ON-FARM EXPERIMENTATION TO TRANSFORM GLOBAL AGRICULTURE

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ABSTRACT:

Restructuring farmer–researcher relationships and addressing complexity and uncertainty through joint exploration are at the heart of On-Farm Experimentation (OFE). OFE describes new approaches to agricultural research and innovation that are embedded in real-world farm management, and reflects new demands for decentralized and inclusive research that bridges sources of knowledge and fosters open innovation. Here we propose that OFE research could help to transform agriculture globally. We highlight the role of digitalization, which motivates and enables OFE by dramatically increasing scales and complexity when investigating agricultural challenges.

New innovation processes are urgently needed for agriculture to meet social, ecological and economic challenges globally[1]. There have been longstanding calls to place farmers at the centre of the innovation processes that serve them so that solutions can be better aligned with their needs and aspirations. Proponents of farmer participatory research championed farmers' enrolment in research, technology development and innovation processes, recognizing that farmers hold knowledge repositories about local production contexts and practices, and are themselves key sources of innovation as they routinely experiment as part of their production processes[2–6]. Despite successes with such approaches, a restructuring of the relationship between researchers and farmers has failed to materialize as standard practice, preventing the effective integration of science-based and farmer-based knowledge[7,8]. This best serves the needs of neither agri-food systems nor formal research, with the latter largely missing out on valuable and abundant knowledge and innovation generated by farmers[9–11].

We introduce here On-Farm Experimentation (OFE) as a new manifestation of collaborative experimental research. At its core is a growing global community that recognizes that building productive relationships between farmers and scientists is critical to develop the new innovation pathways needed to solve the challenges that contemporary agriculture faces. OFE is specifically a response to the inability of small-plot trials commonly used in on-farm research to provide sufficiently actionable insights to farmers, and that new solutions embracing agroecological scales are needed to better guide their practices[1]. OFE is the result of accumulated changes across several domains that individually may not be spectacular, but collectively realize a change substantial enough to acknowledge and start articulating. Often, this change is catalysed by the analytical, learning and decision support opportunities presented by digital technologies.

We define OFE and describe the reasons for its emergence, before estimating the scale of OFE activities. We then offer collective thoughts on how OFE research could help to transform agriculture globally, and argue for concerted and proactive institutional support to accelerate this change.

OFE EMBEDS RESEARCH IN FARM MANAGEMENT

OFE is defined as an innovation process that brings agricultural stakeholders together around mutually beneficial experimentation to support farmers' own management decisions. This vision is underpinned by three mechanisms that build on the complex and intertwined histories of formal and farmer participatory research, yet remain on the margins of scientific experimental practice globally. First, OFE research occurs in farmers' own fields and at scales that are meaningful to them, rather than in small experimental plots that are designed externally. Second, the private interests of farmers and of other OFE participants are explicitly acknowledged as a prerequisite to negotiate their alignment and build productive relationships. Third, experimenting in OFE research is understood as a deliberate process of joint exploration whereby researchers and others engage closely with farming realities to align with the ways farmers learn. The benefits are threefold: harnessing farmers' own knowledge, focusing the external perspective of other experts, and creating value for all by stimulating the production of new insights through co-learning and the hybridization of knowledge.

Implementation integrates these mechanisms through an iterative and flexible process. Field-scale experiments follow action research recommendations inviting participants to plan, act, observe, reflect and repeat, building on the key participatory concepts of demand-driven research, knowledge co-production and mutual learning[2,12–15] (Fig. 1).

