On-Farm Experimentation to transform global agriculture

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Abstract

Restructuring farmer-research relationships, 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 decentralised and inclusive research that bridge sources of knowledge and foster open innovation. Here, we propose that OFE research could help transform agriculture globally. We highlight the role of digitalisation, 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, recognising that farmers hold knowledge repositories about local production contexts and practices, and are themselves key sources of innovation since 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 materialise as standard practice, preventing the effective integration of science-based and farmer-based knowledge[7,8]. This neither best serves the needs of 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 who recognises 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 realise a change significant 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 providing a framework to compare OFE activities. We then offer collective thoughts on how OFE research could help 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 pre-requisite to negotiate their alignment and build productive relationships. Third, experimenting in OFE research is understood as a deliberate process of joint exploration, by which researchers and others engage closely with farming realities to align with the ways farmers learn. The benefits are three-fold: 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 hybridisation 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).

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 with 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 mechanisms[7], 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 contextualised 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 individual OFEs, socialisation 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 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, 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 in the entire agri-food system[15,24]. Two aspects are particularly noteworthy for their relevance to research practice.

First, organising 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 emphasised 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 hybridisation. OFE thus aligns with efforts to support local innovation processes[11] while departing from a long tradition 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 multi-dimensional ramifications of inspiration, ideation, and implementation for problem-solving[36]. In agriculture, experimentation has seldom been recognised as a powerful process in its own right for the formulation of problems and the generation of insights through exploration. Rather, the norm for on-farm experiments has generally been to provide the *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. In contrast, through OFE research, experimentation itself becomes a pragmatic process[20] to generate questions and drive change.

Converging the conversations of agriculture science

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 sports a two-century-long history that culminated in the 1920's, when small-plot experiments and analytical techniques were pioneered to produce generalisable 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 significant problems.

Spatial and temporal variations in crop and livestock production are far greater than trial treatment effect, the stability of which is 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 because experiments are embedded in farmers' management, grounded 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 prioritised 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 recognised need for decentralised, 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].

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 recognised 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 which statistical outputs are by 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 to provide 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 prioritise[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 digitalisation. 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 asking new or different questions 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, OFEs 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 valorisation 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 realise one of the greatest opportunities of digitalisation, 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 toward farmers[35,40,41,49]. OFE could contribute to the responsible digitalisation 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].

OFE associated with digital technologies and big data is also hoped to support research on the biome of agro-ecological 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 range 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 industrialised worlds[25,27,39,45,46,49,50].

Scale of activities and diversity of approaches

OFE initiatives are increasing in numbers across the world, likely involving well over 30,000 farms across 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 organisations, businesses, social enterprises or scientists. Among the latter, an international network involved in 11 OFE initiatives (Fig.

3)[16,25,26,40,52-55] represented by the authors, formed to formalise the emerging scientific field of OFE research.

Great diversity exists even within this subset of the OFE community, reflecting that communication is only recent. Each project evolved to implement their 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. Significantly, 6 of the 11 OFE initiatives described started as a strategy to demonstrate the value of digitalisation.

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 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 be undertaken in a myriad of ways (Fig.2), in a wide range of institutional contexts, even when resources are limited (Fig. 3). Diversity is galvanising the OFE community for it shows that, while 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; prioritised 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 where private interests can converge[45]. That is, insights for farmers, data for scientists, credibility for consultants, prototypes for innovation ecosystem platforms, accelerated learnings for all[3,7,20,23]. Subsequently, a promising avenue is the development of participant-funded business models for OFE, by 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 of 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 recognising 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 industrialised countries[5,13,16,18,42,55]. Today, OFE scientists belong to communities such as those of Precision Agriculture, Open Innovation and Living Labs, or are associated with farmer-led organisations 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 forward the transformational potential of OFE[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 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 better conduct 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 prioritising an agenda for OFE research. The group needs to be open and diverse to foster cross-fertilisation[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.

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Competing interests

The authors declare no competing interests.

Data availability statement

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information file (sources of Fig. 1 and 2).

