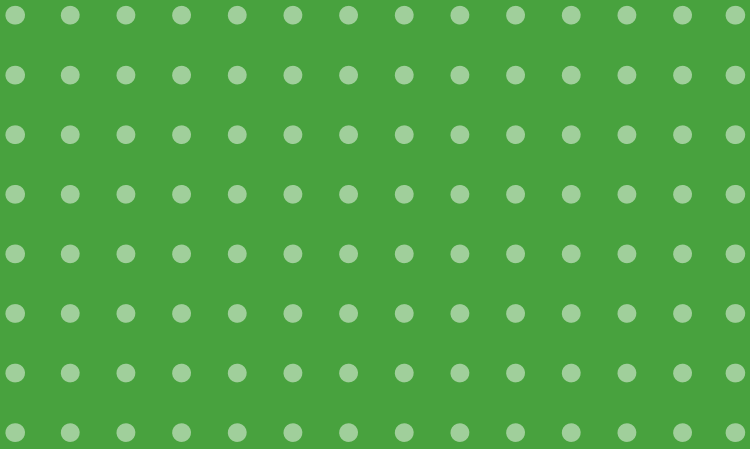
This chapter has covered a number of risks which the development of digital technology in agriculture has brought with it. These risks vary in nature and relate to economic, political, societal, psychological and environmental dimensions, among others. These risks could potentially be inherent to the deployment of this technology, and could be unavoidable or event uncontrollable. How this technology is deployed and used will obviously depend on upstream research, but also – and most importantly – on how stakeholders (citizens, farmers, stakeholders in agribusiness and the food industry, politicians) engage with it, as well as the general functioning of society (economic models, political regimes, standards frameworks, ideologies, etc.). It has long been understood how difficult it is for societies to control the development of technology (*Ellul,* 1977). It will be essential to take all of these factors into consideration when guiding future research in the field, as we have sought to do by identifying the challenges outlined in chapter 6 for making digital responsible, relevant and shared.

Challenges for the future

Providing digital tools to help address the challenges and gaps facing agriculture

Authors – *Ludovic Brossard, Véronique Bellon-Maurel, Pierre Bisquert, Tassadit Bouadi, Frédérick Garcia, Roland Lenain, Pierre Labarthe, Evelyne Lutton, Pierre Maurel, Nathalie Mitton, Alexandre Termier.*

Acknowledgements (contributions, proofreading, editing):) – *Lluis Miquel Pla Aragones, Isabelle Piot-Lepetit, Emmanuel Prados, Xavier Reboud.*



This chapter highlights the needs and challenges linked to the development of responsible digital agriculture in the interests of promoting agroecology, agricultural diversity (including family agriculture) and sustainable food systems. The aim is to look beyond the state-of-the-art (Chapter 3) and to respond to the opportunities presented by digital technology for the agroecological transition and for balancing out value chains (Chapter 4), while avoiding the pitfalls that have been identified (Chapter 5). The focus will be on the challenges facing technological research, while acknowledging the associated economic and organisational challenges, particularly relevant to agriculture.

Based on our needs analysis for promoting implementation of agroecology and balancing out value chains, the chapter is divided into four sections:

- improving collective management, including at the regional level;
- improving farm management;
- balancing out the value chain, both upstream and downstream;
- creating and sharing data and knowledge.

6.1 Providing digital tools for collective management at a regional level

Three key areas have been identified for overcoming the obstacles linked to the use of digital technology for land management (chapter 4.3):

- measurement and monitoring on a large scale;
- data visualisation;
- digital devices for participation, mediation and governance.

Monitoring and measurement at a regional level

The ambition to make agriculture less artificial, getting the most out of local assets and reusing natural resources, will be determined by the capacity to take advantage of material flows, the potential of biological regulation and functions beyond the farm (ecosystem services, land ecology, etc.). Many of the various different interactions can only be understood through a systemic point of view. This extends the scope of our consideration, both in space and in time: some characteristics can only be appreciated at a regional level, such as the extent to which a piece of land can be crossed (which will depend on the intensity of green

and blue belts[76] on it); while others must be considered over time, such as the capacity for resilience and speed of recovery when faced with climatic hazards. Therefore, if we want to employ the principles of agroecology, we must quantify parameters which are difficult to detect using traditional methods. This calls on the need for measurement and monitoring, evaluation (modelling) and the management of data on a large scale.

In terms of measurement and monitoring, the aim will be to identify data which is relevant, useful and currently missing for collective agricultural management at a regional level and to develop the tools for obtaining it, with the following challenges:

- Measuring new, difficult-to-grasp parameters (such as biodiversity, soil/water quality, etc.) as non-intrusively and as frugally as possible.
- Adjusting sampling frequency (temporal and spatial), a crucial component of information theory. Systems either collect data regularly – at different levels of granularity in time and space (sensor networks) – or sporadically (through crowdsourcing, mobile applications, mobile collection vehicles, robots, drones, etc.). Networks must adapt to these types of data, which feature different traffic patterns, in order to be able to convey it within the time limit with minimum data loss. This is applicable at all levels and is dealt with in greater detail in section 6.2.
- Managing heterogeneous data. This results from diversity in terms of the objects observed, sensing and collection techniques (including crowdsourcing), stakeholders, parameters measured, formats (value, images, localisation, etc.), metrological properties (precision, frequency, etc.). In order to deal with this heterogeneity, appropriate filtering and fusion methods will need to be developed. It will sometimes be possible to perform fusion at different levels and more or less iteratively, factoring in the uncertainty linked to each piece of data, the variability of this uncertainty and any consequences it may have on the rest of the information chain. These questions are applicable to all types of data – physical, biological, economic, social, etc. In order to produce coherent reports (e.g. on material flows) and the corresponding uncertainties, mathematical and computing tools for data reconciliation will be employed (these tend to be based on constrained optimisation) (*Courtonne et al.,* 2015).

76. The term "green belt" is used to refer to natural and semi-natural land environments, while "blue belt" refers to wetlands and aquatic environments (rivers, tributaries, ponds, peatlands, etc.). The term "green and blue belt" refers to a set of ecological networks allowing populations of species to move around. These are comprised of wildlife corridors which connect reserves where biodiversity is richest and best represented. These corridors can be linear (hedges, along footpaths, grass strips...) or various different types of landscape structures (https://dicoagroecologie.fr/encyclopedie/trame-verte-et-bleue/).

- Data governance, an issue which is exacerbated in multi-source data systems. This is a general question, which will be explored in 6.4.

In the Global South these needs are becoming ever more pronounced: as outlined in section 4.5, information capital is sorely lacking in these countries at a regional level. This capital is essential for national administrations (for agriculture) and local authorities, producer organisations, research bodies, etc. when it comes to open innovation, anticipating risks (climate risks, health risks) and improving the organisation of regions and sectors. In this context our research will need to take into consideration additional difficulties resulting from the digital divide, illiteracy, multiple dialects, etc. But these difficulties also provide us with avenues to explore with a view towards rethinking our systems and methods and adapting them to this context.

Visualisation

Our visualisation methods will need to be revolutionised for data management at a large regional level. Given its particularities, the agricultural sector has raised research questions with no current equivalents in the field of visualisation, such as:

- visualising multi-scale, heterogeneous data, sometimes in large quantities and sometimes rare: spatial data, symbolic data, temporal data, variable data, incomplete data, uncertain data, erroneous data, semi-quantitative data and even qualitative data depending on variations in structure such as mapping (GIS), images (from satellites, drones), time series, graphs and networks;
- visualising extreme scales, connecting them in a fluid and clear manner – short-range and long-range (time, geographical, etc.) –, and developing suitable and appropriate tools for aggregation and statistics;
- revealing new information semi-automatically by comparing maps or time series, highlighting symmetries, regularities, trends, correlations, etc.;
- meeting contradictory needs such as, for example, the visualisation of massive data, but with mobile applications (mobile phones, tablets, etc.), or guiding users while respecting their autonomy;
- finding innovative ways of representing complex objects, dependencies or models, capable of being used by individuals from a diverse range of backgrounds..

These questions open up new prospects for certain basic subjects, including the visualisation of uncertainties (*Boukhelifa and Duke,* 2009; *Potter et al.,* 2012) and progressive visualisation (*Fekete et al.,* 2019), at the interface between visualisation and AI. It is worth noting that, with regard to visualisation, there has

not been much discussion on issues surrounding privacy and usage rights for data when it comes to building trust (*Charvat et al.,* 2018). The questions listed above could eventually lead to research being carried out on visualisation and HCI specific to the agricultural sector.

Digital devices for participation, mediation and governance

The multi-actor approach is essential at a regional level and requires support tools: the knowledge production mode is changing, with transdisciplinary research requiring significant contributions from external stakeholders, something which may be easier in the digital era (*Bergez et al.,* 2019). In sectors operating at a regional level, it is increasingly common for individual and collective interests to come into conflict with each other (*Ryschawy et al.,* 2019). New digital devices from regional engineering are anticipated, to facilitate dialogue within the world of agriculture and with other regional stakeholders (figure 2)..

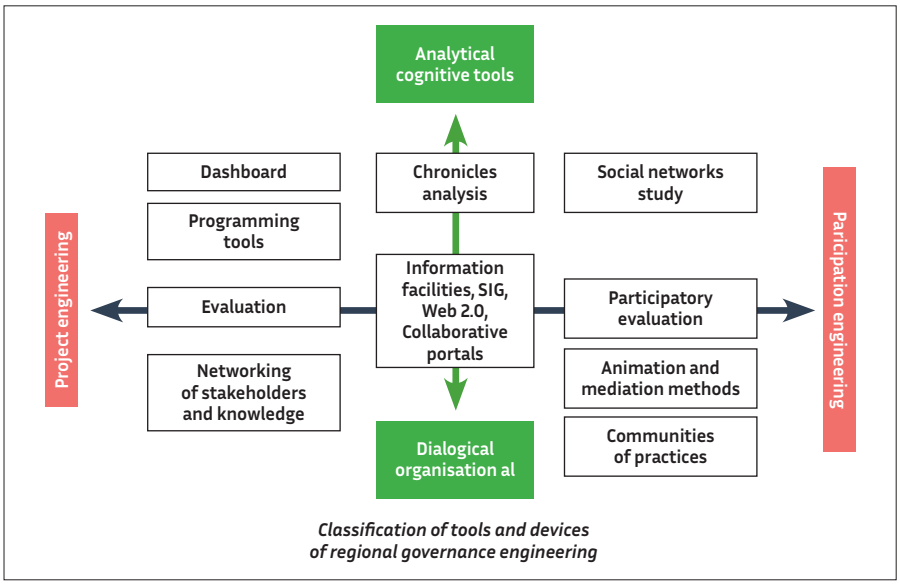


Figure 2: Tools and devices for regional governance engineering (Rey-Valette et al, 2011)..

These digital tools and devices could fulfil a range of functions: analytical, creative, cognitive, interpersonal, decision-based, operational, etc. (*Rey-Valette et al.,* 2011). They could also help to develop collective action by facilitating participation and open innovation, collective decision-making and mediation.

PARTICIPATION AND OPEN INNOVATION

Digital can provide the means to implement open innovation and participation. Confronted with complex problems, analytical approaches (in the lab) and participatory approaches (with stakeholders from a wide range of backgrounds) must be devised jointly – digital technology having the capacity to bridge the gap between the two (facilitating negotiation through modelling and visualisation).

To encourage farmers to engage in the agroecological transition, a gradual approach is the preferred option; the capacity to bring about change collectively will be necessary. It is anticipated that there will be new digital tools available for participatory strategies: support models, digital gamification, digital tools for analysing participatory sessions (video and audio processing for identifying and labelling participants and points of view, etc.).

Open innovation also generates additional research needs, involving management sciences, social sciences and law: on types of collaborations and sources of information in open innovation assisted by digital technology, on economic models, on managing tacit knowledge, etc. (*Enkel et al.,* 2020). Evaluating individual creative contributions in open innovation processes where intellectual protection will come into play, also known as "the paradox of openness" (*Arora et al.,* 2016), raises questions from the perspective of law and economics. Finally, there is the issue of the way in which learning networks are organised so as to facilitate innovation in digital agriculture (*Klerkx et al.,* 2019).

COLLECTIVE DECISION-MAKING

This type of decision-making is based on three different processes: deliberation, negotiation and voting. When it comes to deliberation (*Besnard and Hunter,* 2008), by allowing arguments to be studied in a logical and automatic way, digital technology could help to ensure deliberations are rational, while correcting any erroneous conclusions. With regard to negotiation (*Kilgour and Eden,* 2010), it is argued that a more standardised approach aimed at reaching a fair compromise would lead to engagement and satisfaction on the part of stakeholders and, thus, to sustainable decisions. Lastly, on the subject of voting itself, digital technology could be used to characterise these principles in order to arrive at relevant, desirable decisions, by taking different expressed preferences into account, for example (*Brandt et al.,* 2016).

Tools must be easy to use, complementing other modes of collective decision-making and deliberation, and be capable of being seamlessly integrated into individuals' daily routines (particularly when strategic decisions are being taken) in order to collect their arguments and preferences, for instance. As a consequence, the visualisation of data and decisions is vitally important.

MEDIATION

Digital is reshaping boundary objects (*Trompette and Vinck,* 2009) – through which social groups of diverse interests, practices and codes are able to enter into dialogue and reach a mutual understanding – and intermediary objects (*Vinck,* 1999), which retain a trace of the different stages involved in the collective design of a project or system, helping to boost acceptance and reuse. In Africa and the Global South, the use of commons such as land (agropastoralism, forestry) or water (irrigation) remains widespread. In this context, digital technology could also be employed to reshape management methods. Ongoing experiments with collective learning, living labs and joint, participatory management in places such as West and North Africa could be analysed and replicated.

6.2 Helping farmers to manage their technical journey

Three levers could be applied in tackling the obstacles identified in 4.2 with a view towards the scaling up of agroecology:

- systems for monitoring animals, plants and their environment;
- decision-support tools;
- robotics.

Acquisition and diagnostic systems

The challenge here lies having access in farm to accurate, reliable data at a low cost and with a low environmental impact, providing farmers with rapid, easy-to-understand information about the status of their systems (animals, plants, harvests, etc.), enabling the early detection of malfunctions and assisting them with the decision-making process. Mass, comprehensive capture of data could also help to promote large-scale phenotyping on farms, the goal being to develop new knowledge in the field of agroecology. For livestock breeding, we can add constraints linked to measurement and transmission, ethical questions and a recognised need for unconventional forms of livestock breeding. In the context

of agroecology, one key issue is detecting malfunctions, with the compromise of "coverage" (the area covered by the detection system) versus specificity. Specific measurements (e.g. detecting a virus or bacteria) are complex due to the need to establish contact, the cost, energy supply and the issue of false alarms in livestock breeding (*Dominiak and Kristensen,* 2017). Research must be inclusive, geared towards "moderate levels of instrumentation" and devices accessible to all farmers (*Bergez et al.,* 2019; *Dumont et al.,* 2018).

Research on acquisition systems, sensors and IoT, data management systems and associated digital models linked to farmers' core business and consistent with their strategies could focus on:

- **creating new sensors while respecting constraints typical of agriculture (frugality, cost, energy use, etc.).** It will be necessary to seek compromises between the autonomy of the sensor, its environmental impact, its spatial and temporal resolution weighed against specificity, measurement quality, durability, suitability with regard to the object under study and to the measured environment simplicity of use and maintenance, the last two factors being essential for solution acceptance. With the same goal of simplifying human-computer interfaces, research could be devoted to the development of audio devices enabling farmers to input information (e.g. electronic crop registers): voice recognition, ontology alignment, etc. Finally, in order to improve understanding of these agroecological systems, it is becoming increasingly clear that we must take into account not only the physical parameters of an environment, but also its biological parameters (animal/soil microbiota), which would generate needs in terms of omics methods.
- **Optimising the mode of data transfer so that data is transferred automatically to processing centres, practically eliminating co** (*Wolfert et al.*, 2017), a major factor for large-scale phenotyping on farms; this raises research questions linked to power supplies for sensors, sensor networks (e.g. swarm intelligence), etc.
- The desire to limit the number of sensors (in line with frugality) and to make it easier to measure certain parameters in a non-invasive way also calls for research into smart sensors, i.e. combinations of data from "simple" sensors for estimating these complex parameters through appropriate data processing (e.g. machine learning). The impact of these developments on the quality and uncertainty of information has still to be assessed.

Once collected, information can be used for diagnostic purposes, for characterising the state of agricultural systems and detecting any malfunctions that might require a response. Research could explore the building of diagnostic models. Although this issue is not specific to agriculture and affects other sectors as well, research must incorporate knowledge of the domain (agriculture) in order to address the following priorities:

- selecting which indicators to integrate, factoring in the natural variability of indicators, the propagation of uncertainty from these indicators, sensitivity and specificity adapted to use, adapting to local conditions (farm type and location, risk acceptance, agricultural practices, etc.);
- fusion of big data with point data from varied sources, specific processing (SVM, deep learning), data sharing (individual or collective);
- the hybridisation of data-driven approaches developed in artificial intelligence, based on big data, with modelling approaches which are more concept-driven but less suited to real-time data (*Ellis et al.,* 2020). This will require research into the explainability of data-driven approaches, in addition to research on knowledge-based systems (ontologies).

In a general sense, it is to be hoped that these developments linked to acquisition, communication and processing tools can be made in an integrated and scalable way in order for the system as a whole to be capable of adapting dynamically to each crop or livestock profile, size of farm or agricultural strategy, which all throw up a real scientific and methodological challenge.

The challenges posed by robotisation and the digital transformation of agricultural labour

Digital tools are transforming agricultural labour. How can these be directed in a positive way so that the labour of farmers and agricultural employees is made less arduous and is better respected? Robotics could provide a way of shifting human labour to tasks with higher added value, but there are still a range of scientific and technological obstacles to overcome in the following areas:

SCENE PERCEPTION AND INTERPRETATION IN DYNAMIC ENVIRONMENTS

Improvements will need to be made in scene perception and interpretation in order to boost detection capacity (fruit, leaves, diseases, etc.). Deep learning and, in particular, machine learning will open up avenues, especially given that robots will be equipped with sensors and will therefore generate data. One alternative is to utilise human expertise in perception, which raises questions in relation to human-robot cooperation. Finally, it must be possible to explain and interpret

decisions taken by robots, and robots must be able to refer to experts for difficult detection or decision. This will involve determining confidence criteria for decisions and clarifying decision-making rules taken from learning, an open theme.

ADVANCED APPROACHES TO DECISION-MAKING

Robots are currently limited to one single operating mode. For complex tasks, shifts between command modes are sequential and planned in advance. It is anticipated that significant breakthroughs will be made in the realm of situation and scene recognition (the robot's dynamic, its operating environment, agroenvironmental constraints, etc.), borrowing from artificial intelligence (*Hill et al.,* 2019) for the purposes of adapting features. These problems go beyond the boundaries of autonomous navigation, and are also applicable to active tools so that they work with precision.

DESIGNING NEW ACTIVE TOOLS

Innovation in the field of agricultural robotics is currently focused on autonomous navigation; tools worn are either passive or controlled independently (*Wu et al.,* 2019). For greater repeatability and enhanced execution speed, active tools capable of being synchronised with mobile carriers are expected. In order to achieve this, research will need to be carried out on mobile handling and coordination with a moving carrier.

HUMAN-MACHINE INTERACTION AND SHARED AUTONOMY

In addition to issues surrounding perception or communication interfaces, human-machine interaction also raises questions on autonomy and collaboration: when and how should control be given back to a remote operator? How can robots cooperate with humans? In agriculture cobotics is starting to emerge commercially, with assistance robots (*Laneurit et al.,* 2016), people-carrying robots and, to a lesser extent, exoskeletons – particularly passive exoskeletons – aimed at facilitating the lifting of heavy loads. With more complex levels of collaboration, it will be necessary to interpret human behaviour in order to adapt the actions of robots. Such an approach will help to popularise robots, which will still not replace humans, just as we must ensure that these devices operate safely.

