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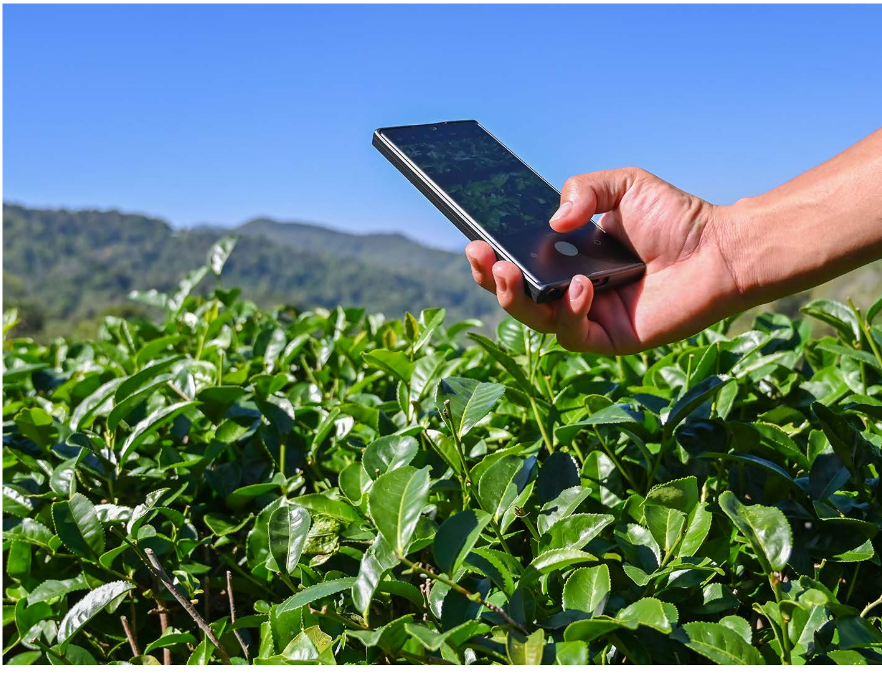
UNDERSTANDING DIGITAL AGRICULTURE

Ten Years of Interdisciplinary Research at the #DigitAg Institute

Edited by Véronique Bellon-Maurel, Karine Gauche, Martha-Lucia Enriquez, Nathalie Lyon-Caen

Prefaced by Vincent Martin



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Preface

Over the past ten years, I have seen first-hand how digital technology can inform our decisions without ever being a substitute for those who practice agriculture from day to day. This conviction—forged through field experience and diverse collaborations with farmers, researchers, engineers, and public policymakers worldwide—forms the basis of my perspective on the role that digital technology can play in service of a more resilient, sustainable, and fair agriculture.

The promises of innovation are many, but one observation stands out: a gap remains between what we are capable of designing and what stakeholders actually adopt in the field. The challenge is not merely to innovate, but to create the conditions for use: trust, support, perceived value, simplicity, governance, and training. An innovation only has impact when it is adopted, adapted, and sustainably integrated into practices and decisions. This is where the transition from potential to impact truly takes place.

This requires responsible research and innovation, mindful of social, environmental, and economic consequences. Responsible, because it is accountable to society and the living world: they must anticipate, protect, and remain answerable. Responsible, because technological progress that weakens, excludes, or obscures is not progress—even when it leverages tools as powerful as artificial intelligence.

Digital technology can be a factor for inclusion, but it can also widen inequalities faster than it bridges them if access, skills, and equity are not designed in from the start. Reducing the digital divide is not a secondary objective; it is a condition for sustainability, efficiency, and fairness. We do not build the future with only a portion of the stakeholders, nor by assuming that technology will impose itself.

This is where the humanities and social sciences come in. They remind us that no technology changes practices by its presence alone. Understanding usage, barriers, perceptions, incentives, stakeholder logic, and power dynamics is necessary to transform potential into actual adoption. Without them, data is deaf, models are blind, and solutions are flawed. Taking usage into account is even more vital in the Global South, where smallholder family farms are in the majority and sit at the heart of food security and territorial resilience. Digital tools will only be relevant there if they adapt to the diversity of farms, socio-economic contexts, and local knowledge.