References

1 Whitfield, S., Challinor, A. J. & Rees, R. M. Frontiers in Climate Smart Food Systems: Outlining the Research Space. *Frontiers in Sustainable Food Systems* **2**, doi:10.3389/fsufs.2018.00002 (2018).

2 Scoones, I. & Thompson, J. (Practical Action Publishing, Worwideshire, UK, 2009).

3 Stone, G. D. Towards a General Theory of Agricultural Knowledge Production: Environmental, Social, and Didactic Learning. *Cult Agric Food Envi* **38**, 5-17, doi:10.1111/cuag.12061 (2016).

4 Hansson, S. O. Farmers' experiments and scientific methodology. *European Journal for Philosophy of Science* **9**, doi:10.1007/s13194-019-0255-7 (2019).

5 Maat, H. & Glover, D. Alternative configurations of agronomic experimentation. *In: Contested Agronomy: Agricultural Research in a Changing World (Oxon, Routledge)*, 131-145 (2012).

6 Šūmane, S. *et al.* Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *J. Rural Stud.* **59**, 232-241, doi:10.1016/j.jrurstud.2017.01.020 (2018).

7 de Janvry, A., Sadoulet, E. & Rao, M. Adjusting extension models to the way farmers learn. Policy brief n°159. *FERDI (Fondation pour les Etudes et Recherches sur le Développement International)* (2016).

8 Cross, R. & Ampt, P. Exploring Agroecological Sustainability: Unearthing Innovators and Documenting a Community of Practice in Southeast Australia. *Soc. Nat. Resour.* **30**, 585-600, doi:10.1080/08941920.2016.1230915 (2016).

9 Rickards, L., Alexandra, J., Jolley, C., Farhey, K. & Frewer, T. Review of agricultural extension. (ACIAR (Australian Centre for International Agricultural Research), Canberra, 2019).

10 MacMillan, T. & Benton, T. G. Engage farmers in research. *Nature* **509**, 25-27 (2014).

11 Waters-Bayer, A. *et al.* Exploring the impact of farmer-led research supported by civil society organisations. *Agriculture & Food Security* **4**, doi:10.1186/s40066-015-0023-7 (2015).

12 Berthet, E. T. A., Barnaud, C., Girard, N., Labatut, J. & Martin, G. How to foster agroecological innovations? A comparison of participatory design methods. *J. Environ. Planning Manage.* **59**, 280-301, doi:10.1080/09640568.2015.1009627 (2015).

13 Cook, S. *et al.* An On-Farm Experimental philosophy for farmer-centric digital innovation. *In: 14th International Conference on Precision Agriculture (Montreal, Quebec, Canada)* (2018).

14 Cook, S. E., Cock, J., Oberthür, T. & Fisher, M. On-Farm Experimentation. *Better Crops* **97**, 17-20 (2013).

15 Richardson, M. *et al.* Farmer research networks in principle and practice. *International Journal of Agricultural Sustainability*, 1-18, doi:10.1080/14735903.2021.1930954 (2021).

16 Thompson, L. J. *et al.* Farmers as Researchers: In-depth Interviews to Discern Participant Motivation and Impact. *Agron. J.* **111**, 2670-2680, doi:10.2134/agronj2018.09.0626 (2019).

17 Sewell, A. M. *et al.* Hatching new ideas about herb pastures: Learning together in a community of New Zealand farmers and agricultural scientists. *Agric. Syst.* **125**, 63-73, doi:10.1016/j.agsy.2013.12.002 (2014).

18 Bramley, R. G. V., Lawes, R. & Cook, S. E. Spatially distributed experimentation. *In: Precision Agriculture for Sustainability and Environmental Protection (Routledge)*, 205-218 (2013).

19 Marchant, B. *et al.* Establishing the precision and robustness of farmers' crop experiments. *Field Crops Res.* **230**, 31-45, doi:10.1016/j.fcr.2018.10.006 (2019).

20 Briggs, J. Indigenous knowledge: A false dawn for development theory and practice? *Progress in Development Studies* **13**, 231–243 (2013).

21 Caron, P., Biénabe, E. & Hainzelin, E. Making transition towards ecological intensification of agriculture a reality: the gaps in and the role of scientific knowledge. *Current Opinion in Environmental Sustainability* **8**, 44-52, doi:10.1016/j.cosust.2014.08.004 (2014).