OPERATIONAL SAFETY

This is a crucial aspect for autonomous machinery operating in open environments. Scientific, technological and legislative progress will need to be made, drawing on driverless vehicles but factoring in difficulties linked to natural environments: (i) maintaining precision in terms of positioning (avoiding obstacles or not crushing crops), (ii) navigating within a pre-determined space, (iii) guarding against the risk of collision, or loss of stability or controllability. Infrastructure

and protocols will be needed to validate operational safety and other types of performance (technical, environmental, etc.).

ADAPTING TO NEW PRODUCTION SYSTEMS

Robots must be designed with frugality and inclusion in mind: the choice of materials and components (minimising the use of rare-earth elements), limited energy requirements, reduced maintenance, repairability, the scalability of robots and their capacity to be updated. Similarly, robotics must provide solutions for all types of agriculture, with levels of sophistication and autonomy adapted to production systems. New crop systems, with a mix of species and the possible introduction of trees (agroforestry), will present problems for navigation.

There are also issues relating to the humanities in terms of how digital technology and robotics are transforming labour, on the loss of autonomy (deskilling) as a result of the use of machinery to replace humans and the rationale of practitioners. In order to avoid these risks, one of the challenges will be to incorporate – from the design phase onwards – the conditions for use, impact on the work and satisfaction of farmers (*Hansen and Straete,* 2020; *Vik et al.,* 2019) and other categories of workers (employees, associates, sub-contractors, etc.).

Modelling to incorporate systemic effects and build practical, usable decision-support tools

Challenges for research involve a number of aspects linked to the building of models and, in particular: representing and understanding interactions; including expert knowledge; building practical, integrated models for farmers; and dealing with uncertainty. Details of these can be found below.

REPRESENTING THESE NEW SOCIO-AGROECOLOGICAL SYSTEMS

This is a first challenge in that agroecological systems are much more far-reaching (incorporating value chains) and much more complex (based on interactions) than is the case with conventional agriculture. Difficulties with modelling are linked to selecting which characteristics and parameters to include (determined by measurement capacity), natural variability in terms of how these characteristics are expressed to the other factors inherent to plants or animals, environments, production or breeding systems (factoring in other individuals from their group), the equipment used and the agricultural strategy employed.

Data-driven approaches (based on statistics, artificial intelligence, etc.) could be combined with concept-driven approaches (biological, economic or social models based on known mechanisms). Consideration may even be given to

creating "digital twins", integrating models developed for sub-systems, in order to test scenarios at a system level (e.g. climate change, local supply on a mass scale, etc.). However, this integration will bring with it alignment difficulties[77] when there is no guarantee of concept correspondence between sub-models or between digital twins and the system being studied.

THE LEVEL OF INTEGRATION FOR EXPERT KNOWLEDGE

This second challenge to overcome in the building of decision-support tools (description, prediction, prescription, see 4.2) is of interest to the humanities: will it be necessary to go as far as prescription, or is observation (or possibly a diagnostic) sufficient, leaving the decision (prescription) up to farmers for precision livestock farming, as suggested by *Ingrand* (2018)? With regard to risk management, other formalisms could be actionable, such as the theory of viability (*Aubin,* 1991), which in principle is compatible, but which poses problems for researchers owing to the fact that models must provide a framework for small (<10) dynamic systems which are both controlled and constrained (*Brias,* 2016). This opens up research questions: what should be done if the model is not dynamic and constrained (compartmentalised models, multi-agent systems), or is even unknown? How can weak signals be utilised in time series (tipping points)? How can a compromise between complexity and control be reached (*Anderies et al.,* 2019)?, etc.

BUILDING PRACTICAL DECISION-SUPPORT SYSTEMS FOR FARMERS

The issue of practicality is central to the design brief, and there are a number of key points that any future research must take into consideration:

- ***the user interface:*** both for visualising inferred outputs, which are essential to effective decision-making, particularly in the context of multi-criteria optimisation (*Lepenioti et al.,* 2020) or in the context of collective approaches (cf. part 6.2), but also for gathering data and identifying strategic objectives or preferences among farmers and incorporating these into decision models: visualisation of compromises, gamification (e.g. the serious digital game *C-Real Game*). It could be worthwhile to explore human-machine interfaces based on oral communication in order to make it easier to input and reproduce data and information in situations where farmers must handle...
- ***the "personalisation" of inferred information*** i.e. adapting models to individual farms or farmers in order to avoid one-size-fits-all prescriptions, to be in alignment with farmers' strategies and factor in their objectives (turnover, revenue, operating modes, etc.). Current prescription models are taken from "broad spectrum" knowledge models from experts in the field; how can it be

77. Alignment involves indicating that a concept outlined in one ontology is semantically identical to another concept outlined in a different ontology, even if the two concepts have different names.

made so that only – or primarily – data collected on individual farms is used, the goal being to infer prescriptions which are more compatible with farms and farmers? This obstacle has raised questions relating to the integration of knowledge from farmers in order to "personalise" inferred information and to increase its relevance in relation to their farm, similar to personalised medicine.

- ***the capacity to create scalable model*** capable of being adapted to environments which are liable to change as a result of both internal factors (strategy) and external factors (environmental, regulation, economic, etc.). This also raises questions linked to updating models (what is known as 'concept drift');
- ***the security of the recommendations made,*** i.e. the guarantee that a recommendation will not lead to a worsening of the situation, particularly in relation to automatic control. This problem is down to the stacking of models and the propagation of uncertainty (*Trnka et al.,* 2007), as well as the characteristics of the actuator. The latter must be made part of the model in order for relevant decisions to be taken (see *Tisseyre and McBratney's* opportunity index, 2008).

UNCERTAINTY AND ITS PROPAGATION

Uncertainty is mentioned in 76% of articles on modelling (*Lepenioti et al.,* 2020): how can it be reduced, how can it be characterised (epistemic, ontological, random) and how can it be represented (*Caquet et al.,* 2020; *Crespo et al.,* 2010; *Groot et al.,* 2012)? How can the issue of incomplete and noisy data and the subjective nature of human knowledge be addressed, particularly in the context of prescription (*Lepenioti et al.,* 2020)? How can a compromise be reached between overly complex, unmanageable modelling and modelling which is simplistic and not sufficiently relevant (*Caquet et al.,* 2020)? Exploring different ways of simplifying models would certainly be useful (stochastic models, mechanistic-stochastic models, metamodels, etc.).

Looking at the Global South in particular, decision-support systems must be designed in such a way as to incorporate the characteristics of agriculture in these countries; these must be multifunctional, with a prevalence for spatial-temporal reasoning and high levels of uncertainty. Decision-support systems and associated information systems must prioritise: (i) introducing or continuing agroecological practices and collective learning (collecting and exchanging data using digital technology); (ii) improving the management of resources (water, organic materials, etc.), from individual plots to whole regions, and harvests (dates, quantities), (iii) building new knowledge based on data and expertise in the context of rare data, but also emerging big data (see 6.5).

6.3 Transforming relationships between stakeholders within sectors

Balancing out sectors to better integrate farmers and consumers will be vital in order to keep family farming attractive and to meet the expectations of consumers with regard to food. In response to these challenges, three key points have been especially identified, both upstream and downstream:

- service: advice, insurance;
- traceability;
- platformisation[78] and the reconfiguration of distribution networks.

Service: advice and insurance

Regarding advice, each of the obstacles identified in chapter 4 (access to digital, the individualisation of decision-making and maintaining decision-making autonomy, the imbalance between upstream and downstream) open up avenues for research on advice and digitalisation in both digital science and the humanities, with three primary areas of focus:

- **developing decision-support tools capable of integrating the specific features of individual farms (pedoclimate, the agronomic techniques employed, agricultural equipment) and the preferences of farmers.** In addition to the points discussed in 6.2, the development of these tools could also draw on a deeper understanding – based on agronomic, sociological, managerial and ergonomic analysis – of the role of advisors and the bonds of trust they form with farmers in the usage profiles of digital solutions;
- **continuing the economic analysis of the modes of decision-making employed by farmers and the dynamics for the adoption of digital innovations** in a context impacted as much by the diversification of how farmers seek out information as by the fragmentation of services as a result of the privatisation of advice. Research could also be conducted to identify sustainable economic models for digital advice;
- **institutional analysis of the governance of the digitalisation of agriculture,** taking us back to the issue of transparency regarding the use of data, the regulation of power relationships and advice as a key factor in the digitalisation process.

78. Platformisation is a business model in which organisations employ the use of a web platform in order to act as an intermediary between consumers, as opposed to a supplier of goods and services. To find out more: https://www.decideo.fr/Entreprise-3-0%C2%A0-vers-une-ineluctable-%C2%A0plateformisation%C2%A0-du-Business-de-l-IT_a9280.html

On the subject of insurance (section 4.2), technological breakthroughs will still need to be made in order to reduce the baseline risk for index-based insurance; this could draw on new data sources (satellites, connected stations, etc.) or suitable types of processing (*De Leeuw et al.,* 2014; *Ghahari et al.,* 2019). Finally, usage-based insurance – which has emerged in the transport sector (*Husnjak et al.,* 2015) – is still unknown in agriculture, but it could be a useful avenue for exploration in the context of connected agriculture. Could this usage-based insurance assist with the adoption of agroecological practices – more complex to implement given the need for greater monitoring, but more resilient in the event of a health or weather disaster – by guaranteeing revenue, provided that crops or herds have been correctly monitored and recommendations from decision-support tools applied? A multidisciplinary approach must be taken when addressing these questions.

Traceability, full supply chain transparency, data life-cycle

As shown in section 4.3, in the current context, the traceability of flows and products in agriculture is crucial in the interests of establishing trust between farmers and consumers. There is a growing interest in the blockchain, for example, for sharing and distributing details on a product's entire life while also limiting fraud. But there remain a number of challenges to overcome in relation to data management at a technical and institutional level, particularly with regard to the overall traceability of practices and products.

THE TECHNICAL CHALLENGES OF THE BLOCKCHAIN

How can current blockchains, which were designed for banking information, be adapted to this new type of data, linked to flows of products which are often perishable, in order to monitor it and archive it efficiently without violating the basic principles of storing data in a blockchain? How can the flow of information which characterises traceability in blockchains be unquestionably linked to the flow of products? How can the costs of identification systems be lowered and who should cover these costs, which benefit everyone along the chain? How can data be protected within an ecosystem with a growing number of data sources?[79] Similarly, as explored in chapter 3, public blockchains use up a lot of energy – in order to be unquestionable, the validation of information is open to a huge number of participants "in virtual competition with each other", known as 'miners', resulting in a huge number of simultaneous calculations. Preference may be given to a private, less energy-intensive blockchain (based on a restricted number of

79. White paper published by the US National Institute of Standards and Technology, outlining security problems affecting the Internet of Things (IoT), in October 2018 (https://csrc.nist.gov/CSRC/media/Publications/white-paper/2018/10/17/iot-trust-concerns/draft/documents/iot-trust-concerns-draft.pdf)

authorised participants) that is also better suited to use in agriculture. However, this raises the issue of the governance of blockchains.

THE STORAGE OF DATA FROM THE AGRICULTURE AND FOOD CHAIN

This data can be said to be industrial in that it relates to agricultural production, but also to upstream and downstream industries. Should it be stored in specific locations or in a distributed manner? How can data sovereignty be ensured? Should certain operators be avoided in light of the Cloud Act?[80]

DATA INTEGRATION

This is an important aspect when it comes to facilitating subsequent analysis. Owing to the significant increase in the volume of data, the need to verify its quality and the value of the information, systems capable of enabling access by relevant and reliable information will become value sources. This will involve verifying company information systems – such as ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) – and engaging them in dialogue with data generated by connected objects managed through the Internet of Things (IoT). It will also involve evaluating and recognising the value created by each individual component of the data production and processing chain, exploring the following questions: what ways are there of getting more out of data in value chains, particularly vis-a-vis consumers? How can these raise awareness of virtuous transitions within agriculture among consumers?

BLOCKCHAIN GOVERNANCE

The challenge here lies in designing a fair and secure system involving all stakeholders in an equitable way, without any individual stakeholder imposing its vision on others or taking control of data usage. This raises a number of questions: how should the data that is generated be shared? What must be put in place in terms of data governance? To what extent will accessibility to information impact the improvement of supply chain governance (*Gardner et al.,* 2019) and power shifts in value chains? What impact will digital technology have on trustworthy relationships and the ways in which value is shared within the sector (*Jakku et al.,* 2019)? How can we prevent the value that is created from being collected exclusively by digital giants (*ANRT,* 2018)? Is there a risk that digital technology will exacerbate existing power imbalances (*Bronson and Knezevic,* 2016; *Carolan,* 2017, 2018; *Wolf and Buttel,* 1996).

80. The "Clarifying Lawful Overseas Use of Data Act" ("CLOUD Act" 162(*)) was passed by the US Congress in March 2018: Its primary aim is to reaffirm the right of US authorities to demand that technical intermediaries subject to their jurisdiction share all data stored, even data stored overseas. Independently, it also provides for specific, reciprocal bilateral agreements with the United States. (https://www.senat.fr/rap/r19-007-1/r19-007-13.html)

Platformisation and reconfiguration of channels

Platforms, new virtual meeting places, are helping to change the economic model within agriculture, facilitating dialogue and collective dynamics. Automatic data input in agriculture, hyperconnectivity, the Internet of Things and automation produce real-time information for optimising the running of the value chain, either individually or as a whole. This growing computerisation has led to increased agility capacities on the part of distribution and processing channels. It will be necessary to introduce agile planning for agricultural and food production in order to meet the growing need for local supply in towns and cities and contract catering. In the interests of promoting family agriculture for towns and cities and contract catering, major issues linked to production planning, coordination between different levels of the supply chain and logistics will need to be overcome in order to ensure everyone's expectations are met and to be resilient to crises (as illustrated by the Covid-19 pandemic). These three points are explored below.

In agriculture production planning is a reality for farmers contracted to agribusiness industries, particularly for frozen, tinned or ready-to-eat vegetables (*Ahumada et al.,* 2012; *Li et al.,* 2015). The challenge now lies in production planning for fresh products in order to guarantee supplies for contract catering, incorporating uncertainties (weather, health, social, etc.) and to factor in demand (*Balaji Prabhu and Dakshayini,* 2020).

One solution to the issue of coordination is the creation of "food hubs", innovative commercial models which bring together small producers in order to meet wholesale demand (*Berti and Mulligan,* 2016). The most integrated "food hubs" are intermediary organisations which use the internet for commercial transactions and which pool together, distribute and market food products from the source (small local and regional producers) to customers (individual consumers or wholesalers). These hubs must have access to production and distribution chain models featuring realistic characteristics, including soft information, logistical integration, risk modelling, the regulatory environment, and the quality and safety of products. Stochastic modelling could be useful in this context (*Ahumada and Villalobos,* 2009).

In order to build urban logistics distribution networks for suburban production with shorter commercial channels, it will be necessary to improve inventory management and distribution planning (particularly for cold products) in order to reduce food waste and the resulting carbon footprint. Little research has gone into planning applied to food supply chains compared to the industry. In particular, there is a clear lack of adequate models for planning operational decisions for the

production, harvesting and distribution of fresh agricultural products (*Ahumada and Villalobos,* 2009). The environmental dimension will need to be taken into consideration (*Melkonyan et al.,* 2020)

In the Global South, challenges linked to improving supply in local distribution channels are even more difficult: this will involve reducing post-harvest losses through organisational support and improved logistics management (channel modelling and optimisation, cold chain logistics, etc.). For longer channels, it is anticipated that frugal, secure traceability systems will be developed for national and international chains.

Finally, there is also the possibility of a move towards personalised food production. *Svetlin et al.* (2016) have proposed "online" and individualised co-design of products through linguistic analysis of consumer preferences and translation into formulation parameters (applied to an orange drink). This type of approach could be employed with more complex food items produced in accordance with demand, restrictions, budgets and individual needs, and delivered ready-made to people's homes (*Académie des technologies,* 2021). This would also make it easier to connect to personalised health monitoring applications.

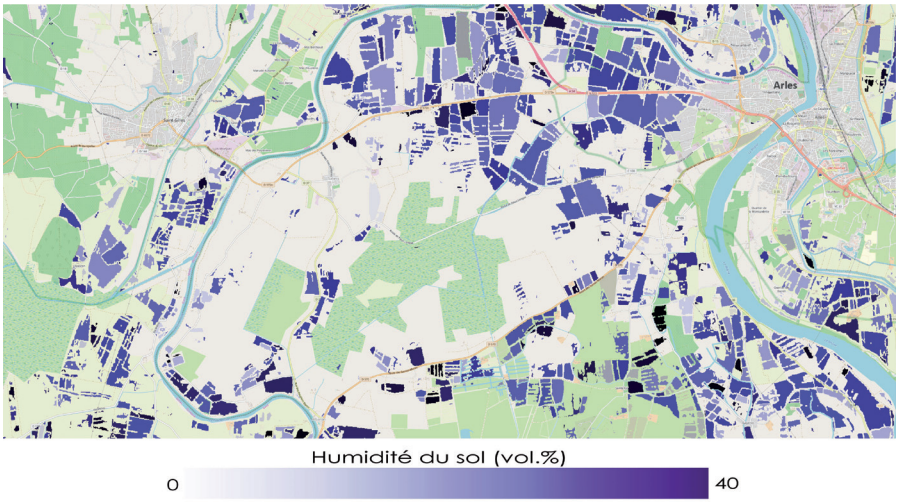
6.4 Creating and sharing data and knowledge

Data and knowledge are central to digital technology helping to promote agroecology: data feeds into knowledge and knowledge feeds into agroecology. This information capital has brought about new technological, regulatory, organisational and institutional challenges. These challenges relate to the origin, the quality (crowdsourcing) and the governance of data, but also to the formalisation and sharing of knowledge, challenges which will require a response in order to build an ethical digital agriculture.

PARTICIPATORY DATA (CROWDSOURCING)

With the development of connectivity and acquisition systems (smartphones, precision agriculture, connected objects, etc.), the collection of data by operators (farmers, advisors, etc.) or laypersons (citizens) has developed, adding to more conventional methods for the gathering of experimental data by scientists. There are technical challenges relating to participatory data collection for environmental documentation or research purposes (4.4): what infrastructure is needed for managing and exchanging this participatory data? How can the quality of data collected through crowdsourcing be ensured? How can the data that is produced be traced in the interests of the fair sharing of intellectual property? There are also questions of interest to the humanities and economics: what has to be done

to encourage farmers to share their data and information and to build trust-based relationships with their advisory and training environments (*Sutherland et al.,* 2013; *Wiseman et al.,* 2019)? How can value be attributed to the data that is produced? What impact will this new role of data collector have on the evolution of the job of being a farmer?



Subcellular and weekly mapping of soil moisture by remote sensing based on Sentinel 1 and 2 images. © *Theia et INRAE.*

GOVERNANCE AND THE SHARING OF DATA AND KNOWLEDGE

When talking about regions or sectors, we have shown that data is increasingly coming from various actors (multisource data). Given that data is generated by separate parties through different systems and is potentially hosted across multiple sites, it will be necessary to determine what the data usage rights are; needs can be contradictory from the point of view of data sharing and data protection (collaborating while remaining competitive). What modes of governance should be employed, in a context in which digital firms and upstream stakeholders are investing heavily in the management of data on agricultural risks and in which agricultural innovation systems are being digitalised (*Fielke et al.,* 2019)? Within chains, an understanding must be reached as to the role played by information in the emergence of cooperation and compliance between stakeholders from different sectors and at different levels of global supply chains (*Gardner et al.,* 2019). How can "ethical and secure" data circulation and state sovereignty be promoted[81]?

81. The French Academy of Technology has recommended *"the introduction of a label for circulation solutions at a European level to prove that they are ethical and secure"* and "emphasise the importance of developing solutions for bringing European clouds together". See https://www.academie-technologies.fr/blog/categories/publications-de-l-academie/posts/pour-une-circulation-vertueuse-des-donnees-numeriques

Clearly, these issues relating to data governance and the risk of power being seized by certain stakeholders within sectors (agricultural supplies, downstream) or by digital companies specialising in artificial intelligence and networks are even more acute in the Global South, where there are fewer regulations.