This is where #DigitAg has made a unique contribution: by creating a common language between disciplines, linking sensors with behaviours, algorithms with usage, and models with territories. Ten years of work have produced not only tools and knowledge but have also structured a community that learns, shares, adjusts and cooperates. This interdisciplinarity is the prerequisite for useful, appropriate and adopted innovation.

It is also with this vision that open innovation initiatives like OccitANum were born within #DigitAg, bringing together researchers, farmers, companies, public actors, and citizens to co-construct digital solutions for the agroecological transition. These experiments prove that open, frugal and regional innovation can be a driver of inclusion, trust and uptake.

This book recounts the ten-year journey of #DigitAg, which began at a time when precision agriculture was the most advanced form of agricultural digitalisation. This path continued with the democratisation of the Internet of Things (IoT) and dedicated applications for agriculture and value chains, stimulated by entrepreneurial fervour and the creation of numerous startups. It continues today with the rise of artificial intelligence (AI), revitalised by the promises of generative AI. Artificial intelligence can offer considerable advances, such as those described in this book (facilitating large-scale phenotyping, early detection of water stress, or analysing satellite imagery time series), but its value depends on the context, the quality of the data, and how it is used. It is neither a shortcut nor a guarantee of results; it is a powerful force, but one at the service of a human, scientific and societal project.

As artificial intelligence further accelerates technological cycles, this book reminds us that no solution will replace listening, cooperation, responsibility and discernment. This is the guiding principle of the roadmap on digitalisation and AI innovation led by the FAO, which in April 2025 brought together a hundred experts and aims precisely to transform intentions into tangible results by creating the conditions for a responsible, inclusive, and useful AI for all.

The success of this transformation also relies on enlightened public policies capable of framing digitalisation to guarantee equity, transparency and sustainability. Our challenge is therefore not to innovate faster, but to innovate with meaning, with method, and with everyone.

I hope these pages inspire, through the use of real-life practical examples, those who want to close the gap between intentions and results and make digital technology and AI a lever for autonomy, resilience and trust. The task is immense, but the course is clear: to put innovation at the service of the living world, local areas and communities, and not the other way around. The path lies ahead of us, and it can only be travelled together.

Vincent Martin
Head of the Office of Innovation
Food and Agriculture Organisation of the United Nations (FAO)

General introduction

Karine Gauche, Véronique Bellon-Maurel

⏩ Digital Agriculture: a strategic lever at the heart of the Agriculture Innovation 2025 report...

Published in 2015, the Agriculture Innovation 2025[1] report presents thirty proposals for building a more sustainable and innovative French agriculture. Coordinated by a team including Jean-Marc Bournigal (President of Irstea), François Houllier (CEO of Inra), Philippe Lecouvey (Director of Acta), and Pierre Pringuet (Chair of the Board of AgroParisTech), it advocates for a systemic approach to innovation: mobilizing research, disseminating results to the field, adapting training and developping public policies or, more broadly, regulations.

To address intense food and environmental pressures, the report emphasizes the urgency of rethinking agricultural models by leveraging innovation, particularly digital technology. Agricultural digitalisation is presented as a major lever for developing more resilient agriculture that integrates competitiveness, sustainability, and societal expectations.

The structuring of interdisciplinary research dedicated to digital agriculture is highlighted to address challenges particularly related to data: its collection (smart sensors), its modelling (voluminous and heterogeneous data, otherwise known as 'big data'), and its use for decision support.

⏩ ...to which #DigitAg, an interdisciplinary Convergences Institute, responds...

Created in 2017 as part of the *Investissements d'Avenir* programmes (PIA), the convergences institute #DigitAg embodies the organisation of a community. Led by INRAE, it brings together sixteen public and private partners with the goal of structuring research for sustainable, competitive, and inclusive digital agriculture in France, Europe and the Global South.

