Agronomy for Sustainable Development (2025) 45:18
https://doi.org/10.1007/s13593-025-01011-8

REVIEW ARTICLE

Farmer-centric On-Farm Experimentation: digital tools for a scalable transformative pathway

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Accepted: 14 February 2025

Abstract
This virtual issue reports on the use of digital technologies in On-Farm Experimentation (OFE) in varied farming systems across the world. The authors investigated diverse questions across contrasted environments and scientific domains, with methodologies that included review, empirical studies, interviews, and reflexive accounts. The contributions thus showcase the multiplicity of research directions that are relevant to OFE. This includes addressing the two intertwined types of research objects in OFE: the farmers' questions (how to improve management) and the methodologies required to address these (how to improve research through OFE)—with the notable support of digital tools. The issue includes a systematic review exploring OFE practices and farmer-researcher relationships as reported in the scientific literature; a meta-analysis comparing experimental scales in the USA; reflexive analyzes on a feed assessment tool and a tree crop decision support system rooted in OFE that are connecting farmers and researchers in Africa; a retrospective on a large CGIAR program combining citizen sciences and OFE; the use of video recordings and work analysis to characterize farmers' knowledge in French vineyards; and in the same sector in Australia, two accounts of the use of digital tools in spatially explicit OFE: one an investigation into farmers' and consultants' perceptions, the other a retrospective on the roles of precision agriculture. Findings from these examples validate the use of varied digital tools to scale the design, implementation, and learning stages of OFE processes. These include how to better harness and bridge the knowledge of farmers, researchers and other parties, examples of data management and analytics, the improved interpretation of results, and capitalizing on experiences. The international conference this issue was part of also led to acknowledgement of a lack of policy linkages, required to scale OFE endeavors by incentivizing institutional change toward more farmer-centric research practices and responsible digital deployment.

Keywords Innovation · Farmer-centric research · OFE · Experimentation · Transformation · Knowledge · Digital agriculture · Complex adaptive systems

On-Farm Experimentation (OFE) is a farmer-centric pathway for improvement in agri-food systems that holds the potential to be transformative, by changing the way actionable knowledge is produced (Fazey et al. 2018; Lacoste et al. 2022). Based on experiments designed with farmers, largely conducted by them, and for their interests first, OFE not only answers farmers' own questions but also provides data for researchers to create more broadly valuable insights. As such, OFE is a practical and adaptive mechanism to bridge the interests of farmers, researchers, extension services, and other stakeholders that is gathering renewed interest. This collaborative action-oriented process, where co-learning is paramount (Van Mierlo et al. 2020) and which can be strengthened by digital tools, promises heightened innovation in agriculture by complementing experimental research with local, distributed, and participatory processes (Fig. 1). Farmer-centric OFE responds to novel questions and enduring problems in agri-food systems, raising methodological challenges, and highlighting pressing demands at the intersection of human, technological, and institutional dimensions.

Researchers have argued that digital and agroecological transitions can progress jointly, through the acquisition and sharing of local data to inform local solutions (Bellon Maurel and Huyghe 2017; Conti et al. 2024b). Collaborations featuring OFE can indeed act as catalysts, offering scientists pragmatic pathways to cater for the real-world heterogeneity of farmer circumstances by directly

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Fig. 1 Farmer-centric On-Farm Experimentation (OFE) is an innovation process whereby knowledge is generated jointly by farmers, researchers, and other parties. Examples of digital technologies supporting OFE in- and off-field include facilitating the recording and sharing of farm-level information (**a**, France - photo credit: INRAE), and the remote capture and interpretation of data (**b**, Tanzania - photo credit: APNI). Visuals for the first and second international conferences on farmer-centric On-Farm Experimentation, #OFE2021 and #OFE2023.