FORMALISATION AND SHARING OF KNOWLEDGE

Digital technology can help to promote the co-construction (participation) and exchange of knowledge, but there remain a number of challenges: how can knowledge be constructed in such a way as to incorporate the uses and knowledge of farmers (expertise gathering, contextualisation, etc.) in order to increase the likelihood of it being adopted? How can satisfactory governance be developed, not only in terms of data but also the knowledge generated through this data? How can the construction of digital commons be accelerated in order to establish knowledge and, in particular, to compare it and gather it together? This raises non-trivial questions regarding the gathering of expertise and ontologies. In particular, how to make ontologies built on different principles compatible (stackable, associable): different uses, different authors, different foundamental ontologies, etc.? Lastly, in the interests of frugality and efficiency, moving away from multiplying tools and getting the most out of existing resources, might it be beneficial to mobilise non-specialist social media sites and platforms for exchanging knowledge? If so, how can this be achieved?

In the Global South, a first challenge is to use digital technology to rethink participatory approaches for collective learning and co-innovation – through "enhanced" interdisciplinarity (cognitive psychology, ergonomics, immersive serious games, design thinking and management science) – and evaluating their impact (*Tesfaye et al.,* 2019). The goal will also be to facilitate communication with farmers and between farmers, in a context of low network coverage, plurality of languages and dialects, etc. (see 4.5).

Conclusion

In light of the risks and issues discussed above, the challenges identified in this chapter should be considered within a general overall context, enabling a multi-faceted framework to be built:

- **The need for a systemic vision for agriculture and digital technology.** Systems and sectors in agriculture are complex systems, comprising multiple elements and stakeholders interacting with each other at different levels (farms, regions, sectors, etc.). Anticipated digital developments will need to be designed and evaluated in light of their direct impact at the level

at which they are applied, but also their indirect impact throughout the system and society as a whole, from a biotechnical, economic, social (e.g. labour), environmental (biodiversity, resources, etc.) and ethical perspective. Considering these indirect impacts and developing methods through which they can be evaluated will be essential in order to have the capacity to ensure that overall energy costs fall some way below the benefits of the development of a given type of technology, therefore without the risk of increasing complexity (see 5.4). Furthermore, developing systemic approaches will be essential in order to anticipate retroaction, such as the rebound effect[82] that often occurs with digital technology. Research is faced with major methodological and conceptual difficulties, primarily relating to the systemic analysis of problems. Approaches must be fundamentally transdisciplinary; certain frameworks, such as the concept of "complex thought" introduced by Edgar Morin, could be useful here (*Morin,* 2014).

- **Searching for frugality.** This involves reducing energy expenses, consumption of other resources (both renewable and non-renewable) and pollution caused by the use of technology. It must incorporate all stages of the data chain, from collection and gathering to reproducing and decision-making. The development of digital solutions must take costs into consideration, whether this is the cost of materials (e.g. components used, size, number, particularly for sensors, robotics, etc.), of the data produced (type, quantity, storage, etc.) or of the processing power required in order to be economic with regard to natural resources (water, minerals, etc.) and energy. This analysis must factor in the entire life cycle of the materials used (resource extraction, manufacturing, transport, use, end-of-life). Although digital calls for a reduction in the use of agricultural inputs and resources (such as water, for example), its own environmental footprint must be taken into consideration when calculating the overall environmental footprint of any new agricultural practice. This will also mean taking a sober, cautious approach when developing and scaling up technological solutions, beforehand exploring organisational and sociopolitical solutions and alternatives which do not use up directly resources or emit pollution.

- **Searching for resilience.** Optimising production and sectors from a cost point of view has guided technological innovations for decades, resulting in specialisation, reductions in stock levels, less room for manœuvre and less autonomy on the part of different stakeholders. This has resulted in a

82. More efficient technology often leads to increased consumption of the resource that is sought to be preserved as a result of changes to consumer behaviour; see https://ecoinfo.cnrs.fr/2015/12/23/les-effets-rebond-du-numerique/

reduction in the resilience of agricultural systems and sectors, i.e. their capacity to resist and to adapt to – at different levels – external crises such as weather events, scarcity of resources and supply chain breakdowns, and economic or health crises (*Biggs et al.,* 2015). Digital solutions must endeavour to promote this resilience, by being the component within a complex system which is based on the seven principles of resilience outlined by *Biggs et al.* (2015),[83] avoiding the trap of complexity, which results in technical or social dependency or security risks (data, operational, etc.), contributing factors to fragility.

- **Cybersecurity.** Although not specific to agriculture, this remains a crucial topic in agriculture given the impact it has on food sovereignty. This is as much about maintaining continuity of food and agricultural production and distribution as it is about the security of information relating to agricultural production. Cybersecurity was covered in detail in a previous white paper (*Inria,* 2019). The European Union is behind the project *GAIA-X* (www.data-infrastructure.eu), the aim of which is to develop autonomous, sovereign data infrastructure which respects European standards, chiefly through a cloud computing network. Agriculture is one of the themes identified in *GAIA-X*.

Factoring in these aspects will help to promote responsibility, relevance and sharing in relation to digital technology, helping to make food systems sustainable, particularly in the context of the agroecological transition.[84] Plotting this course will guide research, not just in terms of the choice of research topics – identified in this chapter – but also in terms of research positioning. We would recommend as a minimum drawing on approaches such as Responsible Research and Innovation or RRI (*Stilgoe et al.,* 2013). Still rarely employed in digital agriculture, RRI is based on the following principles: anticipation (what will happen if…positive/negative impact), reflexivity (what does digital responsibility mean, what limits are there to our hypotheses/choices/knowledge, etc.), inclusion (with who and for who, what values) and responsiveness (how to adjust development trajectories in response to changing circumstances). It draws upon transdisciplinary research. Developing technology for digital agriculture within an RRI framework would help to meet

83. https://whatisresilience.org/wp-content/uploads/2016/04/Applying_resilience_thinking_FR_aktiv.pdf

84. **Responsibility:** fairness, inclusivity, frugality (environmental impact), moving towards a much-needed diversification of cultures, practices and products in a context of reduced inputs, ensuring take-up by a wide-range of stakeholders. **Relevance:** meeting actual needs, delivering effective, acceptable solutions which preserve diversity and freedom. **Sharing:** where users are able to make use of their expertise and local data, give their opinion on outputs (assuming these are clear and well-communicated, with uncertainty estimated), and act on the parameters of tools while remaining within a plausible framework.

the challenges identified while factoring in the global context and considerations on the need to integrate a systemic vision and issues such as frugality, security and resilience.

Definition

The concept of RRI (Responsible Research and Innovation), introduced in the 2010s (*Owen et al.,* 2012; *Pellé et Reber,* 2015; *Stilgoe et al.,* 2013) is characterised by four key aspects, "anticipation, reflexivity, inclusion and responsiveness", all of which must be implemented throughout the research and innovation process (*Stilgoe et al.,* 2013). Research into RRI in agriculture remains limited and does not deal specifically with digital agriculture. However, since the end of the 2010s, *Klerkx and Rose* (2020) have noted a growing interest in RRI within agriculture 4.0 (*Bronson,* 2019; *Eastwood et al.,* 2019; *Rose and Chilvers,* 2018)

Conclusion

The evolution in agriculture and food systems will be one of the most important challenges over the coming years. As has been explained in this white paper, agriculture is already facing and will continue to face major challenges some of them are: food security and how to feed the world in difficult ecological and climate conditions (climate change, the erosion of biodiversity, loss of soil fertility, etc.); changes to agricultural models *via* the agroecological transition in order to limit environmental impact; diversification of production systems; a move towards greater regional integration; food sovereignty, etc.

Challenges for research

The digital revolution is in progress in a number of fields and digital agriculture is both a component and a consequence of it. This white paper has outlined current research into digital technology aimed at tackling challenges facing agriculture. The topics covered were data at large (from acquisition to storage), modelling, learning and knowledge extraction, knowledge engineering for decision-support purposes or automation and robotics. We have also covered the range of opportunities presented by the use of digital technology in agriculture for improving production, promoting agroecology and adapting to external change. This range of opportunities also includes better integration within value chains and improving sharing, learning and understanding. But current research only deals with some of the opportunities that have been identified. Furthermore, although this technology has the potential to be empowering, the risks are also great, including missing out on the agroecological transition, widening inequality and power imbalances, loss of sovereignty and excessive complexity. With regard to these opportunities and risks and the current state of research, we have sought to show the main obstacles that will need to be overcome in order to scale up digital agriculture in a sustainable and responsible way, promoting agroecology, adapting to climate change and balancing out and reterritorialising value chains.

Among the many challenges outlined in this paper, there are a few which we believe to be particularly important and suitable for being tackled jointly by INRAE and Inria:

- In terms of data, what is the most relevant data to acquire at different levels (plants, animals, plots, herds, farms, regions, etc.)? How can this data be acquired and exchanged while minimising energy costs and guaranteeing access and privacy? Data heterogeneity is inherent to an increase in the number of different systems. It will be necessary to take advantage of this heterogeneity, which provides redundancy and complementarity both being, factors for improving measurement results.

- When it comes to supporting farmers: what knowledge will need to be created? What is the best way of using and analysing data in order to discover this knowledge? And how can new knowledge be combined with existing knowledge? How can information be shared with farmers (visualisation)? How can they be assisted with decision-making through the use of diagnostic or decision-support tools? What robots will need to be developed in order for agroecology to be scaled up? Stakeholders from the digital and agricultural spheres will need to work together to come up with these new solutions.

- Uncertainty is inherent to processes in biology, the climate, meteorology, etc., particularly in agricultural production systems applying an agroecological approach. How can complexity be modelled by linking models together (e.g. digital twins) while on the propagation of uncertainty under control? How can complexity be incorporated into models and relayed in order to enable informed decision-making? Handling this uncertainty will require combined expertise from different observational disciplines (depending on the scale, this may be biology, physiology, agronomy, regional engineering, etc.), as well as from mathematics and computer science.

- Participation has been shown to be an effective lever in the context of the agroecological transition and the transformation of food systems: data collection, mediation, governance, experience-sharing, etc. The aim will be to utilise digital technology for participatory processes: crowdsourcing; support models; mediation or boundary objects; sharing, managing and integrating (with other systems) data and knowledge.

- Traceability, transparency and, in a broader sense, product documentation, all along the production chain, are becoming key considerations for agri-food systems. Consideration must now be given as to what data should be "traced", documented and shared (particularly in relation to perishable goods), and how to choose the right tools for storage and transmission (e.g. the blockchain).

- Cybersecurity is crucial to food sovereignty in terms of protecting agricultural production and the information produced as part of it or which is linked to it.

Lastly, it should be borne in mind that there are a number of different agricultural models and that there will be even greater diversity in the future (see the forecast from the JRC[85] or from the CSIRO)[86], which will result in the development of types of digital technology adapted to each model.

85. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC122308/farmers_of_the_future_final_online.pdf
86. https://research.csiro.au/digiscape/digiscapes-social-dimensions-project-what-did-we-learn/

Recommendations

In conclusion to this paper, we have a number of recommendations to make for research which we feel to be important for the future of digital technology in agriculture.

In light of the major challenges cited above which agriculture is currently facing and will face in the future, digital technology can be a major lever in enabling agriculture to meet these challenges by promoting the agroecological transition and the transition in food systems. However, as we have seen, digital technology also brings with it risks, both in environmental and human terms (the cost of resources, the dehumanisation of agriculture, widening inequality, etc.), which must be taken into consideration in future research. We recommend the following main principles: i) adopt a systemic vision by considering the system as a whole and the complexity of food and agriculture systems, ii) promote frugality so that the benefits of digital technology do not come at the expense of rising energy consumption, damaging the overall impact, iii) prioritise resilience, i.e. the capacity of digitally-aided agricultural systems to withstand crises and adapt to different types of changes (linked to the climate, the economy, health, working methods, etc.), iv) draw on the diversity of agricultural systems, using digital technology to support agriculture in all its forms. In this regard, we would recommend taking the approach of responsible research and innovation or RRI (see chapter 6). Finally, in the interests of taking a systemic vision and in light of the complexity of the possible topics for study, steps must be taken to avoid research becoming overly sector-specific in order to really get to grips with the issues raised (see Chapter 5). As a result, it will be important to really take an interdisciplinary and participatory approach to our research into the use of digital technology in agriculture and to emphasise the importance of this type of approach and research within our institutes.

Our aim is not to plot an exact course to follow, but given the broad panorama which we have sketched over the course of this paper, we believe that a number of key themes and principles have emerged which could inform decisions in the future. As stated at the beginning of this paper, we firmly believe that agriculture must evolve towards agroecology and sustainable food systems, and that digital technology has the capacity to be a powerful tool in this transition provided we are mindful of certain pitfalls. Our recommendations are based on this belief.

Research topics

Within the research topics mentioned above, one point which we feel to be most important is that **agroecology will result in the need to produce large quantities of new knowledge.** This knowledge will most likely be produced using digital technology: gathering data on a large scale but also monitoring new indicators (e.g. intra- and interspecies biodiversity, characterised by genomic data), managing these large quantities of data and extracting knowledge based on entirely new data at all levels (from microbiota to satellite imaging). There are a number of ways in which this research can be distinguished from non-specialist data science:

1) the approaches employed must take local contexts into consideration, with a focus on factoring in existing knowledge and gathering and establishing the expert knowledge of farmers;

2) the production of this data (whether measured or simulated) is becoming a challenge, bringing with it questions linked to the quality of the data produced, pre-processing and sharing. The convergence of phenotype data – particularly in real environments – with genomic data should accelerate the creation of knowledge on processes within agroecology, selecting varieties or building new cultural routes in order to anticipate climate change. Another key point to consider will be **digital tools for assisting farmers, advisors and other stakeholders at a sector or regional level.** Firstly, this concerns decision-support tools, which will be the primary interface for implementing knowledge, particularly that discussed previously. Very much central to dialogue between humans and digital models, these tools will require specific research drawing on design science, visualisation and ergonomics in order to facilitate their adoption. Taking into consideration local specificities and technical choices made by operators / political decisions at a regional level will be essential in order to avoid a move towards homogeneity within agriculture. The approaches studied must be able to explain/justify any recommendations that are made in order to enable constructive dialogue with human participants. Meanwhile, new robotic assistance solutions will need to be invented in order to spare farmers having to carry out the most arduous or dangerous tasks. Aside from research questions linked to navigating in uncontrolled environments, safety and how tools and the robots carrying them interact with each other, we believe taking a participatory approach to designing these robot solutions to be a promising means of reducing tension between technology and ecology.

A third focus for research in computing is motivated by the fact that processes within agroecology – in a broad sense – extend beyond farms into value chains and regions. In these areas, priority should be given to **operational research on issues linked to planning** (in time and space) for the use of resources (water, soil) and agricultural production (large-scale supply based on fragmented sources).

Lastly, as is the case with all of the digital systems explored, **cybersecurity** is of vital importance. In the agricultural sphere this must take a number of forms. The aim will be to secure data itself, but also the material systems which produce it, the networks used to transport it and the tools which utilise it in order to ensure that none of these are hacked (data could be intercepted or false data introduced). One possible avenue to explore involves combining "traditional" security systems with new learning techniques specific to agricultural data in order to identify and isolate any malicious nodes and/or detect information leaks.

Types of research

We recommend taking the approach of **responsible research and innovation** or RRI (see Chapter 6). In order to fully grasp the complexity of the subject matter, steps must be taken to ensure that research is not overly sector-specific (see Chapter 5), which will involve taking a systemic view. As a result, it will be important to really take an interdisciplinary and participatory approach to our research into the use of digital technology in agriculture and to emphasise the importance of this type of approach and research within our institutes.

This systemic view will also assist us in addressing the issue of the environmental impact of digital solutions. There is a range of different ways of tackling the avenues for research outlined above, some of which will require the consumption of a significant amount of energy or rare resources. In order to avoid this pitfall, it is our recommendation that a **frugal** approach be taken: the benefits of digital technology must not come at the expense of rising energy consumption, damaging the overall impact. The best way of assessing this impact is to employ a systemic view, considering the system as a whole and the complexity of agriculture and food systems (as opposed to optimising just one indicator).

We also feel it will be critical for any future research to place an emphasis on resilience, i.e. the capacity of digitally-aided agricultural systems to withstand crises and adapt to different types of changes (linked to the climate, the economy, health, working methods, etc.) Lastly, given that there are many different types of agriculture, it will be necessary to draw on the diversity of agricultural systems, **using digital technology to support agriculture in all its forms.**

Social science

We hope this paper has demonstrated that the use of digital technology in agriculture is not simply a question of technology. At all levels, existing or planned solutions are in line with human stakeholders, and can even provide a way of bringing different stakeholders together. **Research in the humanities is therefore an integral part of research into the use of digital technology in agriculture.** One first issue, which may not be new but which will become increasingly significant, is the link between humans and increasingly complex technological solutions: how can a harmonious and fulfilling relationship be built between these solutions and the humans that use them? How can the risk of deskilling be avoided? One avenue that seems particularly promising is putting an emphasis on participatory approaches to design, identifying the best way of involving stakeholders within the sector at the earliest possible stage. These approaches go beyond designing tools: one key concern is to draw on digital technology in order to discover new ways for humans to work together. This will be particularly beneficial when it comes to improving the management of shared resources, where collective and individual interests can come into conflict with each other.

Public policies

Finally, the "digital transition" in agriculture is bringing about changes that will need to be dealt with at a public policy level. The aspect which we feel to be most important is **data governance.** New technology has transformed farmers into data producers, either through the sensors which they use or manual entry on their part (participatory approaches). Urgent consideration must be given to the value of this data, as well as to copyright and privacy. This is a complicated issue: on one hand, sharing the vast quantities of data produced can benefit everyone, but on the other hand too much openness can make farms or regions less competitive. As things currently stand, part of this data is in the hands of private firms (e.g. providers of technology and services), which benefit from a global view without there necessarily being a great deal of reciprocity with regard to the agricultural sector. In order to avoid this pitfall, France's National Digital Council recommends granting agricultural data the status of common good. [87]

Another key subject will be to work on better **quantifying and analysing material flows at different regional levels** so as to facilitate the introduction of alternative economic models falling within the bracket of bioeconomics or biophysical economics.

87. https://cnnumerique.fr/tribune-agriculture

Inria-INRAE - an appropriate partnership for tackling this research

In line with their own missions, bringing together our two institutes – Inria and INRAE – will be beneficial in tackling the subjects outlined in relation to digital agriculture, thanks to the complementarity of the approaches and skills they can draw upon: INRAE, with its culture of experimental tools and data gathering; skills in modelling biological systems, with panels of experts and extensive models; and expertise in economics and social science, with a particular focus on agriculture and its stakeholders, regions and networks, enriched through contact with the profession and knowledge of needs; Inria, through its expertise in digital science and technology – mathematics and computer science –, particularly in modelling, simulation, artificial intelligence, data science, cybersecurity, networks and robotics, plus its culture, rooted simultaneously in research, technological development, transfer and innovation.

The two institutes have a long history of collaborating and interacting with each other (joint project-teams, jointly supervised PhDs, scientific days staged jointly, etc.), something which has intensified recently through flagship projects such as *#DigitAg* (see inset) and **PEPR (Priority Equipment Programme for Research)** "Agroecology and Digital Acceleration Strategy" *SADEA,* launched in 2021 and jointly led by the two institutes. These collaborations have proven highly rewarding for the researchers involved. Given the unprecedented challenges posed by the digital and agroecological transition in agriculture, this collaboration will surely only grow stronger. Together, and with their historic partners in agronomy (CIRAD, the *grandes écoles* of agronomy, IRD, CGIAR, etc.) and mathematics and computing (universities, CNRS, etc.), the two institutes clearly have the potential to address these challenges and to meet the high expectations of society with regard to agriculture.

