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ABSTRACT

New forms of field experimentation are currently emerging to support transitions towards sustainable agriculture, including "multi-actor experimental networks" (MAENs). Both in public policy and in academic research, such networks are increasingly presented as a promising approach for fostering sustainable farming system design. Many studies have inventoried, categorized and compared experimental processes to discuss them in relation to contemporary issues. However, to our knowledge, these studies have not considered how MAENs can be implemented, nor their various contributions to sustainable farming systems design. The present work therefore explores the mechanisms whereby MAENs, depending on the way they are managed, support participatory design processes. Drawing on concepts from the design sciences, we studied 11 MAENs established across Europe to support intercrop (IC) design for field crops. Data on the characteristics of these 11 MAENs and their contributions to IC design were collected through individual and group interviews with the network pilots, and the study of individual MAEN documents. The analysis provides three types of results. First, we identify nine generative functions, that is, various processes through which experiments contribute to IC design, including: (i) finding one best option or highlighting contrasts between different ICs; (ii) highlighting the conditions that must be met for an IC to achieve certain effects; (iii) discovering new ICs or properties of ICs; and (iv) supporting the emergence/continuation of collective action for IC design. Second, we highlight different ways to manage MAENs, in other words ways to manage several experiments (in space and time) with a view to supporting participatory IC design. We show that this involves (i) coordinating several objects under design within a network of experiments, (ii) managing the coexistence of experiments guided by different logics in the same geographical area, and (iii) developing interactions between the experiments at a given point in time and over time to support IC design. Third, based on the previous results, we show consistency between the various contributions of MAENs to IC design and the different ways in which the pilots managed them, and we highlight three strategies for managing MAENs to support IC design: MAENs supporting (i) R&D-led design; (ii) farmer-led

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design; and (iii) distributed design. All these results provide mechanisms, points of reference, MAEN types and characteristics to inspire and foster the reflexivity of R&D actors interested in developing such participatory networks in the future.

1. Introduction

Historically and still today, field experiments are the method most widely used by agricultural research and development (R&D) organizations to both produce knowledge and design innovations (Jas, 2001; Cardona et al., 2018; Maat, 2011). Nowadays, the most common field experimental approaches for designing agricultural innovations consist in experimenting on farm or on station with technical solutions designed by R&D, to solve problems encountered by farmers or to reach new performances (e.g. to manage specific pests, weeds, nutrient deficiency; or to reach performances toward the reduction of pesticide use). These types of field experiments are often called "analytical" or "factorial" experiments, and aim to understand the effects of techniques (e.g. varieties versus fertilizers trials), the relationships between environment and techniques, as well as the interactions between the factors tested, and to identify the optimum for one or two factors (Johnston and Poulton, 2018; Silva and Tchamitchian, 2018; Lechenet et al., 2017; Makowski et al., 2019). Such experiments, which are mainly controlled by R&D actors (Drinkwater, 2002), are no longer considered sufficient to support transitions towards sustainable farming (Lacoste et al., 2022). New questions are being raised, for instance, how can field experiments contribute to the development of locally adapted and adaptive systems combining techniques, in time and space, which are conducive to natural regulations (Bonaudo et al., 2014)? How can they support capacity building for farmers in the design of systems tailored to their situations and preferences (Berkes, 2009)? And how can they foster the emergence of collective action as well as the sharing of knowledge and know-how to encourage change in spite of the many unknowns surrounding temporal and spatial ecological impacts (Brugnach et al., 2008; Šūmane et al., 2018)?

Against this backdrop, and to tackle these challenges, many new forms of experimentation are emerging, associated with the use of new concepts such as "participatory prototyping trials" (Périnelle et al., 2021), "living labs" (Gamache et al., 2020) or "long-term system experiments" (Silva and Tchamitchian, 2018). In this work, we explore the characteristics of a particular type of emerging approach, the value of which is being promoted by its developers and financers (e.g. Eip-Agri EU) to support the design of sustainable agricultural systems. This type of approach consists of networks combining different experiments, spread across different locations, evolving from one year to the next, each with its own logic, and with a specific and dedicated form of management involving actors from different professional backgrounds (e.g. farmers, R&D and agrifood systems actors). We call these approaches "multi-actor experimental networks" (MAENs), in line with the terms used by actors in the field (e.g. Eip-Agri EU). Although new approaches of this kind are developing, little is known about their diverse forms and how, depending on their characteristics and management, they contribute to the design of sustainable farming systems.