22 Kool, H., Andersson, J. A. & Giller, K. E. Reproducibility and external validity of on-farm experimental research in Africa. *Exp. Agric.*, 1-21, doi:10.1017/s0014479720000174 (2020).

23 De Roo, N., Andersson, J. A. & Krupnik, T. J. On-Farm Trials for Development Impact? The Organisation of Research and the Scaling of Agricultural Technologies. *Exp. Agric.*, 1-22, doi:10.1017/s0014479717000382 (2017).

24 Möhring, N. *et al.* Pathways for advancing pesticide policies. *Nature Food* **1**, 535-540, doi:10.1038/s43016-020-00141-4 (2020).

25 Sylvester-Bradley, R. *et al.* Agronōmics: transforming crop science through digital technologies. *Advances in Animal Biosciences* **8**, 728-733, doi:10.1017/s2040470017001029 (2017).

26 Ruiz, J., Dumont, A. & Zingraff, V. Une méthodologie de cocréation pour renouveler l'action collective (chap. 10). *In: Penser le gouvernement des ressources naturelles (Presses de l'Université Laval)*, 293-330 (2019).

27 Fabregas, R., Kremer, M. & Schilbach, F. Realizing the potential of digital development: The case of agricultural advice. *Science* **366**, doi:10.1126/science.aay3038 (2019).

28 Dowd, A.-M. *et al.* The role of networks in transforming Australian agriculture. *Nature Climate Change* **4**, 558-563, doi:10.1038/nclimate2275 (2014).

29 Klerkx, L., van Mierlo, B. & Leeuwis, C. Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. *In: Farming Systems Research into the 21st Century: The New Dynamic (Dordrecht)*, 457-483 (2012).

30 Ingram, J., Gaskell, P., Mills, J. & Dwyer, J. How do we enact co-innovation with stakeholders in agricultural research projects? Managing the complex interplay between contextual and facilitation processes. *J. Rural Stud.* **78**, 65-77, doi:10.1016/j.jrurstud.2020.06.003 (2020).

31 Jackson, L. *et al.* Biodiversity and agricultural sustainagility: from assessment to adaptive management. *Current Opinion in Environmental Sustainability* **2**, 80-87, doi:10.1016/j.cosust.2010.02.007 (2010).

32 Laurent, A., Kyveryga, P., Makowski, D. & Miguez, F. A Framework for Visualization and Analysis of Agronomic Field Trials from On-Farm Research Networks. *Agron. J.* **111**, 2712-2723, doi:10.2134/agronj2019.02.0135 (2019).

33 Kyveryga, P. M. On-Farm Research: Experimental Approaches, Analytical Frameworks, Case Studies, and Impact. *Agron. J.* **111**, 2633-2635, doi:10.2134/agronj2019.11.0001 (2019).

34 Tremblay, N. Modelling and decision support systems in precision agriculture. *In: Precision agriculture for sustainability, Burleigh Dodds Science Limited (Cambridge)*, 145-168, doi:10.19103/as.2017.0032.07 (2019).

35 Bullock, D. S. *et al.* The Data-Intensive Farm Management Project: Changing Agronomic Research Through On-Farm Precision Experimentation. *Agron. J.* **111**, 2736-2746, doi:10.2134/agronj2019.03.0165 (2019).

36 Wyatt, J., Brown, T. & Carey, S. The Next Chapter in Design for Social Innovation. *Stanford Social Innovation Review* **19**, 40-47 (2021).

37 Griffin, T. W., Fitzgerald, G. J., Lowenberg-DeBoer, J. & Barnes, E. M. Modeling local and global spatial correlation in field-scale experiments. *Agron. J.*, doi:10.1002/agj2.20266 (2020).

38 Coudel, E., Tonneau, J.-P. & Rey-Valette, H. Diverse approaches to learning in rural and development studies: review of the literature from the perspective of action learning. *Knowledge Management Research & Practice* **9**, 120-135, doi:10.1057/kmrp.2011.12 (2017).