investigating the interactions between options and contexts (Šūmane et al. 2018; Sinclair and Coe 2019; Prost et al. 2023). The need to explore complexity must be highlighted because, whilst data can improve the certainty of insight, data alone is not sufficient to learn—the conditions, organization, and intentions of the experimental process are essential (Aare et al. 2021; Jackson-Smith and Veisi 2023; Dumont et al. 2025). And yet, even learning might not be sufficient to enable and sustain change, which is contingent to the broader social, economic, and political context (Van Mierlo et al. 2020; Aare et al. 2021; Conti et al. 2024a). Kane (2019) reminds us that people are the key to digital transformation rather than technology itself. In this respect, the effective integration of science-based and farmer-based types of knowledge should be a focus point, even if it is often difficult to achieve. Experimenting on farm plays a crucial role here by providing a space for co-innovation and the co-production of knowledge that challenges researchers while resonating with the ways farmers learn, i.e., drawing from experiential, social, and didactic sources (Waters-Bayer et al. 2015; de Janvry et al. 2016; Stone 2016; Aare et al. 2021; Jackson-Smith and Veisi 2023). As such, OFE is often part of change-oriented projects, where bridges can be built with other modes of innovation (Leclère et al. 2024).

The tension when aiming at increasing the salience, credibility, and legitimacy of OFE research outputs has been to structure scientific reasoning so as to produce situated knowledge that can be adapted to farmers' understanding of their complex systems, while providing more broadly relevant insights that are scientifically sound (Aare et al. 2021). As outlined by Waters-Bayer et al. (2015) and Salembier et al. (2023), OFE can achieve this by fulfilling various functions (e.g., exploring, selecting, gaining know-how, sharing, fostering agency, and the local capacity to innovate), for which multiple boundaries must be navigated by different types of stakeholders (Cash et al. 2003) who often need to embrace new roles and skills (Aare et al. 2021). Within science, methodological progress must thus overlap three broad disciplinary areas to complement specialized advances: those of data, social, and agricultural sciences (Fig. 2). However, OFE expertise often remains confined to given disciplinary fields, as is observed in other emerging scientific communities (e.g., Van Mierlo et al. 2020), with a divide enduring between researchers in agronomy and innovation (e.g., Giannini and Marraccini 2024). To guide the

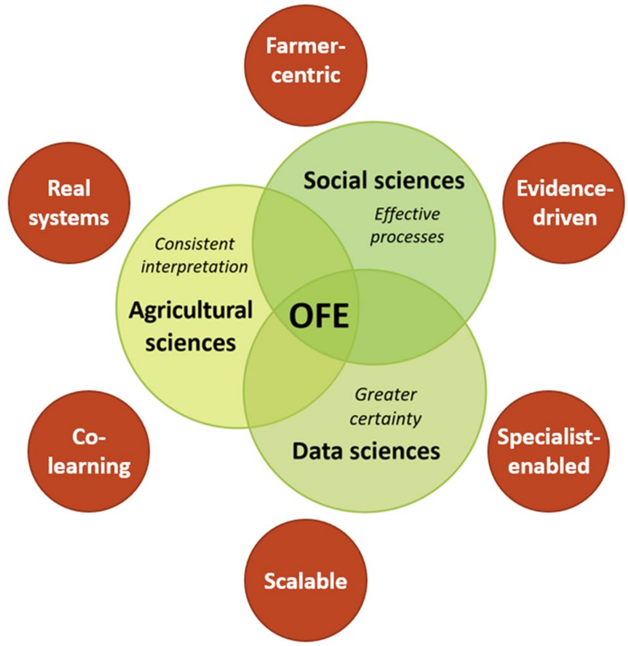

Fig. 2 Crossing disciplinary boundaries is crucial to progress, organize, and deploy OFE processes. Six key principles (red circles) guide the diversity of OFE initiatives and practices. Adapted from Lacoste et al. (2022)

development of coherent frameworks across the diversity of expertise represented by these areas, and across the even greater range of OFE goals and contexts (Richardson et al. 2021; Salembier et al. 2023; Jackson-Smith and Veisi 2023), six key principles have been identified: farmer-centric (farmers fuel the research process), real systems (farm own management and scales), evidence-driven (insights are anchored in data), specialist-enabled (different expertise add value), co-learning (emphasis on engaging by sharing), and scalable (analytical and social processes).