Find out more

#DigitAg, the Digital Agriculture Convergence Lab, led by INRAE, is one of ten French Convergence labs funded by the Investments for the Future Programme (€9.9m). Based in Montpellier and with branches in Toulouse, Rennes and Avignon, it brings together more than 550 individuals (2020 figures) from 8 public and parapublic bodies and is supported by 8 AgTech companies. Launched in 2017 for an initial duration of eight years, its aim is to prepare for the harmonious development of digital technology in agriculture, both in France and in the Global South. For this, its work involves developing multi- and interdisciplinary research, with 60 or so PhDs jointly funded, around 20 or so labelled PhDs, 12 postdoc researchers and 150 master's placements funded. A graduate school has been set up to create an inventory of educational resources for this sector and new courses have emerged (data science). Lastly, the institute is raising awareness of innovation among students through meetings with companies, courses on intellectual property, an IT development department for building web demos based on PhD results, and an observatory for the different uses of digital technology in agriculture. It is highly active internationally, with a particular focus on the Global South, a number of teams from INRAE and Inria working together.

Contributions and acknowledgements

The following people contributed to the writing of this paper

Name	Institute unit, site	Member	Chapters
Bellon-Maurel, Véronique	INRAE, UMR ITAP, Montpellier	#DigitAg, Digigral	Co-editor
Bisquert, Pierre	INRAE, the mixed research unit IATE, Montpellier	#DigitAg, Digigral	6
Bonnet, Pascal	CIRAD, Dept E&S, Montpellier	#DigitAg	4, 6
Bouadi, Tassadit	Univ. of Rennes 1, Lacodam, Inria Rennes - Bretagne Atlantique	#DigitAg	3, 6
Brossard, Ludovic	INRAE, the mixed research unit PEGASE, Rennes	#DigitAg, Digigral	Co-editor
Chambaz, Grégoire	Unisanté, Lausanne, Suisse		5
Courtonne, Jean-Yves	Inria, STEEP, Grenoble		4
Dedieu, Benoit	INRAE, the research support unit ACT, Theix		2
Gandon, Nathalie	INRAE, 'IT and freedoms' officer		5
Garcia, Frédérick	INRAE, the research unit MIAT, Toulouse	#DigitAg	Co-editor
Gautron, Romain	CIRAD, AIDA	#DigitAg	3
Hilgert, Nadine	INRAE, the mixed research unit MISTEA, Montpellier	#DigitAg	3
Ienco, Dino	INRAE, the mixed research unit TETIS, Montpellier	#DigitAg	3
Javelle, Aurélie	L'Institut Agro-Montpellier SupAgro, the mixed research unit Innovation, Montpellier	#DigitAg	5
Labarthe, Pierre	INRAE, the mixed research unit AGIR, Toulouse	#DigitAg, Digigral	4, 5, 6
Lagacherie, Philippe	INRAE, the mixed research unit LISAH, Montpellier	#DigitAg, Digigral	Seminar
Largouët, Christine	L'Institut Agro- Rennes, Lacodam, Inria Rennes - Bretagne Atlantique	#DigitAg	3
Lenain, Roland	INRAE, the research unit TSCF, Clermont-Ferrand		3, 6
Lutton, Evelyne	INRAE, the mixed research unit MIA, Paris	Digigral	3, 6

Name	Institute unit, site	Member	Chapters
Martin-Clouaire, Roger	INRAE, the research unit MIAT, Toulouse	#DigitAg	3
Masson, Véronique	Univ. of Rennes 1, Lacodam, Inria Rennes - Bretagne Atlantique	#DigitAg	3
Maurel, Pierre	INRAE, the mixed research unit TETIS, Montpellier	#DigitAg	4, 6
Mitton, Nathalie	Inria, FUN, Lille		Co-editor
Molenat, Jérôme	INRAE, the mixed research unit LISAH, Montpellier	#DigitAg	Seminar
Mugnier, Marie-Laure	LIRMM, Inria, Montpellier	#DigitAg	3
Neveu, Pascal	INRAE, the mixed research unit MISTEA, Montpellier	#DigitAg	3
Piot-Lepetit, Isabelle	INRAE, the mixed research unit MOISA, Montpellier	#DigitAg, Digigral	6
Pla Aragones, Lluis Miquel	Université de Lleida, Espagne		6
Prados, Emmanuel	Inria, STEEP, Grenoble		2, 5
Preux, Philippe	Inria, Scool, Lille		3
Raynal, Hélène	The mixed research unit AGIR, Toulouse	#DigitAg	3
Reboud, Xavier	INRAE, Agroecology Mixed Research Unit, Dijon		6
Roussey, Catherine	INRAE, the research unit TSCF, Clermont-Ferrand		3
Termier, Alexandre	Univ. of Rennes 1, Lacodam, Inria Rennes Bretagne Atlantique	#DigitAg	Co-editor

Financial support for programmes: *#DigitAg*, #DigitAg, the Digital Agriculture Convergence Lab – funding managed by the French National Research Agency (ANR-16-CONV-0004) as part of the Investments for the Future Programme – and Digigral, a multidisciplinary group commissioned by INRAE to build a programme on the digitalisation of agrifood systems.

Our thanks go to Hervé Monod from INRAE, and Jacques Sainte-Marie and Pascal Guitton from Inria for keeping a close eye on proceedings, and to the management of both institutes for their trust and support.

Bibliographic references

CHAPTER 1

Bellon-Maurel, V., Huyghe, C. (2016) ***L'innovation technologique en agriculture.*** Géoéconomie, 80 – 159-180.

Blezat Consulting, CREDOC, Deloitte Développement Durable (2017). ***Étude prospective sur les comportements alimentaires et élaboration d'un dispositif de suivi,*** Étude commandée par le centre d'étude et prospective du ministère de l'Agriculture, 123p., disponible à https://agriculture.gouv.fr/etude-prospective-sur-les-comportements-alimentaires-de-demain.

Caquet, T., Gascuel, C., Tixier-Boichard, M. (2020) ***Agroécologie : des recherches pour la transition des filières et des territoires.*** Éd Quae, Collection : Matière à débattre et décider, 104 p.

DGE (2019) ***Technologies-clés - Préparer l'industrie du futur 2020,*** **640 p**. Disponible à https://www.entreprises.gouv.fr/files/files/directions_services/politique-et-enjeux/innovation/technologies-cles-2020/technologies-cles-2020.pdf.

Dinesh, D., Campbell, B., Bonilla-Findji, O., Richards, M. (eds). (2017). ***10 best bet innovations for adaptation in agriculture: A supplement to the UNFCCC NAP Technical Guidelines.*** *CCAFS Working Paper no. 215. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).* Disponible à https://www.agroforesterie.fr/actualites/2017/documents/10-best-bet-innovations-for-adaptation-in-agriculture-A-supplement-to-the-UNFCCC-NAP-Technical-Guidelines-CGIAR-Research-Program-on-Climate-Change-Agriculture-and-Food-Security-CCAFS.pdf.

FAO (2018a) ***The future of food and agriculture: alternative ways to 2050,*** FAO, Rome, 202 p.

FAO (2018b), ***Initiative de passage à l'échelle supérieure de l'agroécologie,*** disponible à http://www.fao.org/3/I9049FR/i9049fr.pdf.

FAO (2019) ***Digital Technologies in Agriculture and Rural Areas*** – *Briefing Paper.* 18 p. Disponible à http://www.fao.org/3/ca4887en/ca4887en.pdf.

Isaac, H., Pouyat, M. (2015) ***Les défis de l'agriculture connectée dans une société numérique.*** Ed. Renaissance Numérique, Paris (Fr),106 p., disponible à : https://www.renaissancenumerique.org/system/attach_files/files/000/000/010/original/LB_AGRI_HD.pdf?1485335906.

Malassis, L. (1994) ***Nourrir les Hommes,*** Dominos – Flammarion, Paris, 110 p.

OCDE (2019) ***Digital Opportunities for Better Agricultural Policies***. 23 Sep 2019, 234 p. (EPUB). https://doi.org/10.1787/571a0812-en.

Owen, R., Macnaghten, P., Stilgoe, J., (2012). ***Responsible research and innovation: from science in society to science for society, with society.*** *Sci. Public Policy 39*, pp 751–760.

Scandurra, A., Picchio, C., Ruffino, C., Piertaccini, M., Rocha da Silva, W., Marguglio, A., Antonucci, C., Coraretti, E., Castiello d'Antonio, A. (2020) ***Smart agriculture: Digitalizing the entire agriculture chain from the field to production, up to the management of national and international funds.*** *Ed. Engineering, Italy*, disponible à https://h2020-demeter.eu/smart-agriculture-agriculture-4-0-the-digital-transformation-of-the-agricultural-sector/.

Scholz, R. W., Bartelsman, E.J., Diefenbach, S. , Franke, L., Grunwald, A., Helbing, D., Hill, R., Hilty, L., Höjer, M., Klauser, S., Montag, C., Parycek, P., Prote, J.P., Renn, O., Reichel, A., Schuh, G., Steiner, G., Viale Pereira, G. (2018) ***Unintended Side Effects of the Digital Transition: European Scientists' Messages from a Proposition-Based Expert Round Table.*** *Sustainability*, 10, 2001.

The Hale Group & LSC (2014) ***Digital Transformation of Row Crop Agriculture.*** *A Report to the Iowa AgState Group*, 27 p., disponible à https://www.iasoybeans.com/pdfs/AgStateExecutiveSummary.pdf

CHAPTER 2

Bai, J., Seale, J.L., Jr and Wahl, T.I. (2020) ***Meat demand in China: to include or not to include meat away from home?*** *Aust J Agric Resour Econ*, 64: 150-170.

Bergez, J.-E., Audouin, E., Therond, O. (2019) ***Agroecological Transitions: From Theory to Practice in Local Participatory Design,*** *Springer International Publishing*, XVI, 335 p.

Brown, L. R. (2012) ***Full Planet, Empty Plates*** *– The New Geopolitics of Food Scarcity, W. W. Norton & Co, New-york & London.*

Caquet, T., Gascuel, C., Tixier-Boichard, M. (2020) ***Agroécologie : des recherches pour la transition des filières et des territoires.*** Éd Quae, Collection : Matière à débattre et décider, 104 p.

Charrier, F., Mourad, H., Barbier, M. (2020) ***Rendre l'ingérable gérable par la transformation collective de la situation de gestion : étude du cas de la gestion d'une maladie animale en Corse.*** *Gérer et Comprendre. Annales des Mines,* 139, 33-45.

CITEPA (2018). ***Rapport Secten, Gaz à effet de serre et polluants atmosphériques, Bilan des émissions en France de 1990 à 2017.*** https://www.citepa.org/fr/secten/;

FAO, FIDA, OMS, PAM, UNICEF. (2017) ***L'état de la sécurité alimentaire et de la nutrition dans le monde 2017. Renforcer la résilience pour favoriser la paix et la sécurité alimentaire*** Rome, FAO.

FAO (2019a) ***The State of the World's Biodiversity for Food and Agriculture***, Bélanger, J. & Pilling, D. (eds.). *FAO Commission on Genetic Resources for Food and Agriculture Assessments.* FAO, Rome. 572 p.

FAO (2019b). ***La situation mondiale de l'alimentation et de l'agriculture 2019. Aller plus loin dans la réduction des pertes et gaspillages de denrées alimentaires.*** FAO, Rome.

Gasselin, P., Choisis, J.P., Petit, S., Purseigle, F., Zasser, S. (2015). ***L'agriculture en famille : travailler, réinventer, transmettre.*** EDP Sciences.

Gasselin, P., Lardon, S., Cerdan, C., Loudiyi, S., Sautier, D., Van der Ploeg, J. D. (2021) ***Coexistence et confrontation des modèles agricoles et alimentaires : un nouveau paradigme du développement territorial.*** Éditions Quae.

Geels, F.W. (2002) ***Technological transitions as evolutionary configuration processes: A multi-level perspective and a case-study.*** *Res. Policy*, 31, 1257-1274.

Ghai, D. (2003) ***Travail décent : concept et indicateurs.*** *Revue internationale du Travail*, 42 (2), 121 – 157.

Gibbs, E.P.J (2014) ***The evolution of One Health: a decade of progress and challenges for the future.*** *Veterinary Record*, 174(4), 85-91.

GIEC (2014). ***Contribution du groupe de travail II au cinquième rapport d'évaluation du groupe d'experts intergouvernemental sur l'évolution du climat.*** Disponible le 20-04-2021 sur https://repository.uneca.org/handle/10855/23228.

Hervieu, B., Purseigle, F. (2013). ***Sociologie des mondes agricoles.*** Paris : Armand Colin.

HLPE (2016). ***Sustainable agricultural development for food security and nutrition: what roles for livestock?*** *A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.* Rome, *Italy.* http://www.fao.org/3/a-i5795e.pdf.

Porcher, J. (2011) ***Vivre avec les animaux. Une utopie pour le XXIIème siècle.*** Éd La Découverte/Mauss.

Sánchez-Bayo, F., Wyckhuys, K. A.G. (2019) ***Worldwide decline of the entomofauna: A review of its drivers,*** *Biological Conservation*, 232, 8-27.

Therond, O., Duru, M., Roger-Estrade, J., Richard, G. (2017) ***A new analytical framework of farming system and agriculture model diversities: a review. Agronomy for Sustainable Development,*** 37, 21.

UNESCO (2019). ***Rapport mondial des Nations Unies sur la mise en valeur des ressources en eau 2019 : ne laisser personne pour compte.*** Disponible le 20-04-2021 sur https://unesdoc.unesco.org/ark:/48223/pf0000367303_fre.locale=fr.

Zinsstag, J., Schellin, E., Waltner-Toews, D., Whittaker, M., Tanner, M. (2015) ***One Health: The Theory and Practice of Integrated Health Approaches,*** *CAB International, Wallingford, UK.*

CHAPTER 3

Abdullah, A., Hussain, A. (2006) ***Data mining a new pilot agriculture extension data warehouse.*** *Journal of Research and Practice in Information Technology* 38.3, 229.

Akplogan, M., de Givry, S., Metivier, J.P., Quesnel, G.; Joannon, A., Garcia, F. (2013) ***Solving the Crop Allocation Problem using Hard and Soft Constraints.*** *RAIRO – Operations Research, EDP Sciences*, 47 (2), 151-172.

Aubin, S., Caracciolo, C., Zervas, P., Aventurier, P., Buche, P., Ferreyra, A., Xian, G., Jonquet, C., Koukourikos, A., Pesce, V., Pierozzi, I.J., Roussey, C., Toulet A., Villa, F., Whitehead, B., Zhang, X., Antezana, E. (2017) ***Landscaping the Use of Semantics to Enhance the Interoperability of Agricultural Data****. RDA Agrisemantics Working Group.*

Bahri, O., Mourhir, A., Papageorgiou, E.I. (2020) ***Integrating fuzzy cognitive maps and multi-agent systems for sustainable agriculture.*** Euro-Mediterr J *Environ Integr* 5, 7.

Bahrin, M. A. K., Othman, M. F., Azli, N. N., Talib,M. F. (2016) ***Industry 4.0: A review on industrial automation and robotic.*** *Jurnal Teknologi*, 78 (6 13), 137–143.

Benchini, L., Stöckle, C.O. (2007) ***Integration of a cropping systems simulation model and a relational database for simple farm-scale analyses.*** *Agronomy Journal*, 99 (5), 1226-1237.

Bédard, Y., Rivest, S., Proulx, M.-J. (2007) ***Spatial online analytical processing (SOLAP): Concepts, architectures, and solutions from a geomatics engineering perspective. Data warehouses and OLAP: concepts, architectures and solutions.*** *IGI Global*, 298-319.

Bellon-Maurel, V., Neveu, P., Termier, A., Garcia, F. (2018) ***Le Big Data en agriculture. Annales des Mines – Enjeux numériques 2, 77-81.*** http://annales.org/enjeux-numeriques/2018/resumes/juin/16-en-resum-FR-AN-juin-2018.html .

Bergerman, M., Billingsley, J., Reid, J., van Henten, E. (2016) ***Robotics in Agriculture and Forestry, in Springer Handbook of Robotics,*** *Springer International Publishing*, 1463–1492.

Bergez, J.E., Eigenraam, M., Garcia, F. (2001) ***Comparison between dynamic programming and reinforcement learning: a case study on maize irrigation management,*** in: *Proceedings of the 3rd European Conference on Information Technology in Agriculture (EFITA01),* Montpellier, pp. 343–348.

Bermeo-Almeida, O., Cardenas-Rodriguez, M., Samaniego-Cobo, T., Ferruzola-Gómez, E., Cabezas-Cabezas, R., Bazán-Vera, W. (2018) ***Blockchain in Agriculture:*** *A Systematic Literature Review.* (eds) ***Technologies and Innovation.*** CITI 2018. *Communications in Computer and Information Science,* 883.

Blender, T., Buchner, T., Fernandez, B., Pichlmaier, B., Schlegel, C. (2016) ***Managing a Mobile Agricultural Robot Swarm for a seeding task,*** *in Industrial Electronics Society*, IECON 2016-*42nd Annual Conference of the IEEE*, 6879–6886.

Bommel, P., Bécu, N., Le Page, C., Bousquet, F., Cormas. (2015) ***An Agent-Based simulation platform for coupling human decisions with computerized dynamics. Simulation and Gaming in the Network Society.*** Volume 9 *of the series Translational Systems Sciences* pp 387-410. *Springer,* 2015.

Bouadi, T., Cordier, M.-O., Moreau, P., Quiniou, R., Salmon-Monviola, J., Gascuel-Odoux, C. (2017) ***A data warehouse to explore multidimensional simulated data from a spatially distributed agro-hydrological model to improve catchment nitrogen management.*** *Environmental Modelling and Software 97*, 229-242.

Boukhelifa, N., Bezerianos, A., Lutton, E. (2018) ***Evaluation of Interactive Machine Learning Systems.*** In: Zhou, J., Chen, F. (eds) *Human and Machine Learning Visible, Explainable, Trustworthy and Transparent,* Springer, 341-360.

Borodin, V. (2014) ***Optimisation et simulation d'une chaîne logistique : application au secteur de l'agriculture,*** Thèse de doctorat de l'Université de Troyes.

Box, G. E. P., Jenkins, G. M., Reinsel, G. C., Ljung, G. M. (2015) ***Time Series Analysis: Forecasting and Control,*** *5th Edition. Published by John Wiley and Sons Inc.*

Brun-Laguna, K., Diedrichs, A.L., Dujovne, D., Taffernaberry, C., Leone, R., Vilajosana, X., Watteyne, T. (2018) ***Using SmartMesh IP in Smart Agriculture and Smart Building Applications.*** *Computer Communications*, 121, 83-90.

Bu, F., Wang, X. (2019) ***A smart agriculture IoT system based on deep reinforcement learning.*** *Future Generation Computer Systems*, 99, 500-507.

Casagli, F., Zuccaro, G., Bernard, O., Steyer, J.P., Ficara, E. (2021) ***ALBA: a comprehensive growth model to optimize algae-bacteria wastewater treatment in raceway ponds.*** *IWA Publishing Water Research*. 190.p 116734.

Carpentier, A., Gohin, A., Sckokai, P., Thomas, A. (2015) ***Economic modelling of agricultural production: past advances and new challenges.*** *Review of Agricultural and Environmental Studies*, 96 (1), 131-165.

Chandra, P., Gupta, M. K. (2018) ***Comprehensive survey on data warehousing research.*** *International Journal of Information Technology* 10.2, 217-224.

Charvat, K., Charvat Junior, K., Reznik, T., Lukas, V., Jedlicka, K., Palma, R., Berzins, R. (2018) ***Advanced Visualisation of Big Data for Agriculture as Part of Databio Development.*** *IEEE International Geoscience and Remote Sensing Symposium* (GARS), 2018, 415-418.

Chastant-Maillard, S., Saint-Dizier, M. (2016) ***Elevage de précision.*** Éditions La France Agricole, Paris. 254 p.

Chatelin, M.H., Aubry, C., Poussin, J.C., Meynard, J.M., Massé, J., Verjux, N., Gat,e Ph., Le Bris, X. (2005) ***DéciBlé, a software package forwheat crop management simulation.*** *Agricultural. Systems*, 83, 77–99.