39 Browning, D. M. *et al.* Emerging technological and cultural shifts advancing drylands research and management. *Front. Ecol. Environ.* **13**, 52-60, doi:10.1890/140161 (2015).

40 Maxwell, B. *et al.* Can optimization associated with on-farm experimentation using site-specific technologies improve producer management decisions? *In: 14th International Conference on Precision Agriculture (Montreal, Quebec, Canada)* (2018).

41 Kindred, D. *et al.* Supporting and analysing on-farm Nitrogen tramline trials so farmers, industry, agronomists and scientists can LearN together. *In: 14th International Conference on Precision Agriculture (Montreal, Quebec, Canada)* (2018).

42 Oberthür, T. *et al.* Plantation Intelligence applied Oil Palm operations: unlocking value by analysing commercial data. *The Planter* **93**, 339-351 (2017).

43 Jin, H., Shuvo Bakar, K., Henderson, B. L., Bramley, R. G. V. & Gobbett, D. L. An efficient geostatistical analysis tool for on-farm experiments targeted at localised treatment. *Biosys. Eng.* **205**, 121-136, doi:10.1016/j.biosystemseng.2021.02.009 (2021).

44 Berthet, E. T., Hickey, G. M. & Klerkx, L. Opening design and innovation processes in agriculture: Insights from design and management sciences and future directions. *Agric. Syst.* **165**, 111-115, doi:10.1016/j.agsy.2018.06.004 (2018).

45 Curley, M. Twelve principles for open innovation 2.0. *Nature* **533**, 315-316 (2016).

46 Ryan, S. F. *et al.* The role of citizen science in addressing grand challenges in food and agriculture research. *Proc. Biol. Sci.* **285**, doi:10.1098/rspb.2018.1977 (2018).

47 Herrero, M. *et al.* Innovation can accelerate the transition towards a sustainable food system. *Nature Food* **1**, 266-272, doi:10.1038/s43016-020-0074-1 (2020).

48 Fielke, S. J. *et al.* Conceptualising the DAIS: Implications of the 'Digitalisation of Agricultural Innovation Systems' on technology and policy at multiple levels. *NJAS - Wageningen Journal of Life Sciences* **90-91**, 100296, doi:10.1016/j.njas.2019.04.002 (2019).

49 Cook, S., Jackson, E. L., Fisher, M. J., Baker, D. & Diepeveen, D. Embedding digital agriculture into sustainable Australian food systems: pathways and pitfalls to value creation. *International Journal of Agricultural Sustainability*, 1-22, doi:10.1080/14735903.2021.1937881 (2021).

50 van Etten, J. *et al.* Crop variety management for climate adaptation supported by citizen science. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 4194-4199, doi:10.1073/pnas.1813720116 (2019).

51 Ingram, J. & Maye, D. What Are the Implications of Digitalisation for Agricultural Knowledge? *Frontiers in Sustainable Food Systems* **4**, doi:10.3389/fsufs.2020.00066 (2020).

52 McNee, M. Government support for farmer-based research in the Falkland Islands. *Agricultural Advisory Committee - AAC Agenda 07.11.2019, Falkland Islands Government*, Item 10 (2019).

53 Zhang, W. *et al.* Closing yield gaps in China by empowering smallholder farmers. *Nature* **537**, 671-674, doi:10.1038/nature19368 (2016).

54 Lechenet, M., Dessaint, F., Py, G., Makowski, D. & Munier-Jolain, N. Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nat Plants* **3**, 17008, doi:10.1038/nplants.2017.8 (2017).

55 García, F. *et al.* La red de nutrición de la región Crea Sur de Santa Fe : resultados y conclusiones de los primeros diez años 200-2009 (AACREA, Buenos Aires). (2010).

56 Posner, S. M., McKenzie, E. & Ricketts, T. H. Policy impacts of ecosystem services knowledge. *Proc. Natl. Acad. Sci. U. S. A.* **113**, 1760-1765, doi:10.1073/pnas.1502452113 (2016).

57 Moore, M.-L., Riddell, D. & Vocisano, D. Scaling Out, Scaling Up, Scaling Deep. Strategies of Non-profits in Advancing Systemic Social Innovation. *The Journal of Corporate Citizenship*, 67-84, doi:10.9774/GLEAF.4700.2015.ju.00009 (2015).