Various researchers have conducted studies to inventory, categorize and compare experimental processes, so as to discuss them in the context of the abovementioned contemporary issues. Examples include the typologies of Caniglia et al. (2017), Lechenet et al. (2017), Snapp (2002), and Ansell and Bartenberger (2016), as well as the categorizations proposed by Debaeke et al. (2009), Deytieux et al. (2012), and Navarrete et al. (2021). Deytieux et al. (2012), for instance, distinguish between factorial and system experiments, with systemic approaches allowing for a wider range of agroecosystem interactions to be taken into consideration. Moreover, Navarrete et al. (2021) distinguish between experiments built on open-ended approaches, and those informed by deterministic approaches, with the former being able to capture the uncertain and evolving nature of the systems tested. The typology established by Caniglia et al. (2017) further identifies six types of experiments that support the development of "an evidence-based sustainable science". These types differ according to the object of the experiment (exploring sustainability problems or solutions), as well as the interventions involved and the type of control thereof available to researchers. Lechenet et al. (2017), for their part, distinguish approaches based on the objectives set for an experiment, the representations that the experimenters have of what they are testing (e.g. systemic or analytical representation), how the experimentation is managed over time, and the different experimental layouts adopted. Likewise, Ansell and Bartenberger (2016) identify three different types of experimental processes according to the level of control of the experimental process, the experimental layouts applied (e.g. observational vs interventional), and the objectives of the process (e.g. isolating causalities). All these typologies reveal a wide variety of practices associated with experimentation, including "innovation experiments", "transition experiments" (Caniglia et al., 2017), "generative experiments" (Ansell and Bartenberger, 2016), and "experimental iterative approach experiment [*s*] to design innovative cropping systems" (Lechenet et al., 2017). By introducing these concepts, all these authors have brought to light forms of experimentation explicitly conceived and implemented to support innovation, transition and change processes. However, this literature has not explored what we call MAENs, and it only partially describes the mechanisms underpinning the contributions of experimentations to design processes. The abovementioned studies mainly highlight "objectives" assigned to experimentation, without really studying their contributions to the emergence of new farming systems (over time).

In another field of literature, studies have posited networks of experiments involving different actors as a key approach to mobilize to support farming system design. Examples include the works of Leclère et al. (2018) and Périnelle et al. (2021) to support the design of diversified systems, and the approaches based on step sequences presented by Reckling et al. (2020) and Husson et al. (2016), for instance, in which experiments are central to supporting the development of sustainable farming systems. While these studies emphasize the importance of experimentation for designing farming systems, and often identify general guidelines for optimizing their implementation, they do not analyse the characteristics of experiments and their effects on farming system design processes.

In a third field of literature, authors – often drawing on theoretical frameworks from the social sciences- have explicitly studied the mechanisms and conditions that enable experiments to contribute to transition, innovation or design processes in agricultural systems. For example, Navarrete et al. (2018) have explored how "the [experimental] networks helped farmers to learn new agroecological practices by building analytical vs actionable knowledge, local vs generic knowledge (...) [and] engaged farmers in an agroecological transition". Adamsone-Fiskovica et al. (2021) and Aare et al. (2020) have studied the conditions necessary for experimentation, as a demonstration tool, to support farmers' learning. Lastly, Catalogna et al. (2018) have analysed the effects of what they call experimental itineraries on the learning of the farmers who implement them.