Research is organised around six complementary research axes covering the major issues linked to digital agriculture. Axis 1 examines the transformation of agricultural and rural practices through information and communication technologies (ICT), analysing the impact of digital technology on production systems, agricultural professions and territorial dynamics. Axis 2 focuses on innovation, adoption and diffusion of digital agriculture, studying innovation trajectories and the conditions for

1. https://agriculture.gouv.fr/sites/default/files/rapport-agriculture-innovation2025.pdf

dissemination among agricultural actors. Axis 3 concerns sensors and data acquisition, aiming to develop reliable, autonomous and interoperable sensors for real-time agronomic and environmental data collection. Axis 4 deals with information systems, platforms, and interoperability, with the design of open and interconnected digital infrastructures facilitating access, exchange and utilisation of data. Axis 5 addresses data mining, processing, visualisation and indicators, creating tools for big data analysis to extract knowledge useful for decision-making. Finally, Axis 6 concerns modelling, simulation, and decision support tools (DST), developing predictive models to simulate agricultural scenarios and provide operational recommendations.

These axes, which drive scientific communities, intersect with major identified and declared thematic issues (sustainable livestock farming, agroecology, value chains, etc.), addressed through interdisciplinary research.

⏩ ...characterised by substantial funding and massive support for interdisciplinary research in digital agriculture

Since its inception, #DigitAg has structured a significant scientific community across 30 partner joint research units (UMRs), comprising approximately 600 affiliated researchers. The institute has contributed to the funding of 150 Master's grants, 56 doctoral grants (covering both salary and specific financial support for research activities), 50 labelled PhDs, 18 years of post-doctoral fellowships, 72 months of visiting scientist support, and 12 software developments for demonstrators derived from PhD results. All of this work has been drawn upon for this book, with a particular focus on PhD theses. Several doctoral students and post-doctoral researchers contributed to the writing of these parts.

This volume presents research conducted across the six axes while offering specific, transversal perspectives, including reflective ones and is organised in four parts.

Part 1 (Chapters 1–4) focuses on the development of tools for the digital transformation of agriculture: the sensors and their implementation necessary for acquiring high-quality field data; the processing of massive, multi-source data; the management and integration of data and knowledge to structure and interconnect heterogeneous information; and the modelling, simulation, and data integration required to develop decision support tools (DST).

Part 2 (Chapters 5 to 7) describes and examines in detail the digital transformation of agriculture from different perspectives (processes, systems, practices and actors). Agricultural digitalisation is first analysed in the context of transitions, exploring the accompanying processes, actors and systemic dynamics. Farmers' digital habits and practices are then examined to understand the links between digitalisation and the 'greening' (ecologisation) of agriculture. Finally, digital tools, when viewed as intermediation instruments, reveal the gaps between the many expectations and the realities observed in the field.

Part 3 (Chapters 8 to 10) presents three concrete applications of digital technologies in agriculture at three different scales. First, phenotyping tools for characterizing and analysing plant traits for varietal selection are presented, followed by solutions to assist livestock farmers in herd management, and finally, digital contributions to monitoring and analysing food security, particularly aimed at public policymakers.

Part 4 (Chapters 11 to 13) offers a reflective analysis on the operations and evolution of #DigitAg. First, the challenges of digital agricultural development in the Global South are presented. Next, the practice of interdisciplinarity is analysed in light of funded projects and modes of cross-disciplinary collaboration. Finally, the challenges and prospects of responsible research and innovation (RRI) approaches—resulting from the convergence between the social sciences and digital sciences—are analysed.

The book concludes with an appendix presenting other #DigitAg products aimed at fostering interdisciplinarity among students and promoting the dissemination of their research: namely, video recordings of student webinars and #DigitAg digital showcases, which are web-based demonstrations illustrating PhD research results.

Part 1

Research for digital agriculture: development of digital tools

Chapter 1

Acquiring high-quality field data by improving sensors and their application

Véronique Bellon-Maurel, Ryad Bendoula, Ludovic Brossard, Jean-Michel Roger, Bruno Tisseyre

Data collection is the first, crucial phase of 'data-driven' agriculture. The data concern the plants or animals that will provide agricultural products (monitoring their physiology, detecting dysfunctions such as diseases and deficiencies, predicted or actual yields, etc.), but also their biological environment (presence of pests, competitors) and abiotic environment (data on soils, meteorology, etc.).