List of Figures

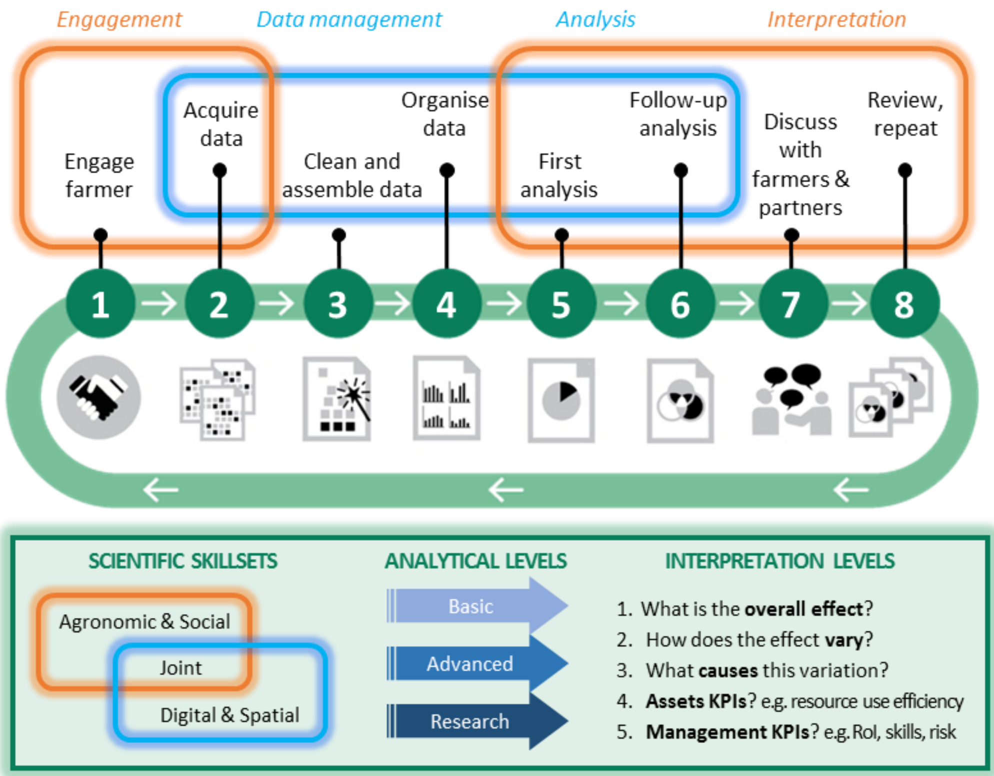

Fig. 1 | The OFE process. On-Farm Experimentation follows an iterative process during which practical information is generated which farmers can easily understand, assess and readily convert to farm practices. Practically, OFE involves changing a management variable, observing, and discussing the outcome 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 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 OFEs. The process thus involves both technological and social considerations. On one hand, OFE revolves around data, produced in the farmers' own fields, of which at least the analysis 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 this data, i.e. to build on its 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, which involves acknowledging their distinct motivations and skill sets to allocate tasks and negotiate rules of engagement (1), as well as the nature of socialisation mechanisms (7) which might constitute entire processes in themselves. Not represented here are scaling mechanisms, which include replication processes. KPIs = Key Productivity Indicators.