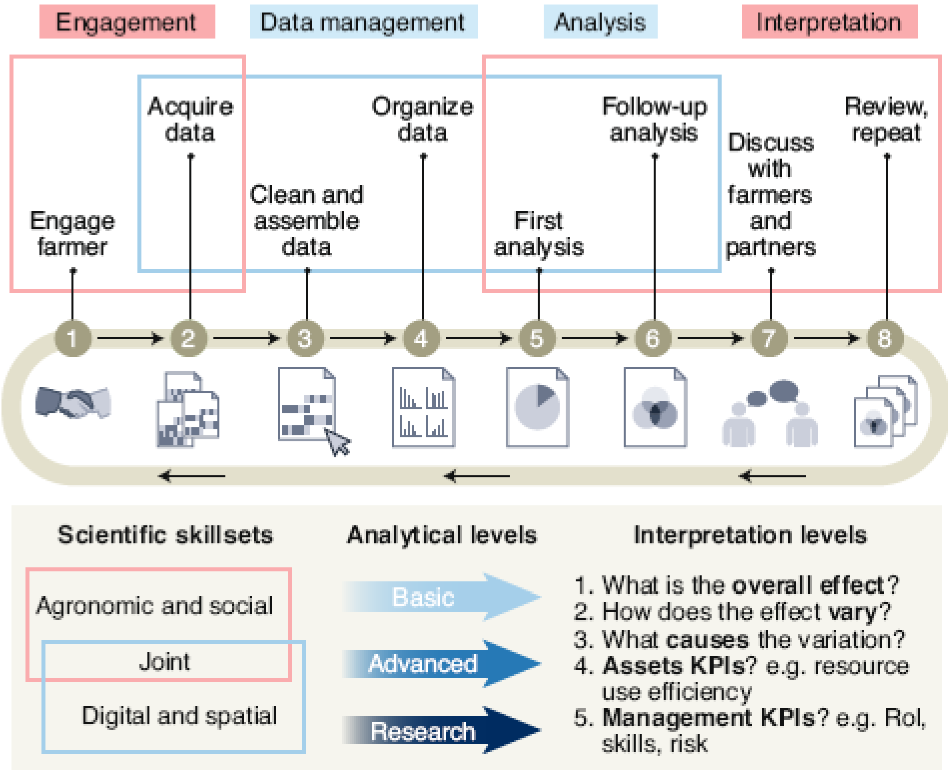

Figure 1 The OFE process. OFE follows an iterative process during which practical information is generated that farmers can easily understand, assess and readily convert to farm practices. Practically, OFE involves changing a management variable, observing and then discussing the outcome, with the primary objective of stimulating evidence-based learning and decisions. OFE implementation takes different forms but generally involves a step-wise process. Experiments are embedded within the farmers' own management and are thus usually conducted at the field scale. Insights are produced during discussions between the farmer and additional stakeholders at different stages of the process. New insights may change the route of this iterative process over time. A key measure of OFE success is the willingness of stakeholders to review outcomes and repeat the process. Progress can only be made when there are effective social mechanisms to promote engagement and learning, both along the way and beyond individual OFE schemes. The process thus involves both technological and social considerations. On the one hand, OFE revolves around data, produced in the farmers' own fields, the analysis of which at least generally requires the involvement of a specialist (steps 2–6). On the other hand, mechanisms such as co-learning and sharing between participants and peers are key to derive decisions from these data; that is, to build on the analysis to create value in the form of useful management insights (steps 5–8). Developing positive and useful relationships from the outset between partners is therefore essential and involves acknowledging their distinct motivations and skill sets to allocate tasks and negotiate rules of engagement (1), as well as the nature of socialization mechanisms (7), which may constitute entire processes in themselves. Scaling mechanisms, which include replication processes, are not represented here. KPIs, key productivity indicators; RoI, return on investment. Centre section reproduced with permission from IPNI.

OFE research is demand driven, because the motivations of farmers to gain information relevant to their own farm drive the research process[14,16,17]. OFE is a concrete, observable activity of clear and immediate interest to farmers[5,18] from which there is always something to learn[4,7]. In contrast to most agronomic research that derives general truths independently of specific conditions on farm[10,19], the intention is to foster a process of enquiry[17] to support private learning mechanisms7, building on existing knowledge in a form that is directly useful to a given farmer, field and context[4,20]. OFE embraces the heterogeneity of farming circumstances, practices and needs, providing practical and contextualized information about how to use, adapt and develop local innovations[11,21–23].

Then, researchers and other stakeholders add value to the experimental process by providing specialist skills and external perspectives to help farmers assess ideas on their terms[10,16,24]. Farmers' empirical knowledge and experiential learning[3,6] are complemented by suggesting metrics and experimental designs, performing analytics and documenting experiences, interpreting results and expanding horizons, proposing opportunities and next steps in the experimental process[4,11,12,14].

Finally, social learning at several scales generates new knowledge[3,7,11,15]. Within OFE, co-learning between partners is key, from the co-design of experiments to the interpretation of results[25,26]. Crucially, anchoring co-learning in the farm's data provides tangible focus. Beyond individuals' experiments, socialization with peers and other stakeholders promotes further co-learning through the sharing of data, ideas or insights[6,16]. These learnings are easily communicable to the local community because they are visible, relatable, not overly complex and not necessarily dependent on external resources to be replicated[7,8]. This promotes the replication of OFE locally to increase confidence in outcomes. It also encourages access to wider knowledge networks—if potential gains justify the investment[17,27]. This generates additional insights both socially, through further sharing and updating[5,12,28–31], and analytically, through meta-analysis and data integration[22,32–35].