Coquet, F., Mémin, J., Slominski, L. (2002) ***On non continuous dirichlet processes.*** *Journal of Theoretical Probability*, 16, 197–216.

Crespo, O., Bergez, J.-E., Garcia, F. (2010) ***Multiobjective optimization subject to uncertainty: Application to irrigation strategy management.*** *Computers and Electronics in Agriculture*, 74 (1), 145-154.

Daudé, E. (2004) ***Apports de la simulation multi-agents à l'étude des processus de diffusion,*** Cybergeo : *European Journal of Geography*, 2004.

DeAngelis, D.L., Diaz, S.G. (2019) ***Decision-making in agent-based Modeling: A current review and future prospectus.*** *Frontiers in Ecology and Evolution*, 6 (article 237).

Drewniak, B., Song, J., Prell, J., Kotamarthi, V. R., Jacob, R. (2013) ***Modeling agriculture in the Community Land Model,*** Geosci. *Model Dev.*, 6, 495–515, https://doi.org/10.5194/gmd-6-495-2013.

Ezanno, P., Andraud, M., Beaunée, G., Hoch, T., Krebs, S., Rault, A., Touzeau, S., Vergu, E., Widgren, S. (2020) ***How mechanistic modelling supports decision making for the control of enzootic infectious diseases.*** *Elsevier Epidemics*, 32, 100398.

Fauvel, K., Masson, V., Fromont, E., Faverdin, P., Termier, A. (2019) ***Towards Sustainable Dairy Management*** – *A Machine Learning Enhanced Method for Estrus Detection.* KDD 2019, 3051-3059.

Ferreira, A.E., Ortiz, F., Costa, L.H.M.K, Foubert, B., Amadou, I., Mitton, N. (2020) ***A study of the LoRa signal propagation in forest, urban, and suburban environments.*** *Annals of Telecommunications* – annales des télécommunications, 75(7-8), 333-351.

Fishwick, P. (2007) ***Handbook of dynamic system modeling.*** Chapman & Hall/CRC *Computer and Information Science.*

Foubert, B., Mitton, N. (2019) https://hal.inria.fr/hal-02308015 ERCIM News, ERCIM, In press, pp.37-38.

Foubert, B., Mitton, N. (2021) ***Routing Over Multiple Technologies with RODENT.*** Percom 2021 (Demo) – *19th International Conference on Pervasive Computing and Communications*, Mar 2021, Kassel, *Germany.*

Gauthier, R., Largouët, C., Gaillard, C., Cloutier, L., Guay, F., Dourmad, J.Y. (2019) ***Dynamic modeling of nutrient use and individual requirements of lactating sows.*** *Journal of Animal Science*, 97(7), 2822–2836.

Garcia, F. (1999) ***Use of reinforcement learning and simulation to optimize wheat crop technical management,*** *Proceedings of the International Congress on Modelling and Simulation* (MODSIM'99) Hamilton, *New-Zealand*, pp 801-806.

Georgeff, M., Pell, B., Pollack, M., Tambe, M., Wooldridge, M. (1970) ***The Belief-Desire-Intention Model of Agency.*** *Lecture Notes in Computer Science.* 10.1007/3-540-49057-4_1.

Guastella, D. C. (2018) ***Ground Vehicle Navigation through Traversability Analysis of Outdoor Environments.*** *PHD thesis, Università degli Studi di Catania*, 143 p. http://dspace.unict.it/bitstream/10761/4143/1/GSTDCL91R14D960H-output_file.pdf.

Gosavi, A. (2015). ***Simulation-Based Optimization. Parametric Optimization Techniques and Reinforcement Learning.*** *Springer*, 508p.

Gros de Beler, A. (1998) ***Le Nil.*** Éditions Molière, Paris.

Guan, S., Nakamura, N., Shikanai, T. Okazaki, T., (2008) ***Hybrid Petri nets modeling for farm work flow.*** *Computers and Electronics in Agriculture*, 62 (2), 149-158.

Gutiérrez, R. (2008) ***Papas nativas desafiando al cambio climático: propuesta de adaptación tecnoló.*** *Soluciones Practicas*, 2008 - 80 pages.

Halachmi, I., Guarino, M., Bewley, J., Pastell, M. (2019) ***Smart Animal Agriculture: Application of real-time sensors to improve animal well-being and production.*** *Annual Review of Animal Biosciences*, 7, 403-425.

Hélias, A., Guerrin, F., Steyer, J.P. (2008) ***Using timed automata and model-checking to simulate material flow in agricultural production systems: Application to animal waste management.*** *Computers and Electronics in Agriculture*, 63 (2), 183-192.

Hill, A., Laneurit, J., Lenain, R., Lucet, E. (2020) ***Online gain setting method for path tracking using CMA-ES:*** *Application to off-road mobile robot control. IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS), 2020, pp. 7697-7702, doi: 10.1109/IROS45743.2020.9340830.

Huber, R., Bakker, M., Balmann, A., Berger, T., Bithell, M., Brown, C., Grêt-Regamey, A., Xiong, H., Bao Le, Q., Mack, G., Meyfroidt, P., Millington, J., Müller, B., Polhill, G., Sun, Z., Seidl, R., Troos, C., Finger, R. (2018) ***Representation of decision-making in European agricultural agent-based models,*** *Agricultural Systems*, 167, 143-160.

Hurley, B., O'Sullivan, B., Allouche, D., Katsirelos, G., Schiex, T., Zytnicki, M., de Givry, S. (2016) ***Multi-Language Evaluation of Exact Solvers in Graphical Model Discrete Optimization.*** *Constraints*, 21(3), 413-434.

Ienco, D., Ose, K., Weber, C. (2019) ***Towards combining Satellite Imagery and VGI for Urban LULC classification.*** JURSE, 1-4.

Jabbar, A., Hansen, K.M.F., Smith, M.L., Smith, L. N. (2017) ***Early and non-intrusive lameness detection in dairy cows using 3-dimensional video.*** *Biosystems Engineering*, 153, 63-69.

Jones, J.W., Antle, M., Basso, B., Boote, B.K., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, R., Wheeler, T.R. (2016) ***Brief history of agricultural systems modeling.*** *Agricultural Systems*, 155, 240–254.

Kaghazchi, A., Shahdany, S.M., Roozbahani, A. (2021) ***Simulation and evaluation of agricultural water distribution and delivery systems with a Hybrid Bayesian network model,*** *Agricultural Water Management,* 245, 106578.

Kaim, A., Cord, A.F., Volk, M. (2018) ***A review of multi-criteria optimization techniques for agricultural land use allocation.*** *Environmental Modelling & Software*, 105, 79-93.

Kamilaris, A., Prenafeta-Boldú, F. X. (2018) ***Deep learning in agriculture: A survey.*** *Computer and Electronics in Agriculture*, 147, 70-90.

Kamilaris, A., Fonts, A., Prenafeta-Boldú, F. X. (2019) ***The rise of blockchain technology in agriculture and food supply chains,*** *Trends in Food Science & Technology*, 91, 640-652.

Karim, F., Majumdar, S., Darabi, H., Harford, S. (2019) ***Multivariate LSTM-FCNs for Time Series Classification,*** *Neural Networks,* 116, 237–245.

Karlsson, I., Papapetrou, P., Boström, H. (2016) ***Generalized Random Shapelet Forests,*** *Data Mining and Knowledge Discovery,* 30(5), 1053–1085.

Knight, C.H. (2020) ***Review: Sensor techniques in ruminants: more than fitness trackers.*** *Animal*, 14 (S1), s187-s195.

Krid, M., Benamar, F., Lenain, R. (2017) ***A new explicit dynamic path tracking controller using generalized predictive control***. *International Journal of Control, Automation and Systems*, 15(1), 303-314.

Kubicek, P., Kozel, J., Stampach, R., Lukas, V. (2013) ***Prototyping the visualization of geographic and sensor data for agriculture.*** *Computers and Electronics in Agriculture,* 97, 83–91.

Kumar, R., Sinhg, J. (2003) ***Regional water management modeling for decision support in irrigated agriculture.*** *Journal of irrigation and drainage engineering*. 129 (6), 432-439.

Lambert, M.J., Sibiry Traoré, P.C., Blaes, X., Baret, P., Defourny, P. (2018) ***Estimating smallholder crops production at village level from Sentinel-2 time series in Mali's cotton belt.*** *Remote Sensing of Environment*, 216, 647.

Léger, B., Naud, O. (2009) ***Experimenting statecharts for multiple experts knowledge elicitation in agriculture.*** *Expert Systems with Applications*, 36(8), 11296-11303.

Li, J., Jiao, X., Jiang, H., Song, J., Chen, L. (2020) ***Optimization of Irrigation Scheduling for Maize in an Arid Oasis Based on Simulation–Optimization Model.*** *Agronomy, 10 (7), 935.*. https://doi.org/10.3390/agronomy10070935.

Li, L., Li, X., Chong, C., Wang, C.-H., Wang, X. (2020) ***A decision support framework for the design and operation of sustainable urban farming systems,*** *Journal of Cleaner Production*, 268, 121928.

Li, M., Fu. Q., Singh, V.P., Liu, D., Li, T. (2019) ***Stochastic multi-objective modeling for optimization of water-food-energy nexus of irrigated agriculture,*** *Advances in Water Resources*, 127, 209-224.

Lin, Y.P., Petway, J.R., Johnathen, A., Mukhtar, H., Liao, S.W., Chou, C.F., Ho, Y.F. (2017) ***Blockchain: The Evolutionary Next Step for ICT E-Agriculture,*** *Environments 4*, no. 3: 50.

S.M., Lee, S.I. (2017) ***A Unified Approach to Interpreting Model Predictions.*** NIPS, 4765-4774.

Manson, S., Jordan, N., Nelson, K., Brummel, R. (2016) ***Modeling the effect of social networks on adoption of multifunctional agriculture,*** *Environmental Modelling & Software*, 75, 388-401, ISSN 1364-8152.

Maqrot, S., de Givry, S., Quesnel, G., Tchamitchian, M. (2017) ***A Mixed Integer Programming Reformulation of the Mixed Fruit-Vegetable Crop Allocation Problem.*** In *30th International Conference on Industrial, Engineering, and Other Applications of Applied Intelligent Systems (IEA/AIE)*, 12 pages, Arras, France.

Martin, G., Martin-Clouaire, R., Rellier, J.-P., Duru, M. A. (2011) ***Simulation framework for the design of grassland-based beef-cattle farms.*** *Environmental Modelling & Software*, 26, 371-385. 2011.

Martin-Clouaire, R., Rellier, J.-P. (2004) ***Fondements ontologiques des systèmes pilotés,*** Tech. report, 2004, Rapport Interne UBIA-INRA, Toulouse-Auzeville (dernière version : juin 2012). https://hal.inrae.fr/hal-03153904/file/Ontol-Syst-pilot.pdf.

Martin-Clouaire, R., Rellier, J.-P. (2009) ***Modelling and simulating work practices in agriculture. International Journal of Metadata,*** *Semantics and Ontologies*, 4(1-2):42-53.

Martin-Clouaire, R., Rellier, J.-P., Paré, M., Voltz, M., and Biarnès, A. (2016) ***Modelling management practices in viticulture while considering resource limitations:*** *the Dhivine model.* PLoS ONE 11(3), 2016.

Martin-Clouaire, R. (2017) ***Modelling Operational DecisionMaking in Agriculture.*** *Agricultural Sciences*, 8, 527-544.

McKinion, J.M., Lemmon, H.E. (1985) ***Expert Systems for Agriculture. Computers and Electronics in Agriculture***, 1, 31-40.

Memmah, M.M., Lescourret, F., Yao, X., Lavigne, C. (2015) ***Metaheuristics for agricultural land use optimization.*** *A review. Agronomy for Sustainable. Developement*, 35, 975–998.

Mendel, Y.G. (1907) ***Recherche sur des hybrides végétaux.*** *Le bulletin scientifique de la France et de la Belgique*, tome 41, 371-419.

Millot, A., Mathonat, R., Cazabet, R., Boulicaut, J.F. (2020) ***Actionable subgroup discovery and urban farm optimization.*** *International Symposium on Intelligent Data Analysis (IDA). Apr 2020*, Konstanz, *Germany.*

Minet, J., Curnel, Y., Gobin, A., Goffart, J.P., Mélard, F., Tychon, B., Wellens, J., Defourny, P. (2017) ***Crowdsourcing for agricultural applications: A review of uses and opportunities for a farmsourcing approach,*** *Computers and Electronics in Agriculture*, 142, 126-138.

Minsky, H. P. (1965) ***Ph.D., The Role of Employment Policy,*** *Hyman P. Minsky Archive*. 270.

Moummadi, M., Abidar, R., Medromi, H. (2011) ***Generic model based on constraint programming and multi-agent system for M2M services and agricultural decision support.*** *International Conference on Multimedia Computing and Systems*, pp. 1-6.

Nada, A., Nasr, M., Hazman, M. (2014) ***Irrigation expert system for trees.*** *International Journal of Engineering and Innovative Technology (IJEIT)*, 3, 170–175.

Ndiaye, S.M. (1999) ***Apprentissage par renforcement en horizon fini: application à la génération de règles pour la Conduite de Culture,*** Thèse de doctorat de l'Université de Toulouse 3.

O'Leary, D.E. (2008) ***A multilingual knowledge management system: A case study of FAO and WAICENT.*** *Decision Support Systems*, 45 (3), 641-666.

Padhy, N., Satapathy, S.C. (2020) ***Digital Advancement in AgriTech by Using Evolutionary Techniques.*** *In:* Satapathy S., Bhateja V., Mohanty J., Udgata S. (eds) *Smart Intelligent Computing and Applications. Smart Innovation, Systems and Technologies*, vol 160. *Springer, Singapore.*

Palpanas, T. (2000) ***Knowledge discovery in data warehouses.*** *ACM Sigmod Record 29.3*, 88-100.

Pappu, N., Sarkar, R., Prabhakar, T. V. (2010) ***Agropedia: Humanization of Agricultural Knowledge.*** *IEEE Internet Computing*, 14 (5), 57-59.

Peart, R.M., Curry R.B. (1978) ***Agricultural Systems Modelling and Simulation.*** Marcel Dekker, New York. CRC Press. 728 pages. ISBN 9780367400859.

Picault, S., Huang, Y.L., Sicard, V., Arnoux, S., Beaunée, G., Ezanno, P. (2019) ***EMULSION: Transparent and flexible multiscale stochastic models in human, animal and plant epidemiology.*** *PLOS Computational Biology 15(9)*, e1007342.

Pierpaoli, E., Carlia, G., Pignattia, E., Canavaria, M. (2013) ***Drivers of Precision Agriculture Technologies Adoption:*** *A Literature Review Procedia Technology 8* (2013) 61 – 69 *doi:* 10.1016/j.protcy.2013.11.010.

Plà-Aragonés, L. M. (Editor) (2015) ***Handbook of Operations Research in Agriculture and the Agri-Food Industry.*** *International Series in Operations Research & Management Science book series* (ISOR, volume 224), 464 p.

Plaisant, C. (2004) ***The challenge of information visualization evaluation. In: Proceedings of the Working Conference on Advanced Visual Interfaces,*** *ACM New York, NY, USA*, pp. 109–16.

Pommier, C., Michotey, C., Cornut, G., Roumet, P., Duchêne, E., Flores, R., Lebreton, A., Alaux, M., Durand, S., Kimmel, E., Letellier, T., Merceron, G., Laine, M., Guerche, C., Loaec, M., Steinbach, D., Laporte, M.A., Arnaud, E., Quesneville, H., Adam-Blondon, A.F. (2019) ***Applying FAIR Principles to Plant Phenotypic Data Management in GnpIS.*** *Plant Phenomics 2019*, 1–15.

Reyniers, F. (1996) ***Principes d'une modélisation biophysique des exploitations.*** *In:* Couplage de modèles en agriculture. Reyniers François (ed.), Benoit-Cattin Michel (ed.). CIRAD-CA. Montpellier : CIRAD, 19-21. (Colloques) ISBN 2-87614-255-4 Couplages de modèles en agriculture, Montpellier, France, 14 Juin 1995/15 Juin 1995.

Ribeiro, M.T., Singh, S., Guestrin, C. (2016) ***"Why Should I Trust You?":*** *Explaining the Predictions of Any Classifier.* KDD 1135-1144.

Rio, A., Maurel, Y., Bugni ,Y., Barais, O. (2019) ***Benefits of Energy Management Systems on local energy efficiency, an agricultural case study.*** *Proceedings of IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm 2019), Beijing, China*, p1-7.

Roussey, C., Chanet, J.P., Soulignc, V., Bernard, S. (2011) ***Les ontologies en agriculture.*** Instrumentation Mesure Metrologie 16. 55-84.

Roussey, C., Bernard, S., Pinet, F., Reboud, X., Cellier, I., Sivadon, I., Simonneau, A., Bourigault, A.L. (2017) ***A methodology for the publication of agricultural alert bulletins as LOD.*** *Computers and Electronics in Agriculture.* 142, 632-650.

Ruiz-Garcia, L., Lunadei, L. (2011) ***The role of RFID in agriculture: Applications, limitations and challenges.*** *Computers and Electronics in Agriculture*, 79, 42-50.

Sakoe, H., Chiba, S. (1978) ***Dynamic programming algorithm optimization for spoken word recognition.*** *IEEE Transactions on Acoustics, Speech and Signal Processing*, 26(1), 43–49.

Salaun, M.C., Bugeon, J., Fatet, A., Hue, I., Hurtaud, C., Nédellec, C., Vernet, J., Reichstadt, M., Le Bail, P.Y. (2018). ***Un outil au service de la standardisation des bases de données: les ontologies ATOL/EOL.*** Cahier des Cahier des Techniques de l'INRA, INRA, 2018, 93, 1-7.

Salim, C., Mitton, N. (2020) ***K-Predictions Based Data Reduction Approach in WSN for Smart Agriculture.*** *Computing, Springer Verlag*, 103 (3), 509-532..

Schmitt, M., Zhu, X. (2016) ***Data Fusion and Remote Sensing: An ever-growing relationship.*** *IEEE Geoscience and Remote Sensing Magazine*, 4(4), 6-23.

Sini, M., Lauser, B., Salokhe, G., Keizer, J., Katz, S. (2008) ***The AGROVOC Concept Server: rationale, goals and usage.*** *Library Review,* 57 (3), 200-212(13).

Soulignac, V., Pinet, F., Lambert, E., Guichard, L., Trouche, L., Aubin, S., (2017) ***GECO, the French Web-based application for knowledge management in agroecology.*** *Computers and Electronics in Agriculture*, 162, 1050-1056.

Spanaki, K., Sivarajah, U., Fakhimi, M., Despoudi, S., Irani, Z. (2021) ***Disruptive technologies in agricultural operations: a systematic review of AI-driven AgriTech research.*** *Ann Oper Res* 308 (2), 1-34.

Stefas, N., Bayram, H., Isler, V. (2019) ***Vision-based monitoring of orchards with UAVs.*** *Computers and Electronics in Agriculture*, 163, 104814.

Street, D. (1990). ***Fisher's Contributions to Agricultural Statistics.*** *Biometrics*, 46(4), 937-945.

Taillandier, P., Vo, D.A., Amouroux, E., Drogoul, A. (2010) ***GAMA: a simulation platform that integrates geographical information data, agent-based modeling and multi-scale control.*** *International Conference on Principles and Practice of Multi-Agent Systems.* 242-258.

Taghikhah, F., Voinov, A., Shukla, N., Filatova, T., Anufriev, M. (2021) ***Integrated modeling of extended agro-food supply chains: A systems approach,*** *European Journal of Operational Research,* 288 (3), 852-868.

Tonda, A., Boukhelifa, N., Chabin, T., Barnabe, M., Génot, B., Lutton, E., Perrot, N. (2018) ***Interactive Machine Learning for Applications in Food Science.*** *Human and Machine Learning*, 19.

Tourrette, T., Lenain, R., Rouveure, R., Solatges, T. (2017) ***Tracking footprints for agricultural applications: a low cost lidar approach,*** *workshop on Agricultural Robotics,* Vancouver.