The present research fits within and contributes to the latter field of literature aiming to understand how to implement experiments, and how to learn from them, to support transitions towards sustainable farming. More precisely, it explores a range of contextualized MAENs, and the specificities of their management, as well as their contributions to sustainable farming system design. This work seeks to shed light on the mechanisms whereby MAENs, depending on the way they are deployed, support design activities, to take a reflexive look at the benefits and limitations of this increasingly mobilized approach, and to support R&D actors who may wish to develop such networks in the future. To this end, we studied several MAENs supporting the design of intercrops (IC) known for their agri-environmental benefits, including reduced synthetic input needs (Pelzer et al., 2012; Jensen et al., 2020; Bedoussac et al., 2015). In the following section, we present the conceptual framework we used to characterize MAENs and their contributions to design processes (Section 2). We then detail the method and the cases studied (Section 3). Finally, we present the results (Section 4) and discuss them in the last section (Section 5).

2. Conceptual framework

We developed this conceptual framework to establish heuristic markers to study the characteristics of MAENs and their contributions to design processes.

2.1. Networks of field experiments: a semi-controlled process for exploring the unknown

The literature on field experimentation is abundant (e.g. Walters and Holling, 1990; Hansen and Tummers, 2019), as are the definitions used to characterize this activity (Maat, 2011). Building on earlier research, this study considers experiments (whether on farm or on station) as "investigative processes" embedded in a socio-technical situation, involving technical instruments, data collection and analysis processes, and material objects (Lechenet et al., 2017; Ansell and Bartenberger, 2016). The method consists in placing an imagined object in a real-world context to explore its characteristics and functioning, and to generate outputs as well as outcomes. What is known about the object before the experiment can vary (Gillier and Lenfle, 2018; Jobin et al., 2021). As Henke (2000) and Catalogna et al. (2018) point out, experimenting with a new object implies having *in abstracto* defined what it is, and having formulated hypotheses regarding its behaviour, its structure, its performance, etc. We here define a "real context" as an existing situated socio-technical and biophysical environment with specific social, cultural, geographical, and ecological characteristics. We consider that experimentation is a "semi-controlled" process: while it is intentional and managed, one cannot fully predict the reality or the results, as unexpected events can influence the process, the actions and the outcomes (Weiland et al., 2017). The "semi-controlled" nature of the process relates to the relationships between the experimenters and their actions, between their actions and the changes they induce, and between their actions, the changes induced and the dynamics of the socio-technical and biophysical environment (Schön, 1983; Weiland et al., 2017; Caniglia et al., 2017). Regarding outputs and outcomes, most R&D experiments aim to gather evidence on how objects evolve, function and react when put to the test of real-life contexts (e.g. evidence of efficiency, causality, Caniglia et al., 2017; Henke, 2000). These experiments sometimes also seek to foster social learning and capacity building (Darnhofer et al., 2009; Kummer et al., 2012; Lacombe et al., 2018).

A field experiment takes place and evolves in a specific location (Henke, 2000; Maat, 2011). Its spatial organization can be split into three levels (Lechenet et al., 2017): (i) the *sites*, that is, the different locations where the experiments are implemented; (ii) the *plots*, in other words the different areas in which the objects under experiment are trialled within a site (a site can be comprised of one or several plots); and (iii) *whole fields, strips or microplots*, terms which capture the spatial organization of the plots where an experiment takes place. Furthermore, we consider a *multi-actor network of experiments* as an actor-led dynamic combination of experiments with different logics, managed and implemented by a range of actors (farmers, R&D and agrifood actors).

2.2. Studying contributions to innovation processes through the prism of design activities

We study innovation processes through the prism of design activities (see e.g. Prost et al., 2018; Salembier et al., 2021). We consider "design" as a process driven by a desire for change, striving to generate something that does not yet exist. This process consists of the gradual emergence of a new object, either material or immaterial, and its integration into socio-technical environments (Simon, 1969; Papalambros, 2015; Wynn and Clarkson, 2018; Hatchuel et al., 2017).