A SHIFT TO THE ENDOGENOUS CREATION OF KNOWLEDGE

OFE brings experimentation forward, which holds profound practical and even philosophical implications for the building of knowledge and innovation in agriculture[3,4]. This knowledge creation is largely endogenous, anchored with farmers but also key actors positioned across the entire agri-food system[15,24]. Two aspects are particularly noteworthy for their relevance to research practice.

First, organizing thinking and activities around experimentation implies repositioning research relationships[5,8,20]. OFE focuses on building productive relationships between science-led and farmer-led experimentation, bridging the knowledge systems underpinning each as a means to foster the endogenous production of locally relevant knowledge. Farmer participatory research has long emphasized co-learning and meaningful interactions[2]. However, farmers typically participate in research that is designed and managed by researchers[15], testing accepted principles and technologies with an objective of diffusion, rather than hybridization. OFE thus aligns with efforts to support local innovation processes[11] while departing from a long tradition in research where the participatory philosophy has often been more of empowerment or consultation than creating new knowledge jointly in a collaborative or collegial fashion[2,5,7].

Second, a focus on experimentation leads to rediscovering the multidimensional ramifications of inspiration, ideation and implementation for problem-solving[36]. In agriculture, experimentation has seldom been recognized as a powerful process in its own right for the formulation of problems and the generation of insights through exploration. The norm for on-farm experiments has instead generally been to provide in situ validation to further the results of simulations and controlled environments.

Otherwise, on-farm trials serve a demonstration purpose, as part of extension efforts or as services purchased by farmers. By contrast, through OFE research, experimentation itself becomes a pragmatic process[20] to generate questions and drive change.

CONVERGENCE OF THE CONVERSATIONS IN AGRICULTURE SCIENCES

The genesis of OFE reflects three major and intersecting conversations in the agricultural sciences around the limitations of conventional experiments, demand for best research practices and growing digital opportunities.

PROGRESSING EXPERIMENTATION.

Conducting field experiments to increase the applicability of particular practices or technologies has a two-century-long history that culminated in the 1920s, when small-plot experiments and analytical techniques were pioneered to produce generalizable agronomic insight in research stations[5,12,14,22,23,31,33,37,38]. Scientists and consultants routinely use the same methods on farms to advise farmers in spite of important problems.

Spatial and temporal variations in crop and livestock production are far greater than trial treatment effects, the stability of which are highly sensitive to the scale, boundaries and descriptors used[18,19,32–34,39]. Furthermore, the statistical significance criteria used by scientists provide no indication as to the scope, meaningfulness or local usefulness of results, leaving to farmers the difficult and risky task of adapting recommendations[4,14,18,21,22,25,37]. OFE overcomes these problems by embedding experiments in farmers' management, grounding the experiments locally at scales that are meaningful to them[20]. OFE captures and manages landscape and in-field variability[13,18,19,35,40–43] (Fig. 2), thus converging with key agroecological principles[12].

Treatment comparisons prioritized by scientists, reflecting their historical origin in varietal selection, represent a subset of possible farm improvements. These are typically aimed at efficiency gains and substitution of management practices[31], whereas managing complexity and testing a suite of relevant activities or interactions fast become impractical, when not eliminated by design[3,14,21] or simply dismissed[4]. Farmers worldwide are increasingly facing complex sustainability problems that challenge their adaptive capabilities and create an altogether more unpredictable decision-making space. OFE offers an opportunity for agricultural experts to complement conventional agronomy research by working with the dynamic farm management that exists in the real world, from building locally relevant indicators to developing a new agronomy that better reflects the trade-offs across multiple dimensions that farmers face[1,3–6,21,23,24,34,39].

OPENING INNOVATION.

Sourcing innovation directly from farmers by supporting their own problem-solving processes stems from a recognized need for decentralized, inclusive and networked approaches to agricultural research, development and extension[3–8]. Disciplines as distinct as agronomy, ecology, geography, anthropology, engineering, business and management are reaching this consensus and arguing for collective action, yet institutional practices have so far changed little[2,5,6,8,10,11,14,15,17,20,21,25,29–31,38,39,41,44,45].