Trépos, R., Lemarié, S., Raynal, H., Morison, M., Couture, S., Garcia, F. (2014) ***Apprentissage par renforcement pour l'optimisation de la conduite de culture du colza.*** *Presented at JFPDA'14.* Journées Francophones Planification, Décision, Apprentissage pour la conduite de système, Liège, BEL (2014-05-12 - 2014- 05-13).

Tse, C., Barkema, H., DeVries, T., Rushen, J., Pajor, E. (2018) ***Impact of automatic milking systems on dairy cattle producers' reports of milking labour management, milk production and milk quality.*** *Animal*, 12 (12), 2649–2656.

Varenne, F., Silberstein, M. (2013). ***Modéliser et simuler. Epistémologie pratique de la modélisation et de la simulation.*** Tome 1. Vol. 1. Collection : Sciences & philosophie.

Vespier, U., Knobbe, A.J., Nijssen, S., Vanschoren, J. (2012) ***MDL-Based Analysis of Time Series at Multiple Time-Scales.*** ECML/PKDD (2) 371-386.

Wachowiak, M.P., Walters, D.F., Kovac, J.M., Wachowiak-Smolíková, R. (2017) ***Visual analytics and remote sensing imagery to support community-based research for precision agriculture in emerging areas.*** *Computers and Electronics in Agriculture*, 143, 149-164.

Wolf, P., Ropertz, T., Feldmann, P., Berns, K. (2019) ***Combining Onthologies and Behavior-based Control for Aware Navigation in Challenging Off-road Environments.*** *In ICINCO (2) Proceedings of the 16th International Conference on Informatics in Control, Automation and Robotics*, Prague, *Czech Republic* (pp. 135-146).

Xiao, G., Calvanese, D., Kontchakov, R., Lembo, D., Poggi, A., Rosati, R., Zakharyaschev, M. (2018) ***Ontology-Based Data Access: A Survey.*** IJCAI, 5511-5519.

Yandun, F. J., Gregorio López, E., Rosell Polo, J. R., Torres-Torriti, M., & Auat Cheein, F. A. (2017) ***Terrain classification using ToF sensors for the enhancement of agricultural machinery traversability.*** *Journal of Terramechanics*, 76 1-13.

Zabala, J., Martínez-Paz, J., Alcon, F. (2021) ***A comprehensive approach for agroecosystem services and disservices valuation,*** *Science of The Total Environment,* 768, 144859.

Zhao, J.C., Zhang, J.U., Feng, Y. and Guo, J.X. (2010) ***The study and application of the IOT technology in agriculture,*** *International Conference on Computer Science and Information Technology*, Chengdu, 462-465.

Zhu, X.X., Tuia, D., Mou, L., Xia, G., Zhang, L., Xu, F., Fraundorfer, F. (2017) ***Deep Learning in Remote Sensing: A Comprehensive Review and List of Resources.*** *IEEE Geoscience and Remote Sensing Magazine*, 5 (4), 8-36.

Zeigler, B. P., Praehofer, H. T., Kim, G. (2000) ***Theory of Modeling and Simulation.*** *2nd ed. Orlando, FL, USA: Academic Press.*

Zelinka, I., Snasael, V. and Abraham, A. (Editor) (2013) ***Handbook of Optimization: From Classical to Modern Approach*** (*Intelligent Systems Reference Library*, 38), *Springer*, 1112 p.

CHAPTER 4

Adams, M.L., Cook, S.E. (1997) ***Methods of on-farm experimentation using precision agriculture technology*** *– American Society of Agricultural Engineers 1, Proceedings of the 1997 ASAE Annual International Meeting. Part 1, Minneapolis (MN, USA) 10-14 August 1997;* Code *48254*; 10p.

Altieri, M.A. (1989) ***Agroecology: A new research and development paradigm for world agriculture Agriculture, Ecosystems & Environment,*** 27 (1–4), 37-46.

Altieri, M.A., Funes-Monzote, F.R., Petersen, P. (2012) ***Agroecologically Efficient Agricultural Systems for Smallholder Farmers: Contributions to Food Sovereignty.*** *Agronomy for Sustainable Development*, 32, 1–13.

Anderson, C. (2012) ***Makers : la nouvelle révolution industrielle,*** Paris, Pearson, 309 p.

ANRT (2018) ***Pour une politique industrielle du numérique,*** Livre blanc. 56 p. disponible sur politique-industrielle-numerique_futuris-anrt-web.pdf.

Antle, J.M., Basso, B., Conant, R.T., Godfray, H.C.J., Jones, J.W., Herrero, M., Howitt, R.E., Keating, B.A., Munoz-Carpena, R., Rosenzweig, C., Tittonell, P., Wheeler, T.R. (2017) *Towards a new generation of agricultural system data, models and knowledge products: Design and improvement.* *Agricultural Systems 155*, 255–268.

Banque Mondiale, 2019, *Future of Food: Harnessing Digital Technologies to Improve Food System Outcomes.* *World Bank, Washington, DC*, 44 pages. https://openknowledge.worldbank.org/handle/10986/31565.

Barreteau, O. (2003) *Our companion modelling approach.* *Journal of Artificial Societies and Social Simulation.* 6 (2), 8 p.

Bécu, N., Neef, A., Schreinemachers, P., Sangkapitux, C. (2008) *Participatory computer simulation to support collective decision-making: potential and limits of stakeholder involvement.* *Land Use Policy*, 25 (4), 498-509.

Bellon-Maurel, V., Huyghe, C. (2016) *L'innovation technologique dans l'agriculture.* Géoéconomie 80 – mai/juin 2016, 159-180.

Bellon-Maurel, V., Neveu, P., Termier, A., Garcia, F. (2018) *Le* Big Data *en agriculture.* Annales des Mines – Enjeux numériques 2, 77-81.

Bellon-Maurel, V., Short, M.D., Roux, P., Schulz, M., Peters, G.M. (2014) *Streamlining life cycle inventory data generation in agriculture using traceability data and information and communication technologies* – *Part I: Concepts and technical basis, Journal of Cleaner Production*, 69, 60-66.

Bellon-Maurel, V., Peters, G., Clermidy, S., Frizarin, G., Sinfort, C., Ojeda, H., Roux, P., Short, M. (2015) *Streamlining life cycle inventory data generation in agriculture using traceability data and information and communication technologies Part II:* *Application to viticulture. Journal of Cleaner Production.* 87 (1), 119-129.

Benjamin, M., Yik, S. (2019) *Precision livestock farming in swine welfare: a review for swine practitioners.* *Animals*, 9, 133.

Bentley, J.W., Van Mele, P., Barres, N.F., Okry, F., Wanvoeke, J. (2019) S*mallholders download and share videos from the Internet to learn about sustainable agriculture.* *International Journal of Agricultural Sustainability*, 17 (1), 92-107.

Bergez, J.-E., Soulignac, V., Pinet, F., Gobert, J. (2016) ***Workshop 4.3: ICT to help on participatory approaches for the agroecological transition of agriculture, in Social and Technological Transformation of Farming Systems: Diverging and Converging Pathways.*** *Proceedings of the 12th European IFSA Symposium, 12th - 15th July 2016 at Harper Adams University, United Kingdom*, Volume 2, Andrew Wilcox and Karen Mills (Eds.).

Bergez, J.-E., Therond, O.(2019) Introduction in Bergez, J.-E., Audouin, E., Therond, O., Eds. (2019) ***Agroecological Transitions: From Theory to Practice in Local Participatory Design,*** *Springer (Open)*, https://doi.org/10.1007/978-3-030-01953-2_1, 335 pp., pp 3-12.

Bioteau, T., Béline, F., Laurent, F., Girault, R., Tretyakov, O., Boret, F., Balynska, M. (2013) ***Analyse spatialisée pour l'aide à la planification des projets de méthanisation collective,*** Sciences Eaux & Territoires 3 (12), 34-41.

Biradar, C.M., Ghosh, S., Löw, F., Singh, R., Chandna, P., Sarker, A., Sahoo, R.N., Swain, N., Choudhury, G., Agrawal, S., Rizvi, N., El-Shamaa, K., Atassi, L., Dong, J., Gaur, A., Wery, J. (2019) ***Geo*** **big data** ***and digital augmentation for accelerating agroecological intensification in drylands.*** *2019 ISPRS-GEOGLAM-ISRS Joint International Workshop on Earth Observations for Agricultural Monitoring; New Delhi (India)* 18-20 Feb 2019, 42 (*Issue 3*/W6) 545-548. *Code* 150236.

Bonnet, P., Faye, E., Roche, M. (2019). ***Éviter une valorisation technologique et économique asymétrique des*** **big data.** Wageningen: SPORE, CTA, 2 pages. https://spore.cta.int/fr/opinions/article/eviter-une-valorisation-technologique-et-economique-asymetrique-des-big-data-sid0726bd8f1-b891-47fc-8993-87861c5806dd.

Bonny, S. (2017). ***High-tech agriculture or agroecology for tomorrow's agriculture?*** *Harvard College Review of Environment & Society*, 2017, 4 (*Spring 2017*), pp.28-34.

Brydegaard, M., Gebru, A., Svanberg S. (2014) ***Super Resolution Laser Radar with Blinking Atmospheric Particles — Application to Interacting Flying Insects.*** **Progress** *In Electromagnetics Research*, 147, 141–151.

Calvet-Mir, L., Benyei, P., Aceituno-Mata, L., Pardo-de-Santayana, M., López-García, D., Carrascosa-García, M., Perdomo-Molina, A., Reyes-García, V. (2018) ***The contribution of traditional agroecological knowledge as a digital commons to agroecological transitions: The case of the CONECT-e platform.*** *Sustainability (Switzerland) 10* (9), 3214.

Caquet, T., Gascuel, C., Tixier-Boichard, M. Eds. (2020) ***Agroécologie : des recherches pour la transition des filières et des territoires.*** Ed Quae, Collection : Matière à débattre et décider, 104 p.

Chastant-Maillard, S., Saint-Dizier, M. (2016) ***Élevage de précision.*** Éditions La France Agricole, Paris, 270 p.

Chowdhary, G., Gazzola, M., Krishnan, G., Soman, C., Lovell, S. (2019) ***Soft Robotics as an Enabling Technology for Agroforestry Practice and Research.*** *Sustainability*, 11, 6751.

Claquin, P., Martin, A., Deram, C., Bidaud, F., Delgoulet, E., Gassie, J., Hérault, B. (2017) ***MOND'Alim 2030, panorama prospectif de la mondialisation des systèmes alimentaires,*** Paris, La Documentation française, 228 p.

Cloet, E., Brocard, V., Lessire, F., Guiocheau, S. (2017) ***Maximizing grazing with a mobile milking robot. In Precision Livestock Farming*** '17, 28-34. Disponible sur demande à: https://orbi.uliege.be/handle/2268/229020.

Cook, S., Cock, J., Oberthür T., Fisher, M. (2013) ***On farm experimentation.*** *Better Crops/Vol. 97* (4), pp.16-20.

Deichmann, U., Goyal, A., Mishra, D. (2016) ***Will Digital Technologies Transform Agriculture in Developing Countries ?*** *Policy Research Working Paper;No. 7669. World Bank, Washington, DC. © World Bank.* https://openknowledge.worldbank.org/handle/10986/24507.

De Leeuw, J., Vrieling, A., Shee, A., Atzberger, C., Hadgu, M.K., Biradar, M.C., Keah, H., Turvey, C. (2014) ***The potential and uptake of remote sensing in insurance: a review.*** *Remote Sensors*, 6, 10888-10912.

Della Chiesa, S., la Cecilia, D., Genova, G., Balotti, A., Thalheimer, M., Tappeiner U., Niedrist, G. (2019) ***Farmers as data sources: Cooperative framework for mapping soil properties for permanent crops in South Tyrol*** (*Northern Italy*). Geoderma, (342), 93-105.

Dhiab, H., Labarthe, P., Laurent, C. (2020). ***How the performance rationales of organisations providing farm advice explain persistent difficulties in addressing societal goals in agriculture.*** *Food Policy*, 101914.

Di Salvo, C. (2014) ***Critical Making as Materializing the Politics of Design.*** *The Information Society*, 30, 96–105.

Divya, B., Santhi, M. (2019) ***SVM-based pest classification in agriculture field.*** *International Journal of Recent Technology and Engineering*, 7 (5) 150-155.

Duru, M., Therond, O., Fares, M. (2015) ***Designing agroecological transitions: a review.*** *Agron Sustain Dev. 35*, 1237–1257.

El Hassane, A., Kadiri, Z., Kuper, M., Quarouch, H. (2015) ***Composer avec l'État : voies d'engagement des jeunes diplômés dans l'agriculture au Maroc.*** Cahiers de l'Agriculture, 24 (6), 356-36.2.

Elijah, O., Rahman, T.A., Orikumhi, I., Leow, C.Y., Hindia, M.N. (2018) ***An Overview of Internet of Things (IoT) and Data Analytics in Agriculture: Benefits and Challenges.*** *IEEE Internet of Things Journal*, 5 (5), 3758-3773.

Enkel, E., Bogers, M., Chesbrough, H. (2020) ***Exploring open innovation in the digital age: A maturity model and future research directions.*** *R and D Management*, *50* (1), 161-168.

Falconnier, G.N., Descheemaeker, K., Mourik, T.A.V., Giller, K.E., (2016) ***Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali.*** *Field Crops Res.* 187, 113–126.

FAO (2020). ***Realizing the potential of digitalization to improve the agri-food system: Proposing a new International Digital Council for Food and Agriculture.*** *A concept note. IT Division.* Rome, *Food and Agriculture Organization of the United Nations.*

Fielke, S. J., Garrard, R., Jakku, E., Fleming, A., Wiseman, L., & Taylor, B. M. (2019) ***Conceptualising the DAIS: Implications of the "Digitalisation of Agricultural Innovation Systems" on technology and policy at multiple levels.*** *NJAS-Wageningen Journal of Life Sciences*, 90, 100296.

Fielke, S., Taylor, B., & Jakku, E. (2020) ***Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review.*** *Agricultural Systems*, 180, 102763.

Fountas, S., Carli, G., Sorensen, C. G., Tsiropoulos, Z., Cavalaris, C., Vatsanidou, A., Liakos, B., Canavari, M., Wiebensohn, J., Tisseyre, B. (2015) ***Farm management information systems: Current situation and future perspectives.*** *Computers and electronics in agriculture*, 115, 40-50.

Fournel, S., Rousseau, A.N., Laberge B. (2017) ***Rethinking environment control strategy of confined animal housing systems through precision livestock farming.*** *Biosystems Engineering*, 155, 96-123.

Galliano, D., Orozco, L. (2011) ***The determinants of electronic traceability adoption: a firm-level analysis of French agribusiness.*** *Agribusiness*, Wiley, 27 (3), 379-397.

Gardner, T.A., Benzi, M., Börner, J., Dawkins, E., Fick, S., Garrett, R., Godar, J., Grimard, A., Lake, S., Larsen, R.K., Mardas, N., Dermott, C.L.M., Meyfroidt, P., Osbeck, M., Persson, M., Sembres, T., Suavet, C., Strassburg, B., Wolvekamp, P. (2019) ***Transparency and sustainability in global commodity supply chains.*** *World Development*, 121, 163-177.

Ghahari, A., Newlands, N.K., Lyubchich, V., Gel, Y.R. (2019) ***Deep Learning at the Interface of Agricultural Insurance Risk and Spatio-Temporal Uncertainty in Weather Extremes.*** *North American Actuarial Journal*, 23 (4) 535-550.

Gopalakrishnan, P. K., Behdad, S. (2019) ***A Conceptual Framework for Using Videogrammetry in Blockchain Platforms for Food Supply Chain Traceability.*** *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 59223, 12..

Grieve, B.D., Duckett, T., Collison, M., Boyd, L., West, J., Yin, H., Arvin, F., Pearson, S. (2019) ***The challenges posed by global broadacre crops in delivering smart agri-robotic solutions: A fundamental rethink is required.*** *Global Food Security*, 23, 116-124.

Groot, J.C.J., Jellema, A., Rossing, W.A.H. (2010) ***Designing a hedgerow network in a multifunctional agricultural landscape: balancing trade-offs among ecological quality, landscape character and implementation costs.*** *European. Journal of Agronomy*, 32 (1) 112-119.

Groot, J.C.J., Oomen, G.J.M., Rossing, W.A.H. (2012) ***Multi-objective optimization and design of farming systems.*** *Agricultural Systems*, 110, 63-77.

Labarthe, P. (2009) ***Extension services and multifunctional agriculture. Lessons learnt from the French and Dutch contexts and approaches.*** *Journal of environmental management*, 90, S193-S202.

Halachmi, I., Guarino, M., Bewley, J.,Pastell, M. (2019) ***Smart Animal Agriculture: Application of real-time sensors to improve animal well-being and production,*** Annual *Review of Animal Biosciences*, 7, 403-425.

Ingrand, S. (2018) ***Opinion paper: "monitoring te salutant": combining digital sciences and agro-ecology to design multi-performant livestock farming systems.*** *Animal 12*, 2–3.

IPES-Food (2016) ***De l'uniformité et la diversité : Changer de paradigme pour passer de l'agriculture industrielle à des systèmes agroécologiques diversifiés.*** Rapport, Frison E.A. Eds., 110 p. http://www.ipes-food.org/_img/upload/files/UniformityToDiversity_FULL.pdf.

Jiménez, D., Pérez-Uribe, A., Satizábal, H., Barreto, M., Van Damme, P., Tomassini, M. (2008) ***A survey of artificial neural network-based modeling in agroecology.*** *Studies in Fuzziness and Soft Computing*, 226, 247-269.

Johannes, A., Picon, A., Alvarez-Gila, A., Echazarra, J., Rodriguez-Vaamonde, S., Navajas, A.D., Ortiz-Barredo, A. (2017) ***Automatic plant disease diagnosis using mobile capture devices, applied on a wheat use case,*** *Computers and Electronics in Agriculture*, 138, 200-209.

Jouanjean, M.A. (2019) ***Digital opportunities for trade in the agriculture and food sectors. OECD Food,*** *Agriculture and Fisheries 122.*

Kadish, D., Dulic, A. (2015) ***Crafting sustainability: approaching wicked environmental problems through high–low tech practice.*** *Digital Creativity 26(1)*, 65-81.

Klerkx, L., Jakku, E., Labarthe, P. (2019) ***A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda, NJAS*** – *Wageningen Journal of Life Sciences 90-91, nr* 100315.

Klerkx, L., Rose, D. (2020) ***Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?*** *Global Food Security, 24, nr 100347.*

Knight, C.H. (2020) ***Review: Sensor techniques in ruminants: more than fitness trackers.*** *Animal,* 14 (S1), s187-s195.

Kos, D., Kloppenburg, S. (2019) ***Digital technologies, hyper-transparency and smallholder farmer inclusion in global value chains.*** *Current Opinion in Environmental Sustainability*, 41, 56-63.

Leclère, M., Loyce, C., Jeuffroy, M.-H. (2018) ***Growing camelina as a second crop in France: a participatory design approach to produce actionable knowledge.*** *European Journal of Agronomy*, 101, 78–89.

Leibovici, P.E. (2015) ***La plate-forme, nouvelle frontière de l'économie.*** *Les Echos* 12 Nov 2015. Acc le 10 Aout 2020 sur https://www.lesechos.fr/2015/11/la-plate-forme-nouvelle-frontiere-de-leconomie-280276.

Lemeilleur, S., Allaire, G. (2020) ***Système participatif de garantie dans les labels du mouvement de l'agriculture biologiques. Une réappropriation des communs intellectuels,*** *Économie Rurale*, 365, Juillet-septembre, 7-26.

Lepenioti, K., Bousdekis, A., Apostolou, D., Mentzas, G. (2020) ***Prescriptive analytics: Literature review and research challenges.*** *International Journal of Information Management, 50,* 57–70.