These principles encapsulate a combination of processes that digital technologies are expected to support, and even sometimes enable (Cook et al. 2022). Much interest comes from dramatically facilitating the collection, aggregation, and analysis of heterogeneous agronomic data, including spatially explicit information, using remote sensing technologies, on-site sensors, and models to manage field variability. Related work is primarily reported in the precision agriculture literature for broadacre cropping systems (Kyveryga 2019; Jindo et al. 2021; Bellon-Maurel et al. 2022; Tanaka et al. 2023; Colaço et al. 2024). Digitalization can also support individual and social learning by capturing, visualizing, and sharing a broad range of information and experiences. In addition to decision support systems and online repositories (Ingram et al. 2022), examples include fostering engagement (e.g., with digital soil maps, McNee and Lacoste 2022), stimulating ideation (e.g., with videos, Zossou et al. 2009), facilitating networked OFEs (e.g., through a social platform, Garnier et al. 2022), or enabling farm-level experimentation (e.g., using a federated network of sensors, Pesonen and Ronkainen 2022). However, relatively few academic publications describe processes of engagement, co-learning and co-creation in OFE (Waters-Bayer et al. 2015; Reckling and Grosse 2022), reflecting that farmers are not routinely part of co-design in formal agronomy (Briggs 2013; Andrieu et al. 2024; Giannini and Marraccini 2024), and that reporting researchers' own learning and changed knowledge trajectories is not incentivized. Even fewer document the digital facilitation of OFE initiatives—with studies reporting disappointing or adverse impacts remaining scarce (Lember et al. 2019; Trubert et al. 2022). Equally little attention has been paid to understanding on-farm capacities for effectively using such tools (Ingram and Maye 2023).

This virtual issue comprises articles that illustrate some of these varied ways in which digital technologies can prove useful to OFE, its processes, and its sciences (Fig. 3). Contributions were made from around the world, also showcasing the diversity of OFE environments and endeavors.

Toffolini and Jeuffroy (2022) decipher with nuance this great diversity of OFE practices, as reported in the scientific literature. The authors identified seven types of OFE, weaving key OFE facets such as the type of knowledge targeted, the role of participants, and the processes and tools used for implementation and interpretation—notably discussing the actual or potential roles of digital technologies. Laurent et al. (2022) showed that OFE can provide similar or better statistical results in broadacre cropping than small plot experiments, based on nearly a thousand trials collected across five US states. Alexandre et al. (2023) draw key lessons on how to manage multi-party challenges during the development and deployment of a decision support system for tree crop production anchored in OFE, in Senegal and Côte d'Ivoire. In smallholder livestock systems of Kenya and Rwanda, Duncan et al. (2023) showed how a participatory digital tool for feed assessment bridges the knowledge systems of farmers and researchers. De Sousa et al. (2024) document the evolution of the Tricot approach, a large CGIAR program implemented in Latin America, Africa, and India that blends OFE with citizen sciences. Tricot scales a decentralized research process to provide more locally relevant varietal recommendations, taking in farmers' assessments as a legitimate and credible source of data. Bénézet et al. (2022) provide a rare investigation into the mobilization of farmers' experiential knowledge in French vineyards using video recordings and self/allo-confrontation methodology, with direct application for farming system transitions. In Australia, Song et al. (2022) compared the value that grape growers and viticultural consultants perceived of a simplified spatial approach to experimentation vs their own methods. In the same industry, Bramley et al. (2022) recounted