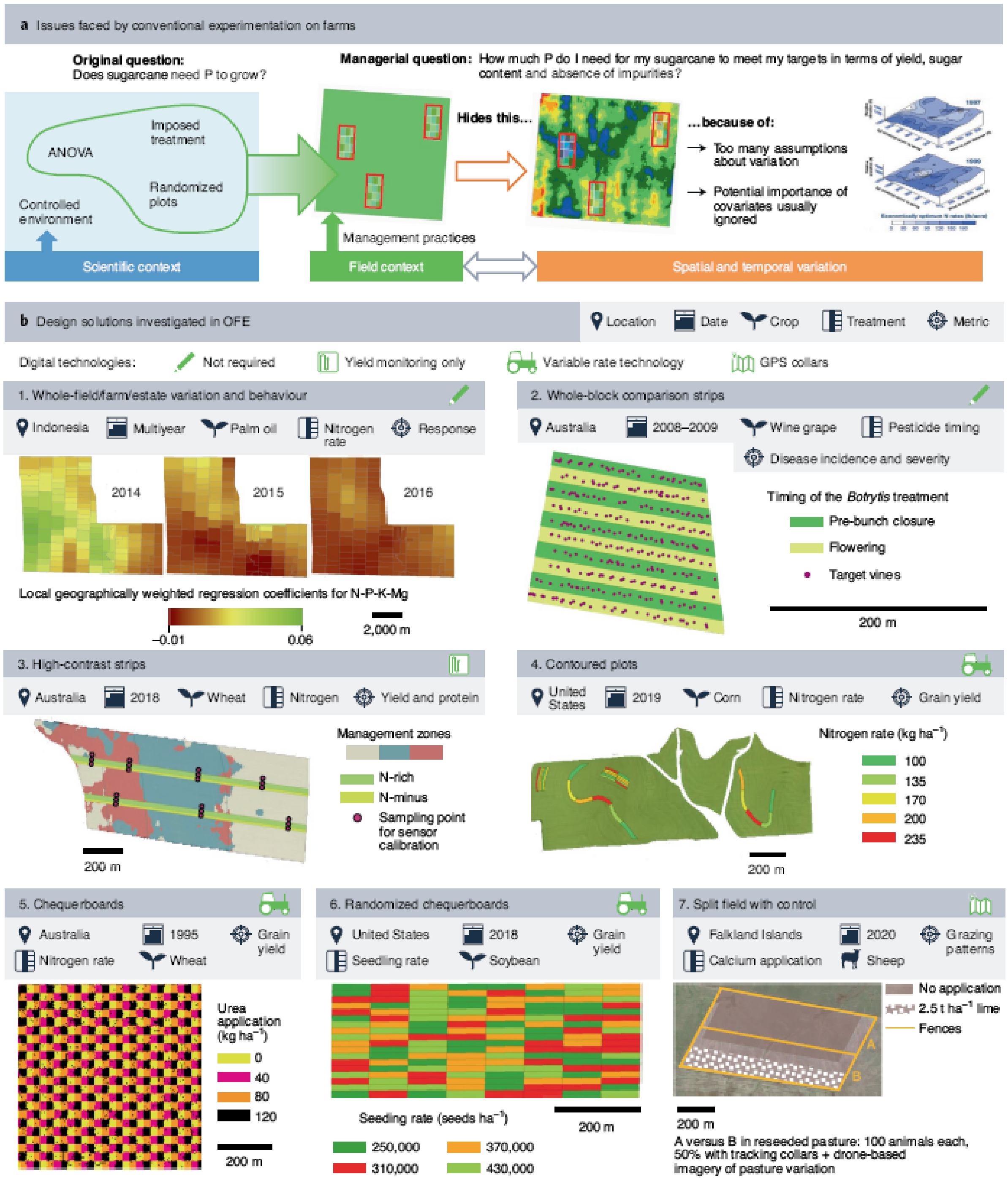

Figure 2 OFE designs to capture field-scale variations. a, Experimenting at the field scale may involve straightforward assessments of variation, especially in smallholder and subsistence farming, but also because farmers may attach low priority to statistical results and replications. One objective of OFE is to capture and utilize spatial and temporal variability. This is a problem that conventional trial methods cannot solve. ANOVA, analysis of variance. b, OFE initiatives across the world are developing a range of field-scale designs to address the issue. Challenges include addressing machinery requirements, data collection, spatial analytics and managerial relevance. Strategies range from the observations of yearly changes (1) to purposeful sampling (3, 4) or the utilization of the entire field (2, 5–7), especially in precision agriculture (3–6). Digital technologies add benefits (for example large datasets, ease of implementation, automation) as well as challenges (such as data processing).