Leveau, L., Bénel, A., Cahier, J.P., Pinet, F., Salembier, P., Soulignac, V., Bergez, J.E. (2019) ***Information and Communication Technology (ICT) and the Agroecological Transition.*** **In Bergez, J.-E., Audouin, E., Therond, O., Eds. (2019)** ***Agroecological Transitions: From Theory to Practice in Local Participatory Design,*** *Springer*, https://doi.org/10.1007/978-3-030-01953-2_1, 335 pp.

Li, N., Ren, Z., Li, D., Zeng, L. (2020) ***Review: Automated techniques for monitoring the behaviour and welfare of broilers and laying hens: Towards the goal of precision livestock farming.*** *Animal*, 14 (3), 617-625.

Lixi, M., Dahan, M. (2014) ***ICT as an Enabler of Transformation in Ethiopia.*** *World Bank, Washington, DC. © World Bank* https://openknowledge.worldbank.org/handle/10986/20076.

López, O., Martinez, M., Migallon, H., Malumbres, M., Bonastre, A., Serrano, J.J. (2012) ***Monitoring Pest Insect Traps by Means of Low-Power Image Sensor Technologies,*** *Sensors*, 12(11), 15801-15819.

Lowder, S. K., J. Skoet, et al. (2016) ***The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide.*** *World Development*, 87, 16-29.

Luvisi, A. (2016) ***Electronic identification technology for agriculture, plant, and food. A review.*** *Agronomy for sustainable development*, 36 (1), 1-14.

Mattia, C.M., Lovell, S.T., Davis, A. (2018) ***Identifying barriers and motivators for adoption of multifunctional perennial cropping systems by landowners in the Upper Sangamon River Watershed, Illinois.*** *Agroforestry Systems. 92(5)*, 1155-1169.

Messmer, J.G. (2013) ***Les circuits courts multiacteurs : émergence d'organisations innovantes dans les filières courtes alimentaires.*** Rapport INRA – MaR/S, 669p.

Meynard, J.-M. (2017) ***Agroecology, a new relationship to knowledge and innovation, OCL - Oilseeds and fats,*** *Crops and Lipids*, 24 (3), *Article number D303.*

Miah, J.H., Griffiths, A., McNeill, R., Halvorson, S. , Schenker, U., Espinoza-Orias, N., Morse, S. , Yang, A.D. (2018) ***A framework for increasing the availability of life cylce inventory data-based on the role of multinational companies.*** *International Journal of Life Cycle Analysis*, 23 (9), 1744-1760.

Milgroom, J., Bruil J., De Leeuwis C. (2016) ***Co-creation in the practice, science and movement of agroecology.*** *Farming Matters 32:6–8*, disponible à https://www.ileia.org/2016/03/23/editorial-co-creation-practice-science-movement-agroecology/.

Mol, A. P. J., Oosterveer, P. (2015) ***Certification of markets, markets of certificates: Tracing sustainability in global agro-food value chains.*** *Sustainability (Switzerland), 7(9)*, 12258–12278.

Molden, D. (2007) ***Water for Food, Water for Life: A Comprehensive Assessment of Water Management in agriculture.*** *International Water Management Institute, Earthscan, London*, 645 pp.

Moura, D.J., Silva, W.T., Naas, I.A., Tolón, Y.A., Lima, K.A.O., Vale, M.M. (2008) ***Real time computer stress monitoring of piglets using vocalization analysis.*** *Computers and Electronics in Agriculture*, 64 (1), 11-18.

Mul, M.F., Ploegaert, J.P.M., George, D.R., Meerburg, B.G., Dicke, M., Groot Koerkamp, P.W.G. (2016) ***Structured design of an automated monitoring tool for pest species.*** *Biosystems Engineering*, 151, 126-140.

Neethirajan, S. (2017) ***Recent advances in wearable sensors for animal health management.*** *Sensing and Bio-Sensing Research*, 12, 15-29.

OCDE (2011) ***Payer pour la biodiversité : améliorer l'efficacité coût des paiements pour services écosystémiques,*** Éditions OCDE, https://www.oecd.org/fr/env/ressources/46900333.pdf.

Panten, K., Bramley, R.G.V., Lark, R.M., Bishop, T.F.A. (2010) ***Enhancing the value of field experimentation through whole-of-block designs.*** *Precision Agriculture*, 11 (2) 198-213.

Pesche, D., Losch, B. Imbernon, J. (dir.) (2016) ***Une nouvelle ruralité émergente. Regards croisés sur les transformations rurales africaines.*** Atlas pour le Programme Rural Futures du NEPAD, deuxième édition revue et augmentée, Montpellier, Cirad, NEPAD, 76 p.

Pham, X., Stack, M. (2018) ***How data analytics is transforming agriculture.*** *Business Horizons*, 61(1) 125-133.

Piepho, H.-P., Richter, C., Spilke, J., Hartung, K., Kunick, A., Thöle, H. (2011) ***Statistical aspects of on-farm experimentation.*** *Crop and Pasture Science*, 62 (9) 721-735.

Pingali, P.L. (2012). ***Green revolution: impacts, limits, and the path ahead.*** *Proc. Natl. Acad. Sci. U. S. A, 109 (31)*, 12302–12308.

Prada, R., Prendinger, H., Yongyuth, P., Nakasoneb, A., Kawtrakulc, A. (2014) ***AgriVillage: A game to foster awareness of the environmental impact of agriculture,*** *Computers in Entertainment 12(2)*, 1-18.

Rao, K.N. (2010) ***Index based crop insurance.*** *Agriculture and Agricultural Science Procedia*, 1, 193-203.

Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Bachinger, J. (2020) ***Re-designing organic grain legume cropping systems using systems agronomy.*** *European Journal of Agronomy*, 112.

Renting, H., Oostindie, H., Laurent, C., Brunori, G., Barjolle, D., Jervell, A., Granberg, L., Heinonen, M. (2008) ***Multifunctionality of agricultural activities, changing rural identities and new institutional arrangements.*** *International Journal of Agricultural Resources, Governance and Ecology*, 7(4), 361-385.

Reynolds, D., Baret, F., Welcker, C., Bostrom, A., Ball, J., Cellini, F., Lorence, A., Chawade, A. Khafif, M., Noshita, K., Mueller-Linow, M., Zhou, J., Tardieu, F. (2019) ***What is cost-efficient phenotyping? Optimizing costs for different scenarios.*** *Plant Science,* Elsevier, 282, 14-22.

Rey-Valette, H., Pinto, M., Maurel, P., Chia, E., Guiheneuf, P.Y., Michel, L., Nougaredes, B., Soulard, C., Jarrige, F., Guillemot, C., Mate, M.S., Ollagnon, H., Delorme, G., Prouheze, N., Laurent, A., Suita, L.A., Bertrand, J., Dieudonne, C., Champorigaud, A., Barbe, E. (2011) ***Guide pour la mise en œuvre de la gouvernance en appui au développement durable des territoires,*** Montpellier, INRA Éditions. 155pp.

Rieutort, L. (2009) ***Dynamique rurales françaises et re-territorialisation de l'agriculture,*** *L'information géographique*, 73, 30-48.

Rotz, S., Duncan, E., Small, M., Botschner, J., Dara, R., Mosby, I., Reed, M., Fraser, E.D.G. (2019) ***The Politics of Digital Agricultural Technologies: A Preliminary Review.*** *Sociologia Ruralis*, 59 (2), 203-229.

Rowe, E., Stamp Dawkins, M., Gebhardt-Henrich, S.G. (2019) ***A systematic review of precision livestock farming in the poultry sector: is technology focussed on improving bird welfare?*** *Animals*, 9, 614.

Sharma Ghimire, P., Tripathee, L., Chen, P., Kang, S. (2019) ***Linking the conventional and emerging detection techniques for ambient bioaerosols: a review.*** *Reviews in Environmental Science and Biotechnology*, 18(3), 495-523.

Schmidt, P., Möhring, J., Koch, R.J., Piepho, H.-P. (2018) ***More, larger, simpler: how comparable are on-farm and on-station trials for cultivar evaluation ?*** *Crop Sciences, 58*, 1508–1518.

Schnebelin, E., Labarthe, P., Touzard J.M. (2021). ***How digitalisation interacts with ecologisation? Perspectives from actors of the French Agricultural Innovation System.*** *J. of Rural Studies,* 46, 599-610.

Schultz, A., Wieland, R., Lutze, G. (2000) ***Neural networks in agroecological modelling - Stylish application or helpful tool ?*** *Computers and Electronics in Agriculture*, 29 (1-2) 73-97.

Seaborn, K., Fels, D.I. (2015) ***Gamification in theory and action: A survey;*** *International Journal of Human Computer Studies*, 74, 14-31.

Shalloo, L., O'Donovan, M., Leso, L., Wener, J., Ruelle, E., Geoghegan, A., Delaby, L., O'Leary, N. (2018) ***Review: Grass-based dairy systems, data and precision technologies.*** *Animal*, 12 (S2), 262-271.

Speelman, E.N., García-Barrios, L.E., Groot, J.C.J., Tittonell, P. (2014) ***Gaming for smallholder participation in the design of more sustainable agricultural landscapes,*** *Agricultural Systems*, 126, 62-75.

Tirole, J. (2016) ***Économie du bien commun, Chap. 14 Quand le digital modifie la chaîne de valeur,*** Paris, PUF.

Tixier, P., Peyrard, N., Aubertot, J.-N., Gaba, S., Radoszycki, J., Caron-Lormier, G., Vinatier, F., Mollot, G., Sabbadin, R. (2013) ***Modelling interaction networks for enhanced ecosystem services in agroecosystems.*** *Advances in Ecological Research 49*, 437-480.

Tsan, M., Totapally, S., Hailu, M., Addom, B.K. (2019) ***The Digitalisation of African Agriculture Report,*** 2018-2019, CTA, https://www.cta.int/en/digitalisation/issue/the-digitalisation-of-african-agriculture-report-2018-2019-sid0d88610e2-d24e-4d6a-8257-455b43cf5ed6.

Tullo, E., Borgonovo, F., Grilli, G., Micheletti, A., Aletti, G., Lolli, S., Guarino, V.F.M. (2018) ***Application of an early warning to detect enteropathies in intensive broiler farming.*** *In:10th International Livestock Environment Symposium, ILES 2018; Omaha (United States)*, 25-27 September 2018, p. 2-6. https://doi.org/10.13031/iles.ILES18-073.

Van der Burg, S., Bogaardt, M.-J., Wolfert, S. (2019) ***Ethics of smart farming: current questions and directions for responsible innovation towards the future.*** *Njas -Wageningen J. Life Sci.* 90-91, 100289.

Van Hirtum, A., Berckmans, D. (2004) ***Objective recognition of cough sound as a biomarker for aerial pollutants.*** *Indoor Air 14*, 10–15.

Vanloqueren, G., Baret, P. (2009) ***How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations.*** *Research Policy*, 38, 971–983.

Vasconez, J.P., Kantor, G.A., Auat Cheein, F.A. (2019) ***Human–robot interaction in agriculture: A survey and current challenges.*** *Biosystems Engineering 179*, 35-48.

Veissier, I., Kling-Eveillard, F., Mialon, M.-M., Silberberg, M., De Boyer des Roches, A., Terlouw, C., Ledoux, D., Meunier, B., Hostiou, N. (2019) ***Élevage de précision et bien-être en élevage : la révolution numérique de l'agriculture permettra-t-elle de prendre en compte les besoins des animaux et des éleveurs.*** INRA Productions Animales, 32 (2), 281-290.

Vrieling, A., Meroni, M., Shee, A., Mude, A.G., Woodard, J., de Bie, C.A.J.M. (2014) ***Historical extension of operational NDVI products for livestock insurance in Kenya.*** *Int. J. Appl. Earth Obs. Geoinf. 28*, 238–251.

Vroege, W., Dalhaus, T., Finger, R. (2019) ***Index insurances for grasslands – A review for Europe and North-America.*** *Agricultural Systems*, 168, 101-111.

Wegener, J.K., Urso, L.M., von Hörsten, D., Minßen, T.F., Gaus, C.G. (2017) ***Developing new cropping systems – which innovative techniques are required?*** *Landtechnik,* 72(2), 91–100.

Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.J. (2017) Big Data *in smart farming–a review.* *Agricultural Systems*, 153, 69-80.

Wyckhuys, K.A.G., Bentley, J.W., Lie, R., Nghiem, L.T.P., Fredrix, M. (2018) *Maximizing farm-level uptake and diffusion of biological control innovations in today's digital era.* *BioControl,* 63 (1) 133-148.

Xin, H., Liu, K. (2017) *Precision livestock farming in egg production.* *Animals Frontiers,* 27 (1), 24-31.

CHAPTER 5

Allen, T. F. H., Tainter, J. A., & Hoekstra, T. W. (1999) *Supply-Side Sustainability.* *Systems Research and Behavioral Science,* 16(5), 403–427.

Arthur, WB. (1994) *Increasing returns and path dependence in the economy.* Ann Arbor, *Michigan: University of Michigan Press (Economics, Cognition, and Society)*, 224 p.

Blandin, M.-C. (2016) *100 millions de téléphones portables usagés : l'urgence d'une stratégie.* Rapport d'information n° 850 (2015-2016), mission d'information du Sénat.

Bos, J., Bovenkerk, B., Feindt, P., Dam, Y. (2018) *The Quantified Animal: Precision Livestock Farming and the Ethical Implications of Objectification.* *Food Ethics. 2.*

Bouissou, J. et Albert, E. (2021) *Bois, cuivre, puces électroniques... La planète touchée par une pénurie de biens.* *Le Monde*, 14 mai 2021.

Boullier, D. (2019) *Sociologie du numérique.* Paris : Armand Colin.

Bournigal, J.-M. (2014) *Définir ensemble le futur du secteur des agroéquipements.* Rapport de la mission Agroéquipements.

Bowler (1986) *Intensification, concentration and specialisation in agriculture: the case of the European Community.* *Geography 71 (1)*, 14-24.

Bronson, K., Knezevic, I. (2016) Big Data *in food and agriculture.* Big Data *& Society,* 3(1), 1-5.

Brue, S. L. (1993) *Retrospectives: The Law of Diminishing Returns.* *Journal of Economic Perspectives*, 7(3), 185–192.

Burton, R. J., Riley, M. (2018) ***Traditional Ecological Knowledge from the internet? The case of hay meadows in Europe.*** *Land Use Policy,* 70, 334-346.

Busse, M., Schwerdtner, W., Siebert, R., Doernberg, A., Kuntosch, A., König, B., Bokelmann, W. (2015) ***Analysis of animal monitoring technologies in Germany from an innovation system perspective.*** *Agricultural Systems*, 138, 55-65.

Carbonell, I. (2016) ***The ethics of*** **big data** ***in big agriculture.*** *Internet Policy Review*, 5(1), 1-13.

Carolan, M. (2020) ***Acting like an algorithm: digital farming platforms and the trajectories they (need not) lock-in.*** *Agriculture and Human Values*, 37 (4), 1041-1053.

Chambaz, G. (2019) ***The Evolutionary Dynamics of Societies: Critical Synthesis of the Work of J.A. Tainter et al. On Sustainability, Collapse, Resilience and Energy Transitions, Master's thesis.*** Université de Lausanne.

Clap, J., Ruder, S.-L. (2020) ***Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability*** **Global** ***Environmental*** **Politics,** 20 (3), 49–69.

David, P. (1985) ***Clio and the Economics of QWERTY.*** *The American Economic Review, Vol. 75, No. 2, Papers and Proceedings of the Ninety-Seventh Annual Meeting of the American Economic Association*, 332-337.

Deléage, E. (2013) ***Agricultures à l'épreuve de la modernisation.*** Paris, Éditions Quæ, « Synthèses », 95 p.

Delannoy, L., Longaretti, P.-Y., Murphy, D. et Prados, E. (2021). ***Peak oil and the low-carbon energy transition: a net energy perspective.*** *Applied Energy*, Elsevier, 304, 1-17..

Dhar, P. (2021) ***Cybersecurity Report: "Smart Farms" Are Hackable Farms,*** *in IEEE Spectrum – Risk Factor, March 15.* https://spectrum.ieee.org/riskfactor/telecom/security/cybersecurity-report-how-smart-farming-can-be-hacked.

Elhefnawy, N. (2004) ***Societal Complexity and Diminishing Returns in Security.*** *International Security*, 29(1), 152–174.

Elhefnawy, N. (2008) ***A Long-Term Trend Toward the Depletion of Fiscal-Macroeconomic Slack in the World Economy?*** *(SSRN Scholarly Paper ID 3182381). Social Science Research Network.*

Ellul, J. (1977) ***Le Système technicien.*** Paris, Calmann-Lévy.

Fielke, S., Taylor, B., Jakku, E. (2020) ***Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review.*** *Agricultural Systems*, 180, 102763.

Gupta, M., Abdelsalam, M., Khorsandroo, S., Mittal, S. (2020) ***Security and Privacy in Smart Farming: Challenges and Opportunities,*** *IEEE Access, 8,* 34564-34584.

Isaac, H., Pouyat, M. (2015) ***Les défis de l'agriculture connectée dans une société numérique. 16 propositions pour repenser la production, la distribution et la consommation alimentaires à l'ère du numérique.*** Livre Blanc Renaissance Numérique.

Javelle, A., Kazic, D., Tassin, J. (2021) ***Introduction au dossier Repenser Le Statut Des Plantes, La pensée écologique,*** Presses Universitaires de France.

Klerkx, L., Jakku, E., Labarthe, P. (2019) ***A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda.*** *NJAS-Wageningen Journal of Life Sciences*, 90.

Labarthe, P. (2010) ***Services immatériels et verrouillage technologique. Le cas du conseil technique aux agriculteurs.*** *Économies et sociétés*, 44(2), 173-96.

Lagneaux, S., Servais, O. (2014) ***De la traite robotisée au raid d'avatars. Incorporation et virtualisation.*** *Parcours anthropologiques*, 9, 73-101.

Larrère, C., Larrère, R. (1997) ***« Le contrat domestique »,*** *Le courrier de l'environnement*, n° 30 http://www7.inra.fr/dpenv/larrec30.htm.

Longuet, G. (2019) ***Le devoir de souveraineté numérique,*** Rapport fait au nom de la commission d'enquête du Sénat, n° 7 tome I (2019-2020).

Marquet, K., Combaz, J., Berthoud, F. (2019) ***Introduction aux impacts environnementaux du numérique.*** 1024, bulletin de la Société Informatique de France, 85-97.

Meuret, M., Tichit, M., Hostiou, N. (2013) ***Élevage et pâturage « de précision » : l'animal sous surveillance électronique.*** Courrier de l'environnement de l'INRA (63): 13–24.

Meynard, J.-M., Charrier, F., Fares, M., Le Bail, M., Magrini, M.B., Charlier, A., Messéan, A. (2018) ***Socio-technical lock-in hinders crop diversification in France.*** *Agronomy for Sustainable Development. 38*, 54.

Miles, C. (2019) ***The combine will tell the truth: On precision agriculture and algorithmic rationality.*** Big Data *& Society, 6(1).*

Mundler, P., Labarthe, P., Laurent, C. (2006) ***Les disparités d'accès au conseil. Le cas de la région Rhône-Alpes.*** Économie rurale. Agricultures, alimentations, territoires, (291), 26-41.

Pitron, G. (2018) ***La guerre des métaux rares. La face cachée de la transition énergétique et numérique.*** *Les Liens qui Libèrent*, 296 p.

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., Fraser, E. (2019) ***Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities.*** *Journal of Rural Studies*, 68, 112-122.

Schneider, I. (2020) ***Democratic Governance of Digital Platforms and Artificial Intelligence? Exploring Governance Models of China, the US, the EU and Mexico.*** JeDEM 12(1), 1-24.

Servigne, P. (2014) ***Nourrir l'Europe en temps de crise : Vers des systèmes alimentaires résilients.*** *Nature et progrès.*

Stiegler, B. (2015) ***La Société automatique : 1. L'avenir du travail,*** Fayard, 300 p.