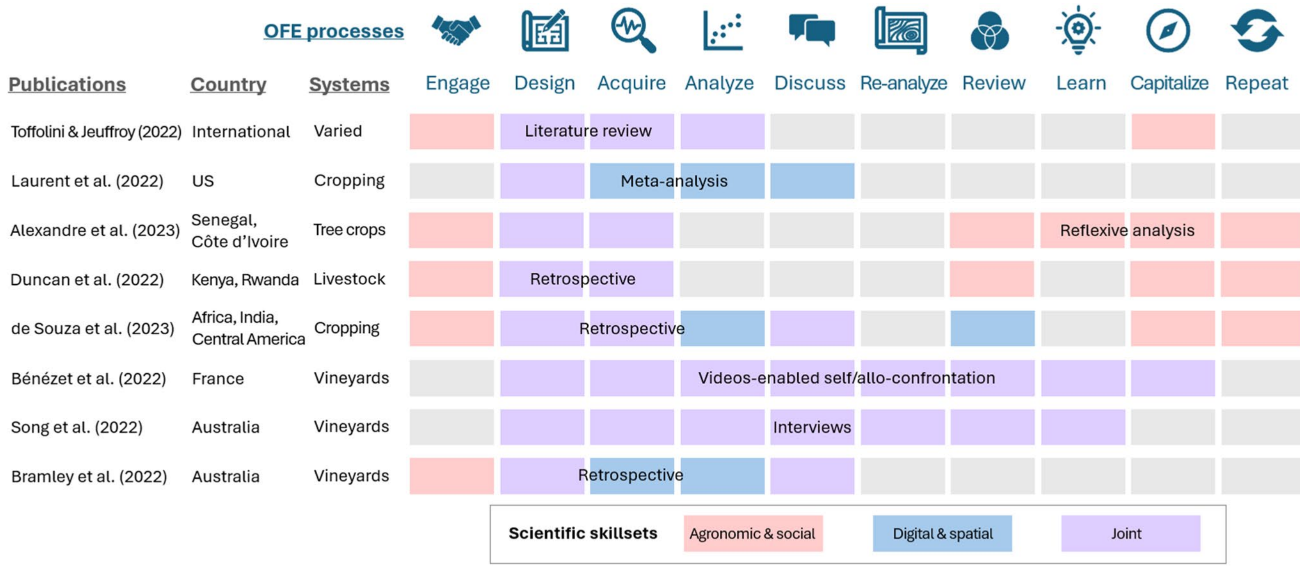

Fig. 3 Major OFE processes addressed and methodologies used in the contributions to the virtual issue. "Re-analyze" is understood as "with the addition of farmers' own observations and perspectives, that may not have been collected originally as data in the OFE," i.e., with added contextualization. Processes adapted from Lacoste et al. (2022).

experiences and synergies between OFE and Precision Agriculture, highlighting the need to integrate the farm business perspective, from crop performance to assessment tools and data governance.

The virtual issue was initiated at #OFE2021, the first International Conference on Farmer-centric On-Farm Experimentation with the theme "Digital Tools for a Scalable Transformative Pathway." The conference was organized by INRAE-#DigitAg (French National Institute for Agriculture and the Environment, Digital Agriculture Convergence Lab) and the ISPA OFE-C (International Society for Precision Agriculture, OFE Community), with sponsorship from the OECD Co-operative Research Programme on Sustainable Agricultural Systems. The three goals of the conference were to share global experiences of OFE, explain the OFE innovation process as a pathway for change, and identify mechanisms for digital applications, scaling, and OFE institutional uptake. A total of 180 participants from 36 countries participated in a hybrid format online and in Montpellier (France). It was the first time that a significant number of specialists, researchers, farmers' representatives, policy-makers, and start-ups could exchange specifically on OFE scientific and technical advances, and set the foundation for new routes to encourage the development of OFE, with a focus on digital tools. A total of 190 items were contributed including papers (https://ofe2021.com/proceedings.html) and recorded presentations (https://rb.gy/4et333) (Bellon Maurel et al. 2022). A second conference organized by Cornell University, #OFE2023, gathered online 160 participants from 41 countries on the theme "Exploring Shared Value Propositions" (Longchamps et al. 2024). Concurrently, a group dedicated to connecting OFE communities worldwide was created: GOFEN, the Global On-Farm Experimentation Network (https://www.gofen.org).