In animal production, the functioning of a livestock system can be improved according to the principles of agroecology through animal monitoring: health, behaviour, welfare, performance (growth, ingestion, reproduction, milk production, etc.), and physiology. However, this monitoring is complex. Depending on the species considered, access to individual data is more or less difficult (for example, pigs or fish versus dairy cows), due to the number of animals and their ease of handling. This monitoring task is difficult in large-scale livestock operations. In extensive systems, this difficulty is also linked to whether or not the animals are accessible (as in pastoralism). Several studies by the #DigitAg community have enabled advances in this field: embedded sensors or remote measurement methods. They will be briefly described here and discussed again in Chapter 9.

In crop production, optical sensors offer the benefit of high acquisition speed, generally contactless detection, and, with some, high specificity. This is the favoured field of expertise for #DigitAg teams. This chapter will describe proximity sensors for measurement at a short distance from the object of interest, between a few tens of centimetres and a few tens of metres (drones). Remote sensing, which uses various types of electromagnetic sensors (optical, radar), has a fundamental place in digital agriculture. It is addressed in Chapter 2.

⏩ Special optical devices

Certain phenomena are difficult to detect: changes of small magnitude (water stress), of small size (detection of droplets, spores, etc.), or of low intensity (early detection of a disease). In such cases, it is advantageous to design optical devices that improve signal sensitivity, as a prerequisite for any processing. #DigitAg has approached this subject from two directions: the coupling of hyperspectral imaging and polarisation, and evanescent wave optical interfaces.

Coupling hyperspectral imaging and polarisation

ITAP joint research unit developed polarised hyperspectral imaging (Xu *et al.*, 2019), a technique that is more selective than standard spectral imaging, as it differentiates information coming from the surface, the superficial cell layers, and the depth of the observed object (in Figure 1.1, a leaf). For each pixel, a spectrum is collected in several configurations of the polariser/analyser pair (Figure 1.1). Spectra of perpendicularly polarised reflectance (R⊥), parallel polarised reflectance (R//), and combinations of these spectra are obtained, providing access to specular reflection (RSS) or back-scattered reflection (RBS). RSS is similar to an image as viewed by a human. Here, different properties of sunflower leaves are detected: the variety, growth stage, and presence/absence of diseases (powdery mildew, Septoria leaf spot) (Xu et al., 2019).

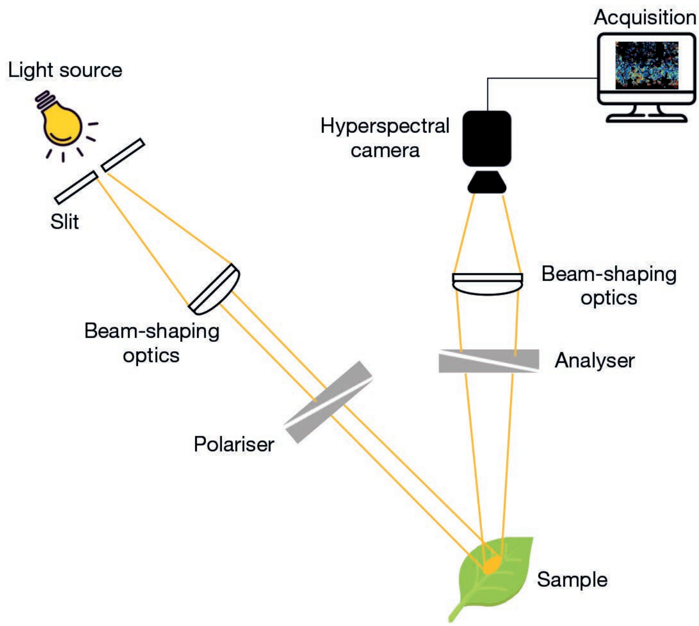

Figure 1.1. Set up for capturing polarised hyperspectral images at UMR ITAP. Source: R. Bendoula.

To detect diseases, the best model utilises the R⊥ spectra, which means that the sub-surface or deep-tissue spectra are essential. Figure 1.2 shows the images of the upper surface of infected leaves in RSS and R⊥. On one side in pseudo-colours, and on the other, the first and second principal components (PC 1 and 2) of their respective principal component analyses (PCA). These show that the infected areas, i.e. two spots on either side of the central vein, halfway up the leaf, which are very difficult to detect with the naked eye, appear clearly on the R⊥ pseudo-image and on PC 1 and 2. This research paves the way for early disease detection via hyperspectral or multispectral imaging.