Understanding how agricultural knowledge is produced has underpinned the paradigm shift from knowledge transfer to include knowledge exchange[38]. Exploration, co-learning, self-motivation and networks incorporating varied hybrid actors are known to be more conducive to positive change than top-down linear approaches[12,17,21,30]. However, commonly used farmer engagement approaches do not fundamentally challenge or restructure farmer– research relationships and roles, but instead further entrench the hierarchy and separation between the two[20]. The enduring and routine use of on-farm field trial plots, and statistical outputs that are by and large inaccessible to farmers, exemplifies the way analytical approaches continue to be formatted to suit scientific expertise and orthodoxy, rather than to embrace farm-scale challenges and the system-level processes that shape the enterprises of farmers and value-chain stakeholders. Furthering the problem is the shrinking of outreach services that leave a void of capacity and mechanisms to connect researchers and farmers[1,9,46].

In this context, OFE fulfils recommendations to 'open' innovation in agriculture through a highly actionable approach that connects sectors often working in silos[24,30,44]. In effect, OFE is a concrete mechanism for providing stakeholders with opportunities to demonstrate the relevance of different types of knowledge[12,14,15], enabling co-learning and building trust[6,16,17] around constructive dialogue[47]. This locally appropriate knowledge[4,10,36] can have long-lasting impacts[11], providing clear signals about what issues farmers prioritize[16]: those that they believe matter and that they can realistically do something about. OFE can thus help define clear transition pathways for agri-food systems[47] while reducing the risk that research steers towards outputs that mean much to scientists or other parties but little to primary users[3,14,21].

ENABLING DIGITALIZATION.

OFE does not require digital technologies, but the rise of investment and opportunities globally is a strong motivator[1,33,48,49].

On the one hand, digital technologies are enablers of OFE. Not only do they greatly facilitate implementation and analysis, they also allow new or different questions to be asked by collecting and logging very large amounts of information that could not be accessed otherwise, even in marginal environments[27,32,35,39,50].

On the other hand, OFE initiatives are enablers of digital technologies. The OFE process can be used to test the usefulness of data-driven advice, tailoring tools to real (rather than anticipated) needs[27]. For instance, OFE can contribute to platforms engaging farmers around the valorization of large amounts of data routinely produced but seldom used, such as within-field yield mapping or satellite imagery[18,25,51].

OFE could therefore help to realize one of the greatest opportunities of digitalization, which is to provide farmers, advisors and industry with business intelligence[42] in the form of a data-driven ability to understand local drivers of variability by testing decision rules, while actively rebalancing the control of data and the ownership of innovation processes towards farmers[35,40,41,49]. OFE could contribute to the responsible digitalization of knowledge systems by increasing understanding among all actors, providing much needed analytical capabilities while promoting data privacy and proactive governance[25,27,48,51,52].

It is also hoped that OFE associated with digital technologies and big data will support research on the biome of agroecological landscapes by informing the integration of analytical scales[25,31,34,39]. Other promising applications include building agricultural versions of citizen science databases on a variety of key agricultural and public interest issues—ranging from the presence of pests or available water to monitoring landscape and climate change impacts, to informing indicators of food security, sustainability, and even rural social justice—in the increasingly connected sectors of both the developing and industrialized worlds[25,27,39,45,46,49,50].

SCALE OF ACTIVITIES AND DIVERSITY OF APPROACHES

OFE initiatives are increasing in number across the world, probably involving well over 30,000 farms in more than 30 countries. This conservative estimate originates from the observation of varied groups globally[8,11,15,33,42] that signal the existence of a distinct and growing community of practice.

These groups are led by farmers, civil organizations, businesses, social enterprises or scientists. Among the latter, an international network involved in 11 OFE initiatives[11,16,25,26,40,52–55], represented by the authors, formed to formalize the emerging scientific field of OFE research around six core principles (Fig. 3).

Great diversity exists even within this subset of the OFE community, reflecting that communication is only recent. Each project evolved to implement its own solutions, each rooted in contextual conditions and therefore led by varying objectives and available resources, rather than shared strategies[20,56]. For instance, research topics should be framed by farmers or other primary stakeholders; however, mirroring the participatory experience[2], some initiatives follow a more scientist-driven approach for the benefits of added explanatory power or scalability. Scaling strategies, analytical approaches and data production practices differ as well, from monitoring only a few variables of interest to systematically inputting very large datasets from electronic harvest records into information systems. Importantly, 6 of the 11 OFE initiatives described started as strategies to demonstrate the value of digitalization.

TRANSFORMATIONAL POTENTIAL

OFE could reach much further and become a vehicle for transformational change[28] in agriculture. Four key features suggest this potential.

SYSTEMIC.