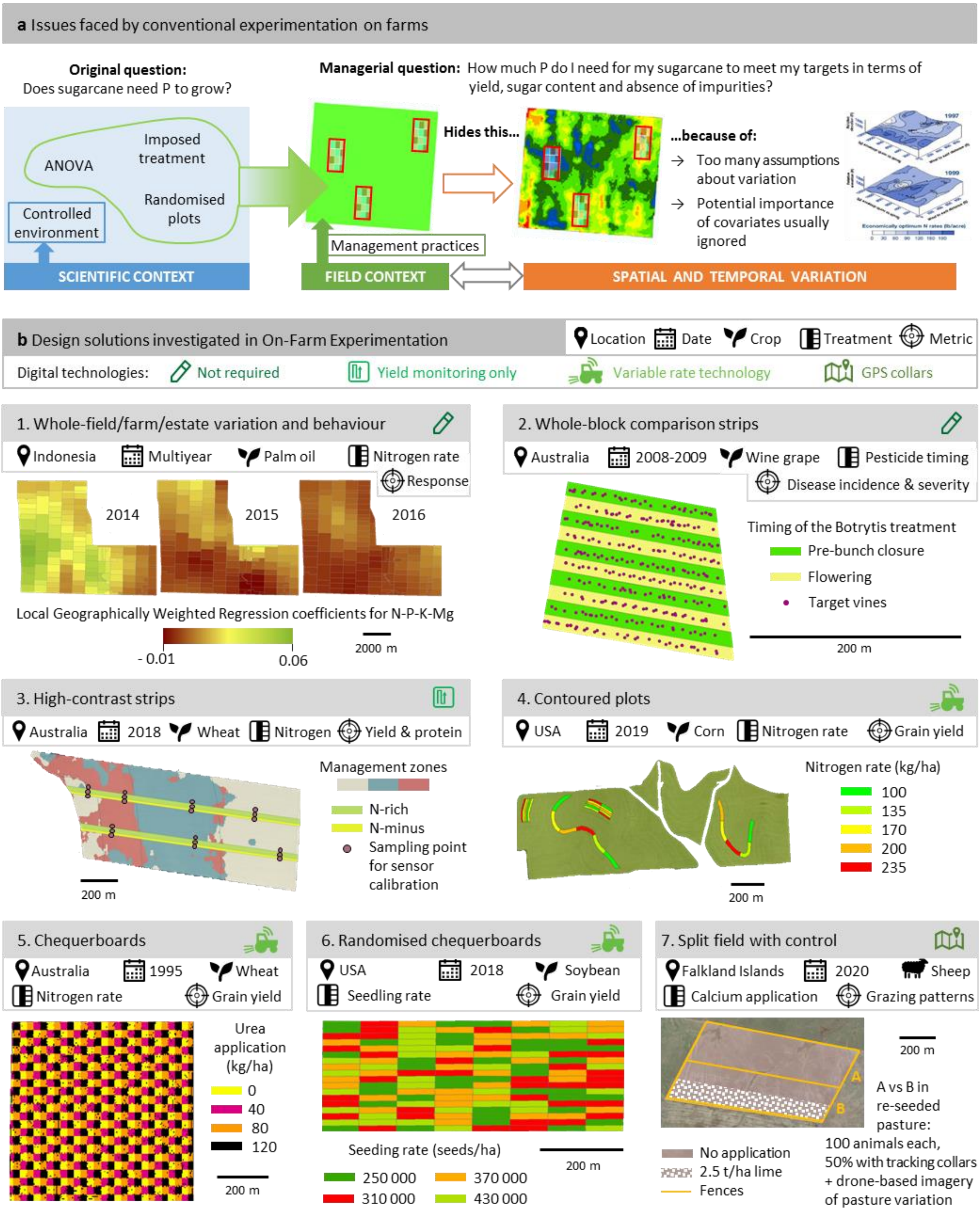

Fig. 2 | OFE designs to capture field-scale variations. Experimenting at field scale may involve straightforward assessments of variation, especially in smallholder and subsistence farming, but also because farmers may attach low priority to statistical results and replications. One objective of OFE is to capture and utilise spatial and temporal variability. This is a problem that conventional trial methods cannot solve (a). OFE initiatives across the world are developing a range of field-scale designs to address the issue (b). Challenges include addressing machinery requirements, data collection, spatial analytics, managerial significance. Strategies range from the observations of yearly changes (1.) to purposeful sampling (3.4.) or the utilisation of the entire field (2.5.6.7.) especially in precision agriculture (3.4.5.6.). Digital technologies add benefits (e.g. large datasets, ease of implementation, automation) as well as challenges (e.g. data processing).