Tainter, J. A. (1990) ***The Collapse of Complex Societies,*** *Cambridge University Press.*

Tainter, J. A. (2009) ***Complexity, collapse, and sustainable problem-solving. In K. W. Hippel (Ed.), Conflict Resolution*** Vol. 2, pp. 349–390. *Eolss Publishers.*

Tainter, J. A., Patzek, T. W. (2012) ***Drilling down: The Gulf oil debacle and our energy dilemma.*** *Copernicus Books and Springer Science+Business Media.*

Tainter, J. A. (2016) ***Agriculture and the energy-complexity spiral.*** *Behavioral and Brain Sciences,* 39, 37–38.

Wolf, S. A., Buttel, F. H. (1996) ***The political economy of precision farming.*** *American Journal of Agricultural Economics*, 78(5), 1269-1274.

CHAPTER 6

Académie des technologies (2021) ***Innovation dans les industries alimentaires : impacts de la révolution numérique.*** Rapport de l'académie des technologies, Paris, 110p.

Ahumada, O., Villalobos, J.R. (2009) ***Application of planning models in the agri-food supply chain: a review.*** *European Journal of Operational Research*, 196(1), 1–20.

Ahumada, O., Villalobos, J.R., Nicholas Mason, A. (2012) ***Tactical planning of the production and distribution of fresh agricultural products under uncertainty.*** *Agricultural Systems*, 112, 17-26.

Anderies, J.M., Mathias, J.D., Janssen M.A. (2019) ***Knowledge infrastructure and safe operating spaces in social–ecological systems.*** *Proceedings of the National Academy of Sciences*, 116 (12), 5277-5284.

ANRT (2018) ***Pour une politique industrielle du numérique,*** Livre blanc. 56 p. disponible sur politique-industrielle-numerique_futuris-anrt-web.pdf.

Arora, A., Athreye, S., Huang, C. (2016) ***The paradox of openness revisited: collaborative innovation and patenting by UK innovators.*** *Research Policy*, 45, 1352-1361.

Aubin, J.P. (1991) ***Viability Theory.*** *Birhaüser, Boston.*

Balaji Prabhu, B.V., Dakshayini, M. (2020) ***An effective multiple linear regression-based forecasting model for demand-based constructive farming.*** *International Journal of Web-Based Learning and Teaching Technologies,* 15 (2), 1-18.

Bergez, J.-E., Audouin, E., Therond, O., Eds. (2019) ***Agroecological Transitions: From Theory to Practice in Local Participatory Design,*** *Springer*, 335 pp. https://doi.org/10.1007/978-3-030-01953-2_1.

Berti, G., Mulligan, C. (2016) ***Competitiveness of Small Farms and Innovative Food Supply Chains: The Role of Food Hubs. Creating Sustainable Regional and Local Food Systems.*** *Sustainability*, 8 (7), 616, https://doi.org/10.3390/su8070616.

Besnard, P., Hunter, A. (2008) ***Elements of argumentation.*** *Cambridge: MIT press, 47..*

Biggs, R., Schlüter, M., Schoon, M.L. (2015) ***Principles for Building Resilience: Sustaining Ecosystem Services in Social–Ecological Systems.*** *Cambridge University Press*, 390.

Boukhelifa, N., Duke, D.J. (2009) ***Uncertainty visualization: why might it fail?*** CHI EA '09: CHI '09 *Extended Abstracts on Human Factors in Computing SystemsApril 2009* pp. 4051–4056.

Brandt, F., Conitzer, V., Endriss, U., Lang, J., Procaccia, A.D. (Eds.) (2016) ***Handbook of computational social choice.*** *Cambridge University Press.*

Brias, A. (2016) ***Conjurer la malédiction de la dimension dans le calcul du noyau de viabilité à l'aide de parallélisation sur carte graphique et de la théorie de la fiabilité : application à des dynamiques environnementales.*** Thèse Irstea-LISC, soutenue en décembre 2016 à l'Université Clermont Auvergne.

Bronson, K. (2019). ***Looking through a responsible innovation lens at uneven engagements with digital farming.*** *NJAS – Wageningen Journal of Life Science*, 90–91, 100294.

Bronson, K., Knezevic, I. (2016) Big Data ***in food and agriculture.*** Big Data *& Society*, 3 (1), 1-5.

Caquet, T., Gascuel, C., Tixier-Boichard, M. (2020) ***Agroécologie : des recherches pour la transition des filières et des territoires.*** Éd Quae, Collection : Matière à débattre et décider, 104 p.

Carolan, M. (2017). ***Publicising food:*** **big data*, precision agriculture, and coexperimental techniques of addition.*** *Sociologia Ruralis*, 57(2), 135-154.

Carolan, M. (2018) ***'Smart' farming techniques as political ontology: Access, sovereignty and the performance of neoliberal and not so neoliberal worlds.*** *Sociologia ruralis*, 58(4), 745-764.

Charvat, K., Charvat Junior, K., Řezník, T., Lukas, V., Jedlička, K., Palma, R., Berzins, R. (2018) ***Advanced Visualisation of Big Data for Agriculture as Part of Databio Development,*** IGARSS 2018 - 2018 *IEEE International Geoscience and Remote Sensing Symposium, Valencia*, 2018, pp. 415-418. *doi:* 10.1109/IGARSS.2018.8517556.

Courtonne, J.Y., Alapetite, J., Longaretti, P.Y., Dupré, D., Prados, E. (2015) ***Downscaling material flow analysis: The case of the cereal supply chain in France.*** *Ecological Economics*, 118, 67-80.

Crespo, O., Bergez, J., Garcia, F. (2010) ***Multiobjective optimization subject to uncertainty: application to irrigation strategy management.*** *Computers and Electronics in Agriculture*, 74, 145–154.

De Leeuw, J., Vrieling, A., Shee, A., Atzberger, C., Hadgu, M.K., Biradar, M.C., Keah, H., Turvey, C. (2014) ***The potential and uptake of remote sensing in insurance: a review.*** *Remote Sensors*, 6, 10888-10912.

Dominiak, K.N., Kristensen, A.R. (2017) ***Prioritizing alarms from sensor-based detection models in livestock production - A review on model performance and alarm reducing methods.*** *Computers and Electronics in Agriculture*, 133, 46-67.

Dumont, B., Groot, J.C.J., Tichit, M. (2018) ***Review: Make ruminants green again – how can sustainable intensification and agroecology converge for a better future?*** *Animal*, 12(s2), S210-S219.

Eastwood, C., Klerkx, L., Ayre, M., Dela Rue, B. (2019) ***Managing socioethical challenges in the development of smart farming: from a fragmented to a comprehensive approach for responsible research and innovation.*** *Journal of Agricultural and Environmental Ethics*, 32 (5-6), 741-768.

Ellis, J.L., Jacobs, M., Dijkstra, J., van Laar, H., Cant, J.P., Tulpan, D., Ferguson, N. (2020) ***Review: Synergy between mechanistic modelling and data-driven models for modern animal production systems in the era of*** **big data.** *Animal*, 14 (S2), s223-s237.

Enkel, E., Bogers, M., Chesbrough, H. (2020) ***Exploring open innovation in the digital age: A maturity model and future research directions.*** *R and D Management,* 50 (1), 161-168.

Fekete, J.D., Fisher, D., Nandi, A., Sedlmair, M. (2019) ***Progressive Data Analysis and Visualization (Dagstuhl Seminar 18411).*** *Dagstuhl Reports.* https://drops.dagstuhl.de/opus/volltexte/2019/10346/

Fielke, S.J., Garrard, R., Jakku, E., Fleming, A., Wiseman, L., Taylor, B.M. (2019). ***Conceptualising the DAIS: Implications of the 'Digitalisation of Agricultural Innovation Systems' on technology and policy at multiple levels.*** *NJAS-Wageningen Journal of Life Sciences*, 90, 100296.

Gardner, T.A., Benzi, M., Börner, J., Dawkins, E., Fick, S., Garrett, R., Godar, J., Grimard, A., Lake, S., Larsen, R.K., Mardas, N., Dermott, C.L.M., Meyfroidt, P., Osbeck, M., Persson, M., Sembres, T., Suavet, C., Strassburg, B., Wolvekamp, P. (2019) ***Transparency and sustainability in global commodity supply chains.*** *World Development*, 121, 163-177.

Ghahari, A., Newlands, N.K., Lyubchich, V., Gel, Y.R. (2019) ***Deep Learning at the Interface of Agricultural Insurance Risk and Spatio-Temporal Uncertainty in Weather Extremes.*** *North American Actuarial Journal*, 23 (4), 535-550.

Groot, J.C.J., Oomen, G.J.M., Rossing, W.A.H. (2012) ***Multi-objective optimization and design of farming systems.*** *Agricultural Systems*, 110, 63-77.

Hansen, B. G., Stræte, E. P. (2020) ***Dairy farmers' job satisfaction and the influence of automatic milking systems.*** *NJAS-Wageningen Journal of Life Sciences*, 92, 100328.

Hill, A., Lucet, E., Lenain, R., Laneurit, J. (2019) ***Neuroevolution with CMA-ES for real-time gain tuning of a car-like robot controller.*** *Proceedings of the 16th International Conference on Informatics in Control, Automation and Robotics* (ICINCO 2019), pp. 311-319.

Husnjak, S., Perakovića, D., van Forenbacher, I., Mumdziev M. (2015) ***Telematics System in Usage Based Motor Insurance,*** *Procedia Engineering*, 100, 816-825.

Ingrand, S. (2018) ***Opinion paper: 'monitoring te salutant:' combining digital sciences and agro-ecology to design multi-performant livestock farming systems.*** *Animal*, 12, 2–3.

Inria (2019) ***Cybersecurity: Current challenges and Inria's research directions,*** 168 p, Inria, Le Chesnay, France.

Jakku, E., Taylor, B., Fleming, A., Mason, C., Fielke, S., Sounness, C., Thorburn, P. (2019) ***"If they don't tell us what they do with it, why would we trust them?" Trust, transparency and benefit-sharing in Smart Farming.*** *NJAS-Wageningen Journal of Life Sciences*, 90, 100285.

Klerkx L., Rose D. (2020) ***Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?*** *Global Food Security*, 24, 100347.

Klerkx, L., Jakku, E., Labarthe, P. (2019) ***A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda,*** *NJAS - Wageningen Journal of Life Sciences*, 90-91, 100315.

Kilgour, D. M., Eden, C. (Eds.) (2010) ***Handbook of group decision and negotiation.*** *Springer Science & Business Media, 4.*

Laneurit, J., Chapuis, R., Debain, C. (2016) ***TRACKBOD, an accurate, robust and low cost system for mobile robot person following.*** MCG 2016 – 5th *International Conference on Machine Control & Guidance "Facing complex outdoor challenges by inter-disciplinary research"* Vichy, France, *October 5-6th*, 2016, 6 p. Accessible sur https://mcg2016.irstea.fr/wp-content/uploads/2017/05/MCG2016_paper_31.pdf.

Lepenioti, K., Bousdekis, A., Apostolou, D., Mentzas, G. (2020) ***Prescriptive analytics: Literature review and research challenges.*** *International Journal of Information Management,* 50, 57–70.

Li, J., Rodriguez, D., Zhang, D., Ma, K. (2015) ***Crop rotation model for contract farming with constraints on similar profits.*** *Computers and Electronics in Agriculture*, 119, 12-18.

Melkonyan, A., Gruchmann, T., Lohmar, F., Kamath, V., Spinler, S. (2020) ***Sustainability assessment of last-mile logistics and distribution strategies: The case of local food networks.*** *International Journal of Production Economics*, 228, 107746.

Morin, E. (2014) ***Introduction à la pensée complexe,*** Éditions du Seuil, « Points essais » n°534.

Owen, R., Macnaghten, P., Stilgoe, J. (2012) ***Responsible research and innovation: from science in society to science for society, with society.*** *Science and Public Policy*, 39(6), 751–760.

Pellé, S., Reber, B. (2015) ***Responsible innovation in the light of moral responsibility.*** *Journal on Chain and Network Science*, 15(2), 107-117.

Potter K., Rosen P., Johnson C.R. (2012) ***From Quantification to Visualization: A Taxonomy of Uncertainty Visualization Approaches.*** *In: Dienstfrey A.M., Boisvert R.F. (eds) Uncertainty Quantification in Scientific Computing. WoCoUQ 2011. IFIP Advances in Information and Communication Technology, vol 377. Springer, Berlin, Heidelberg,* pp. 226-249.

Rey-Valette, H., Pinto, M., Maurel, P., Chia, E., Guiheneuf, P.Y., Michel, L., Nougaredes, B., Soulard, C., Jarrige, F., Guillemot, S.C., Mate, M.S., Ollagnon, H., Delorme, G., Prouheze, N., Laurent, A., Suita, L.A., Bertrand, J., Dieudonné, C., Champorigaud, A., Barbe, E. (2011) ***Guide pour la mise en œuvre de la gouvernance en appui au développement durable des territoires.*** Montpellier, INRA Editions. 155 p.

Rose, D.C., Chilvers, J. (2018) ***Agriculture 4.0: broadening responsible innovation in an Era of smart farming.*** *Frontiers in Sustainable Food Systems*, 2, 87.

Ryschawy, J., Moraine, M., Péquignot, M., Martin, G. (2019) ***Trade-offs among individual and collective performances related to crop–livestock integration among farms: a case study in southwestern France.*** *Organic Agriculture*, 9(4), 399-416.

Stilgoe, J., Owen, R., Macnaghten, P. (2013) ***Developing a framework for responsible innovation.*** *Research Policy*, 42, 1568– 1580.

Sutherland, L. A., Mills, J., Ingram, J., Burton, R. J., Dwyer, J., Blackstock, K. (2013) ***Considering the source: Commercialisation and trust in agri-environmental information and advisory services in England.*** *Journal of environmental management,* 118, 96-105.

Svetlin, I., Makatsoris, H., Jreissat, M., Wagner, C. (2016) ***Linking human and machine - towards consumer-driven automated manufacturing.*** *Proceedings. of 2016 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), Vancouver, CN*, pp 1789-1796.

Tesfaye, A., Hansen, J., Kassie, G.T., Radeny, M., Solomon, D. (2019) ***Estimating the economic value of climate services for strengthening resilience of smallholder farmers to climate risks in Ethiopia: A choice experiment approach.*** *Ecological Economics,* 162, 157-168.

Tisseyre, B., McBratney, A.B. (2008) ***A technical opportunity index based on mathematical morphology for site-specific management: An application to viticulture.*** *Precision Agriculture*, 9 (1-2), 101-113.

Trnka, M., Eitzinger, J., Kapler, P., Dubrovský, M., Semerádová, D., Žalud, Z., Formayer, H. (2007) ***Effect of estimated daily global solar radiation data on the results of crop growth models.*** *Sensors*, 7 (10), 2330-2362.

Trompette, P., Vinck, D. (2009) ***Retour sur la notion d'objet-frontière.*** *Revue d'anthropologie des connaissances*, 3(1), 5-27.

Vik, J., Stræte, E. P., Hansen, B. G., Nærland, T. (2019) ***The political robot–The structural consequences of automated milking systems (AMS) in Norway.*** *NJAS-Wageningen Journal of Life Sciences*, 90, 100305.

Vinck, D. (1999) ***Les objets intermédiaires dans les réseaux de coopération scientifique. Contribution à la prise en compte des objets dans les dynamiques sociales.*** *Revue Française de Sociologie*, XI, 385-414.

Wiseman, L., Sanderson, J., Zhang, A., Jakku, E. (2019) ***Farmers and their data: An examination of farmers' reluctance to share their data through the lens of the laws impacting smart farming.*** *NJAS-Wageningen Journal of Life Sciences,* 90, 100301.

Wolf, S.A., Buttel, F.H. (1996) ***The political economy of precision farming.*** *American Journal of Agricultural Economics,* 78(5), 1269-1274.

Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M.J. (2017) Big Data *in Smart Farming* – *A review.* *Agricultural Systems,* 153, 69-80.

Wu, X., Aravecchia, S., Pradalier, C. (2019) ***Design and implementation of computer vision based in-row weeding system.*** 2019 *International Conference on Robotics and Automation (ICRA)*, 2019, p. 4218–4224.

Glossary

- **ANRT:** French National Association for Research and Technology
- **AOC:** Controlled Designation of Origin
- **CAP:** Common Agricultural Policy
- **CATI:** Automated Data Processing Centre
- **CITEPA:** Technical Reference Centre for Air Pollution and Climate Change
- **DAS:** Decision Aid System
- **DBMS:** Database Management System
- **DGE:** Senior Management
- **DSS:** Decision Support System
- **ERP:** Enterprise Resource Planning
- **ETSI:** European Telecommunications Standards Institute
- **FAO:** Food and Agriculture Organization of the United Nations
- **FNSEA:** French National Federation of Farmers' Unions
- **GDPR:** General Data Protection Regulation
- **GHG:** Greenhouse Gas
- **GIS:** Geographical Information Systems
- **GPS:** Global Positioning System
- **HCI:** Human-Computer Interaction
- **HLPE:** High Level Panel of Experts (UN)
- **I■ CT:** Information and Communication Technology
- **INRAE:** French National Research Institute for Agriculture, Food, and Environment

Inria: French national research institute for digital science and technology

- **IoT:** Internet of Things

IPCC: Intergovernmental Panel on Climate Change

- **ITU:** IT University of Copenhagen
- **JA:** French Young Farmers' Union
- **MIT:** Massachusetts Institute of Technology
- **NGO:** Non-Governmental Organisation
- **OECD:** Organisation for Economic Cooperation and Development
- **OIE:** World Organisation for Animal Health (formerly Office International des Epizooties)
- **OLAP:** On Line Analytical Processing
- **ONF:** French National Forestry Office
- **OWL:** Web Ontology Language
- **PDO:** Protected Designation of Origin
- **PEPR:** Priority Equipment Programme for Research
- **PES:** Payment for Ecosystem Services
- **PGS:** Participatory Guarantee System
- **RDA:** Research Data Alliance
- **RFID:** Radio Frequency Identification
- **RRI:** Responsible Research and Innovation
- **SADEA:** Sustainable agricultural systems and agricultural equipment contributing to the ecological transition
- **SAREF:** Smart Applications Reference ontology
- **UE:** Experimental Unit
- **UMR:** Mixed Research Unit
- **UMT:** Mixed Technology Unit
- **UN:** United Nations
- **UNESCO:** United Nations Educational, Scientific and Cultural Organization
- **WEEE:** Waste Electrical And Electronic Equipment
- **W3C:** World Wide Web Consortium

Inria project-teams

https://www.inria.fr/en/list-of-project-teams

INRAE research units

https://annuaire.inrae.fr/accueil.action#ongletStructure

- **UMR AGROECOLOGY :** https://www6.dijon.inrae.fr/umragroecologie_eng/
- **UMR BAGAP :** https://www6.rennes.inrae.fr/bagap_eng/
- **UMR BIOEPAR :** https://www6.angers-nantes.inrae.fr/bioepar_eng/
- **UMR BOA :** https://web.univ-tours.fr/umr-0083-biologie-des-oiseaux-et-aviculture-boa
- **UMR CBGP :** https://www6.montpellier.inrae.fr/cbgp_eng/
- **UMR GENPHYSE :** https://genphyse.toulouse.inra.fr
- **UMR MISTEA :** https://www6.montpellier.inrae.fr/mistea_eng/
- **UMR MOSAR :** https://www6.jouy.inrae.fr/mosar_eng/
- **UMR PEGASE :** https://www6.rennes.inrae.fr/pegase_eng/
- **UMR SAS :** https://www6.rennes.inrae.fr/umrsas_eng/
- **UMR SELMET :** https://umr-selmet.cirad.fr
- **UMR SMART LERECO :** https://www6.inrae.fr/umt-stratege/Partenaires/INRAE/UMR-1302-SMART-LERECO
- **UMR Tetis :** https://umr-tetis.fr/index.php/fr/
- **UMR TOXALIM :** https://www6.toulouse.inrae.fr/toxalim_eng/
- **UMR UMRH :** https://umrh-bioinfo.clermont.inrae.fr/Intranet/web/UMRH/en

© Inria - 02/2022

Domaine de Voluceau, Rocquencourt BP 105
78153 Le Chesnay Cedex, France
Tel.: +33 (0)1 39 63 55 11
www.inria.fr