OFE provides a much needed[5,6,9,21,29] systemic process to link the knowledge of farmers, researchers, consultants and other stakeholders, creating new tools and channelling methodologies to investigate emerging questions, as well as enduring problems[1,57]. Although not immune to power imbalances[2,20], OFE can help to overcome hierarchies between formal and informal knowledge systems. Openly negotiating the private interests of varied participants[4,6,12,17,23,24,29–31] ensures salience, credibility against vested interests through scientific scrutiny and, most importantly, legitimacy[3,16,56].

As such, OFE can be both a vehicle for technological innovation and a social and institutional innovation[29]—crucial conditions for systemic change that are often overlooked[11,21,47]. OFE research enables both local and wider-reaching learning that not only challenges and changes understanding and beliefs, but also redefines the pathways that lead to them, which is key to transformational change in agriculture[15,28,38,57].

ADAPTABLE.

Adaptability is a crucial feature of social innovations that achieve scale and impact[36,57]. Unlike small-plot agronomic research and most participatory endeavours[15], experimenting and learning[3] in OFE can

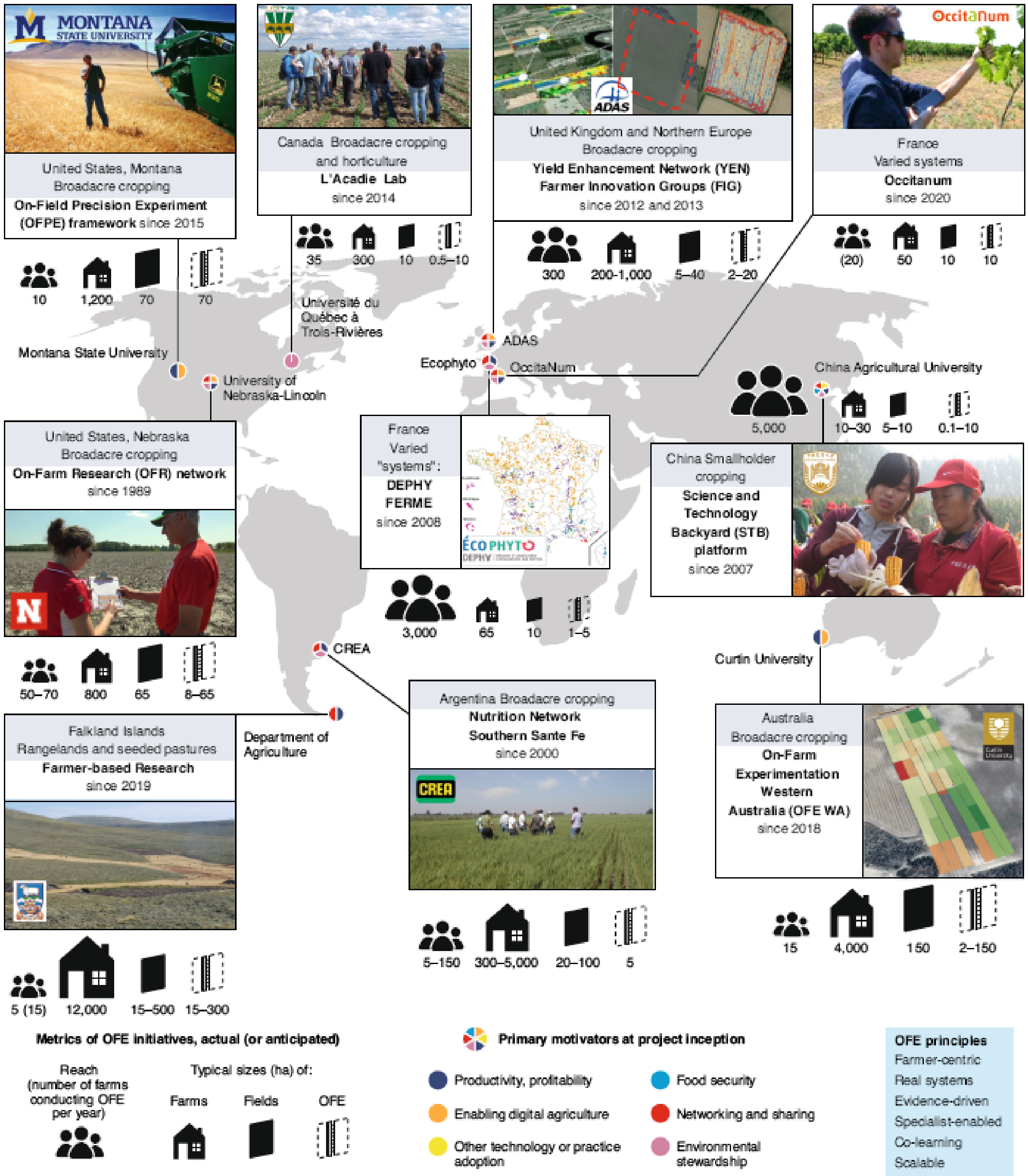

Figure 3 Examples of OFE initiatives connecting across the world. OFE has emerged largely independently in very different environments. The 11 OFE initiatives described here have started to connect and share experiences, demonstrating the existence of an active community of practice. All OFE initiatives share a farmer-centric philosophy, through which the collaborative research process is embedded in farmers' management, which involves sourcing information from farmers and their managed fields to provide insights that are directly relevant to farmers. Image at top right (France: varied systems) reproduced with permission from ref. 58. Map of France adapted with permission from EcoPhytoPIC/ACTA under Creative Commons license CC BY-NC-SA 4.0. Image from the "China: Smallholder cropping" box reproduced from ref. 59, Springer Nature Limited.

be undertaken in myriad ways (Fig. 2), and in a wide range of institutional contexts, even when resources are limited (Fig. 3). Diversity is galvanizing the OFE community because it shows that, although there is no one-size-fits-all operational recipe[15], even in digitally driven projects[48,49], much can be learnt by understanding the solutions others have found in specific contexts[1,9,26,30].

Critically, OFE can stand alone as well as fit within broader processes to support change. For instance, OFE initiatives (Fig. 3) have built and nurtured relationships between research institutions, farmers, consultants, students, governments and industries; tested technological innovations within varied contexts; refined methodologies to support pesticide reduction or adaptation to climate change; created resources for education and training; and prioritized mechanisms leveraging the allocation of resources for research.

VALUED.