Another optical device using polarisation to monitor variations in the optical scattering properties of leaves employs the 'biospeckle' approach. This consists of creating patterns through the interference of a coherent laser beam with light backscattered by a scat-

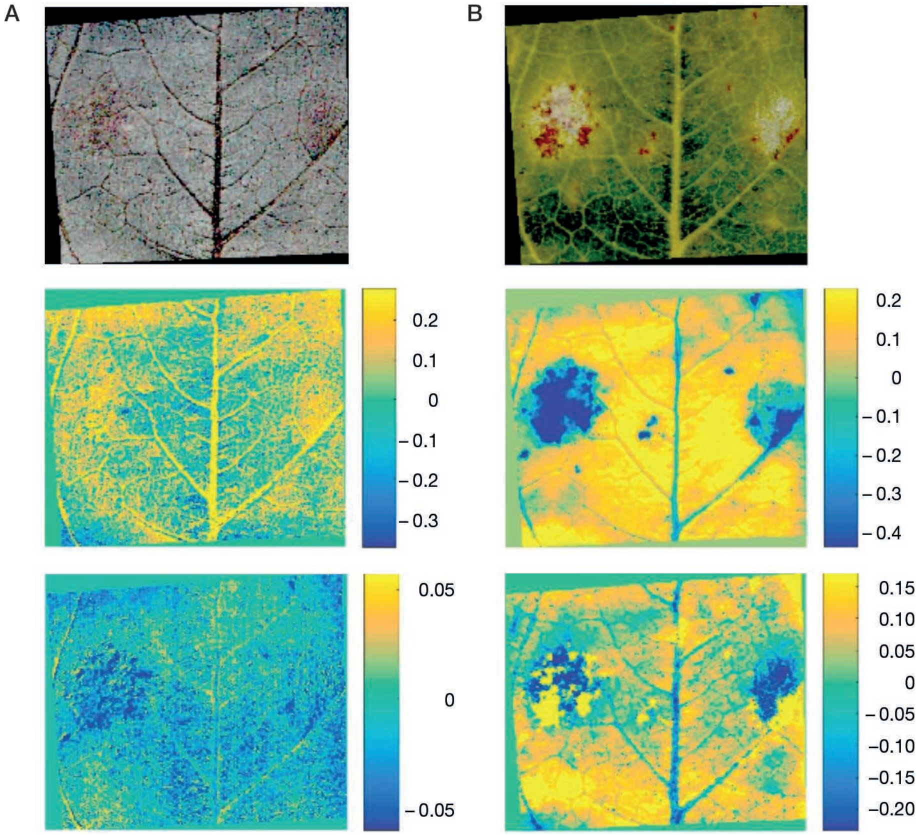

Figure 1.2. Disease detection using polarised hyperspectral imaging of the upper surface of sunflower leaves infected with *Septoria* leaf spot (SLS) and powdery mildew (PM), (A) in specular reflection (R_{SS}) and (B) in orthogonal polarisation (R_1) showing from top to bottom: pseudo-colour image, principal component 1, and principal component 2. Source: adapted from Xu *et al.* (2019).

tering medium—in our case, plant tissue—which depends on stationary particles and mobile elements within that tissue. The device, developed by Bouzaouia *et al.* (2024), comprises a 785 nm laser diode. This wavelength is located on a plant reflectance plateau that promotes interference patterns. Time-series of biospeckle images are analysed to derive a classic biospeckle indicator: the absolute value of difference (AVD) (Braga *et al.*, 2011). Throughout the experiment, AVD values decrease with the increase in water stress (Figure 1.3). The biospeckle approach is likely to become a tool for fine phenotyping of water stress, initially in the laboratory, and in the longer term, in the field.

Evanescent wave optical interfaces

The surface of a waveguide—an optical material that transmits light between a transmitter and a receiver—can become an optical transducer, i.e., a sensitive element, via the phenomenon of evanescent waves. The latter are electromagnetic waves formed at the interface between two media of different refractive indices. These waves are modified by liquids placed on the surface of the waveguide. *Rib* waveguides (Figure 1.4)