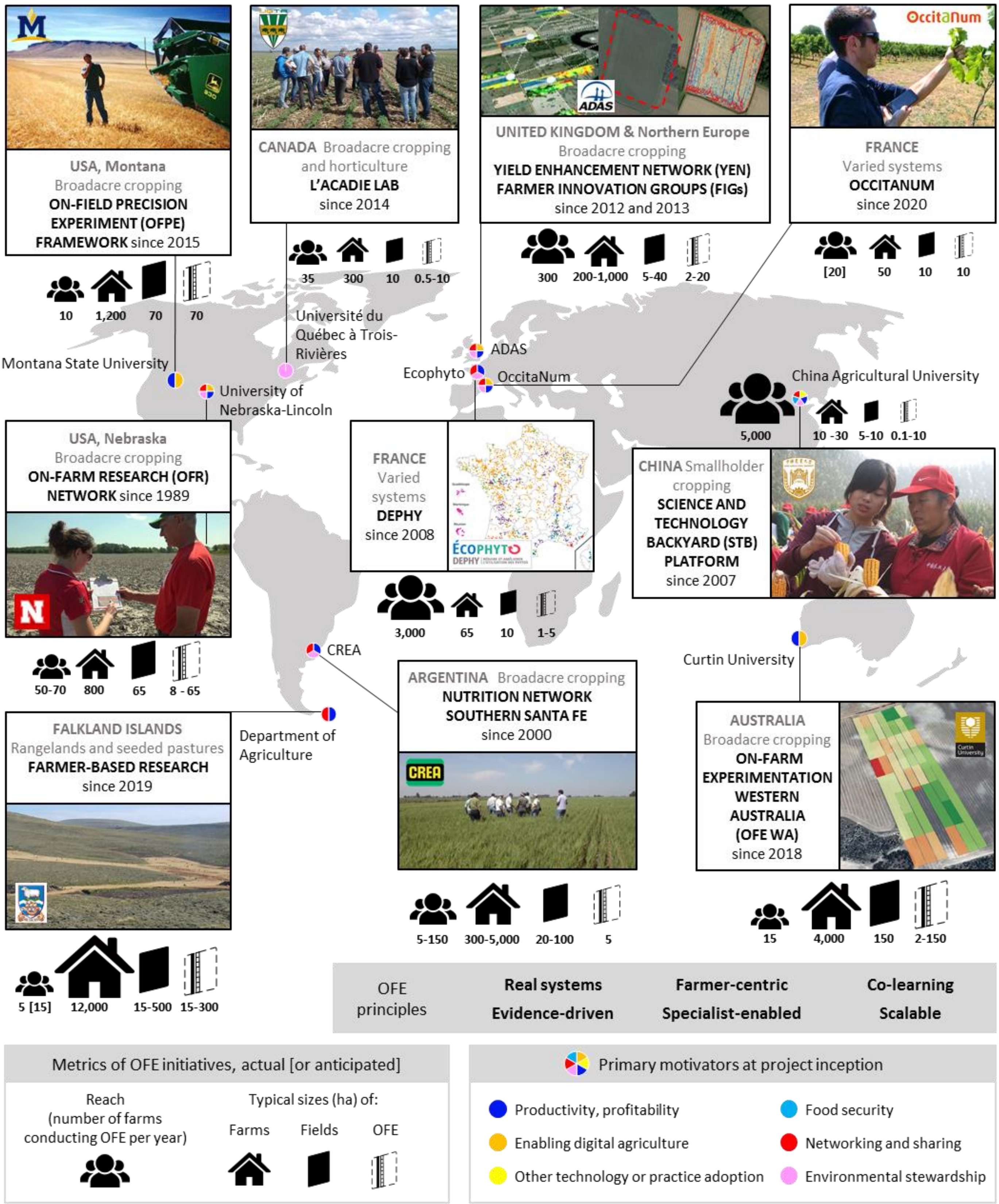

Fig. 3 | Examples of OFE initiatives connecting across the world. OFE has emerged largely independently in very different environments. The 11 OFE initiatives described here have started to connect and share experiences, demonstrating the existence of an active community of practice. All OFE initiatives share a farmer-centric philosophy by 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.