A third powerful feature to sustain scaling and large system change is the value OFE creates for participants. Public funds must play a role in OFE to demonstrate common good outcomes such as environmental impact, food security or productivity[27]. However, OFE also incentivizes participants by providing a platform wherein private interests can converge[45]. That is, insights for farmers, data for scientists, credibility for consultants, prototypes for innovation ecosystem platforms and accelerated learnings for all[3,7,20,23]. Following from this, a promising avenue is the development of participant-funded business models for OFE, in which the open innovation process is based on practical operations, insights are coupled with client demand and value is demonstrated, rather than expected[13,36,42]. Crucially, this path would alleviate the historical reliance on public funds for participatory research and extension services[7].

DISRUPTIVE.

The emergence of a global OFE community is in itself an important transformative factor. A growing number of stakeholders are recognizing that current approaches are yet to integrate key insights developed in social and physical sciences and that experimentation in agriculture must evolve to answer the new questions brought up by transitioning systems and changing opportunities. People are reacting and adapting to change, developing new ways of learning[38]. As such, OFE research represents a disruption.

Theoretical roots and early projects were pioneered decades ago, driven by research or commercial partners in both developing and industrialized countries[5,13,16,18,42,55]. Today, OFE scientists belong to communities such as Precision Agriculture, Open Innovation and Living Labs, or are associated with farmer-led organizations asking for resources to conduct OFE. Tremendous interest has been registered globally. Leveraging both farmers' empirical knowledge and digital technologies is building bridges between social and technical sciences, opening new opportunities to braid research perspectives and practices.

STRENGTHENING THE OFE COMMUNITY

Current conditions are allowing OFE to gain momentum[13]. This is happening in spite of current structures and incentives within the agricultural sciences, with funding mechanisms and norms favouring conventional experimentation. Researchers and influencers need the strategic alignment and support of their institutions to carry the transformational potential of OFE forward[8,15].

OFE qualifies as a systemic innovation that stimulates wide-reaching and holistic change through complex and multi-level thinking. Such processes require ongoing provision to build relationships, skills and operational capacity[9,16,26,36,47], but also to foster flexibility, creativity and agility[29–31]. In practice, initiating, promoting, coordinating and scaling OFE inclusively also requires continuity in support[11,25] to enable programmes to work with farming communities and varied stakeholders long-term[17,24,31], particularly when OFE is coupled with the production of public goods[26].

OFE is challenging the status quo, especially in experimental agronomy, where a long tradition exists[14,44]. Evolving an established system implies a transaction cost that is typically greater than that anticipated[57] and cannot be supported by individuals alone.

OFE ideas have not yet sufficiently permeated the scientific community. As with the broader area of farmer-led research[11], there simply is not a critical mass of OFE documentation, results or reviewers who are part of the mainstream conversation to make visible the emerging scientific field of OFE research, catalyse activities and enable institutional culture change[9,36,45,57].