A key finding of #OFE2021 was the lack of explicit attention dedicated to institutional and policy dimensions, which echoes previous observations (Waters-Bayer et al. 2015). If not addressed, OFE, like other context-specific participatory approaches before, will remain a set of tools and niche activity, rather than an approach that can be scaled to fulfill its transformational potential to shift the way agricultural knowledge is produced and utilized (Fazey et al. 2018; Hall 2021). At present, the governance of innovation systems across the world is rarely conducive to truly farmer-centric OFE (Waters-Bayer et al. 2015; Leclère et al. 2024). For instance, abundant insights from farmer-initiated OFE continuously elude academic channels. It can also be argued that most of the OFE efforts that are reported and discussed, including in this issue, are mostly products of the socially constructed reality, and associated value system, of researchers and their scientific disciplines (Briggs 2013). Digital technologies have an important role to play in effective innovation systems where farmers are not just passive recipients of expert insights but also active contributors to a broader pool of knowledge built from both scientific and empirical sources (Šūmane et al. 2018). As with any innovation, digitalization is not neutral (Fielke et al. 2022; Conti et al. 2024b). Related recommendations apply to digitally-enabled OFE as well as questioning how to reframe the interface between formal science and farmers. Consequently, in addition to institutional innovation, such as data governance and interoperability standards, the development of individual and organizational capabilities together with new patterns of partnership are required, for instance based on value propositions and business models, inclusion of civil society organizations and informal grass-root movements, power redistribution, multi-disciplinarity, adaptive funding, and changed reward systems (Waters-Bayer et al. 2015; Lember et al. 2019; Richardson et al. 2021; Rossing et al. 2021; Ingram et al. 2022; Fielke et al. 2022; Cook et al. 2022; Bellon-Maurel et al. 2022; Jackson-Smith and Veisi 2023; Giannini and Marraccini 2024; Conti et al. 2024a). Policy innovation, in the form of infrastructure investment but also regulation (Hall 2021), is critical in creating the enabling environment for digital technologies to be effectively (and responsibly) deployed, in scaling farmer-centric OFE and beyond.

Acknowledgements The authors are grateful for the support and contributions of the #OFE2021 and #OFE2023 Scientific and Organizing Committees, its working groups, and participants for making the conferences a success.

Authors' contributions All authors contributed to the manuscript conception. The first draft was written by Myrtille Lacoste and all authors, i.e., Véronique Bellon-Maurel, Isabelle Piot-Lepetit, Simon Cook, Nicolas Tremblay, James Taylor, Julie Ingram, Ivan Adolwa, and Andrew Hall, commented on previous versions. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. No funding was received to assist with the preparation of this manuscript.

The #OFE2021 conference was financially supported by the Co-operative Research Programme (CRP) - Sustainable Agricultural and Food Systems of the Organisation for Economic Co-operation and Development (OECD), #DigitAg - the Digital Agriculture Convergence Lab of INRAE (French National Institute for Agricultural and Environmental Research, grant no. ANR-16-CONV-0004), the Agropolis Foundation, the Occitanie region, Occitanum, Agreenium, RMT Modelia, and RMT NAEXUS, INRAE (MathNum and Agro-EcoSystem Divisions of INRAE). Support was also provided by the MAK'IT-FIAS Fellowship programme (Montpellier Advanced Knowledge Institute on Transitions – French Institutes for Advanced Study) co-funded by the University of Montpellier and the European Union's Horizon 2020 Marie Skłodowska-Curie Actions (co-fund grant agreement no. 945408). The #OFE2023 conference was financially supported by the Cornell College of Agricultural and Life Sciences, the Cornell Atkinson Center for Sustainability, and the Cornell Institute for Digital Agriculture (CIDA) from Cornell University, 1000FARMS (ClimMob, Alliance Bioversity-CIAT), APNI (the African Plant Nutrition Institute), #DigitAg-INRAE, and the CEIA (Centre for Effective Innovation in Agriculture). Additional support was provided by GFAR (the Global Forum on Agricultural Research and Innovation) and the ISPA (International Society of Precision Agriculture).

Data availability Not applicable.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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