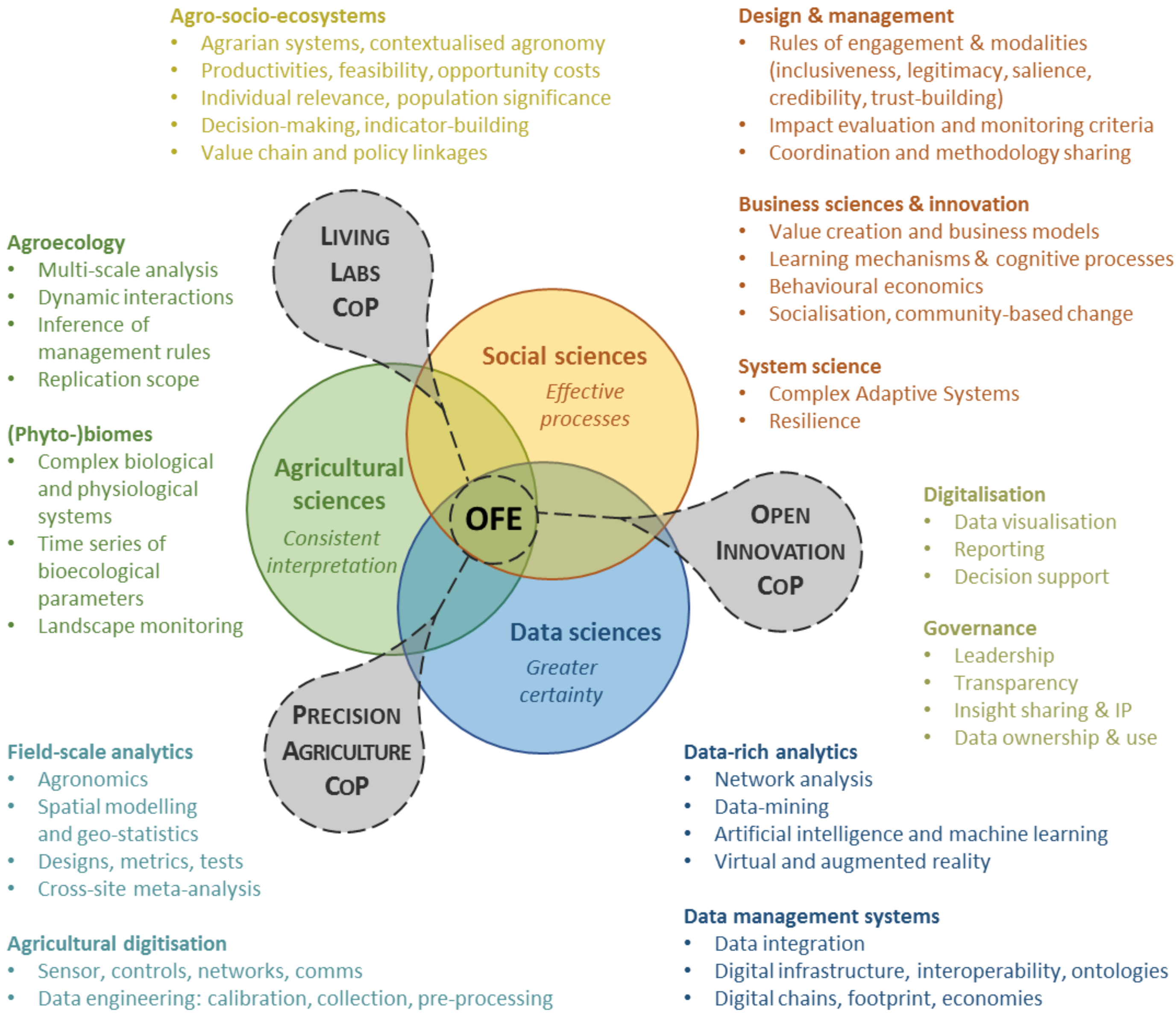

Fig. 4 | OFE scientific directions. There are two intertwined types of research objects in OFE: the farmers' questions (how to improve management), and the methodologies required to best address these (how to improve research through OFE). Multiple research directions exist that are relevant to OFE. Strategically, the growing OFE community of practice must organise and prioritise 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.