Consequently, achieving transformational change through OFE will not be a passive process. Challenges involve institutional policy as much as research practice[2,6,20]. The foremost priority is to develop the sciences of OFE, which are all those applicable to conducting better experimentation with farmers. Theoreticians and practitioners need to align their work conceptually, methodologically and empirically to provide a solid and unified foundation for future efforts. A dedicated group would accelerate the development of OFE sciences by sharing methodologies[18,25], reflecting on practice[2,12,14,23,29], recruiting others and enabling the strategic coordination of efforts, notably by prioritizing an agenda for OFE research. The group needs to be open and diverse to foster cross-fertilization[1,27] (Fig. 4), yet must remain linked around its central concepts[44,45], consolidating scientific foundations to continue demonstrating the worldwide relevance of OFE.

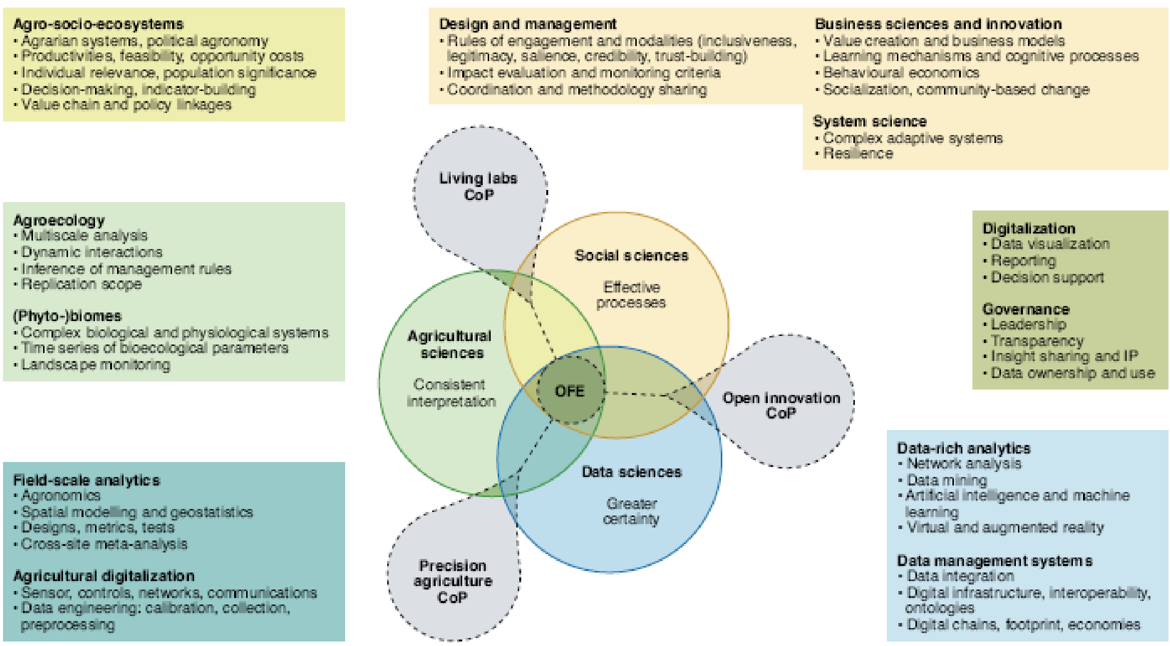

Figure 4 OFE scientific directions. There are two intertwined types of research objects in OFE: the farmers' questions (how to improve management) and the methodologies required to best address these (how to improve research through OFE). Multiple research directions exist that are relevant to OFE. Strategically, the growing OFE community of practice must organize and prioritize its own research directions to align conceptually, methodologically and empirically. Disciplinary overlaps are crucial to adapt scientific concepts and methodologies to the specific requirements of OFE, and to succeed in providing the new insights in

which reside its value. No scientist covers all three disciplinary domains; therefore, the inclusion of integrative generalist skills and the development of transdisciplinary communication tools are vital. CoP, community of practice; IP, intellectual property.

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AUTHOR CONTRIBUTIONS

M.L. and S.C. developed the study concept. M.M., D.G., J.I., V.B.-M., T.M., R.S.-B. and A.H. contributed additional concept development. M.L. and D.G. obtained the data and prepared the results. M.L., M.M., L.T., D.K., F.O.G., B.M., V.B.-M., J.R., C.H. and W.Z. contributed data. M.L. wrote the manuscript with input from all other authors.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information (sources of Figs. 1–3).

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