To study the contributions of multi-actor experimental networks to design (so called MAENs), we draw on the notions and concepts of the Concept-Knowledge theory of design reasoning (Hatchuel and Weil, 2003) and the work of Schön (1983). As these authors point out, the design of a new object is a process of exploration of the unknown, intimately linked to what the designers know and learn. A design process involves the formulation of a target, which refers to an unknown and desirable object (Le Masson et al., 2017). In other words, what exists is insufficient for the designers, who want something new (and desirable) to emerge, but do not yet know what this object will be since it is unknown. According to Hatchuel and Weil (2003), the emergence of the new object relies on the gradual definition of *its identity,* which is the representation that the designer has of it, through the gradual characterization of its *properties*: its composition, the way it can be used, by whom, when, and in what conditions, etc. As Hatchuel and Weil (2003) show, the gradual characterization of these properties involves producing and gathering knowledge, developing systemic representations, assessing and choosing between different options, etc. Furthermore, these explorations arise through negotiations between designers and sometimes other stakeholders, to integrate the new object into socio-technical environments. Thus, the design process is highly dynamic and collective. As Schön (1983) demonstrated, the object under design evolves through encounters with unexpected or fortuitous situations over the course of the action (i.e. the implementation of the object in the real world).

Studying the contributions of MAENs to farming system design therefore involves studying how MAENs, depending on the way they are managed, foster the emergence of new farming systems.

2.3. Intercrops as an object under design

In this research, we study experiments with ICs and the design of these ICs. Willey (1979) defines the IC concept as the cultivation of at least two species on the same plot, during at least part of their crop cycle. In the agronomic literature (e.g. Hauggaard-Nielsen et al., 2009, 2013), ICs are characterized by their structural dimensions, such as the species (and cultivars) intercropped and their spatial configuration (e.g. rows, alternate rows) which, once implemented, are difficult to change. ICs are also characterized by their management during the crop cycles, which involves technical choices that can be adjusted, such as irrigation, fertilization, pest management, tillage. In this analysis, we consider all the different arable ICs experimented with in the MAEN we studied (e.g. lupin + oat; pea + clover + serradella + phacelia + grass + vetch; pea + spring barley; wheat + faba bean; vetch + oat; oat + camelina + clovers; spelt + clovers; wheat + lentils; barley + chickpea; sainfoin + ryegrass), and we use the concept of IC to denote the species intercropped, their spatial configuration, and the *variants* (ICVs) involved in their management.

3. Presentation of the method and MAENs

3.1. A multi-case study

Our research builds on the methodological propositions of Salembier et al. (2021): we adopted a theory-building approach (Eisenhardt and Graebner, 2007) based on a multiple-case study with embedded units of analysis (Yin, 2003). This approach allowed us to explore the convergences and divergences between cases to contribute to a shared theoretical construct. We selected 11 cases, all part of the H2020 ReMix Project dedicated to arable intercrop development from 2017 to 2020, based on the following criteria: (i) R&D actors had set out to implement MAENs, to support the emergence of new ICs; (ii) they worked on a range of ICs, for different farming systems (organic, conventional), and for various outlets (feed, food for humans); (iii) they all managed one MAEN, involving farmers and other actors; and (iv) the R&D actors belonged to different organizations, with different backgrounds regarding intercrop practices and work with farmers. We use the term "pilots" to refer to the R&D actors who carried out the various tasks associated with the management of the experimental networks. Moreover, the study is based on their point of view (i.e. data on the characteristics and the management of the experiment as well as the design processes at play come from the pilots' statements and writings).

3.2. Description of the MAENs

We here present three overarching characteristics of the different cases studied (Table 1, Fig. 1). We provide a description of each case in the supplementary material.

First, *each MAEN involved two to 15 experiments* per year (e.g. Fig. 1), spread across one to 13 sites, on station or on farms, and scattered across a region or the whole country (Table 1). Each experiment had its own logic:

(i) each tested one or several ICs and ICVs;
(ii) the experiments were deployed to achieve one or several objectives, such as empowering farmers in IC design (Case 4), gaining knowledge on an unknown IC for scientific purposes (e.g. Case 9), or identifying components of the value chains that enable IC development (e.g. Case 6);
(iii) the ICs experimented with were all formulated based on different design targets (e.g. IC to increase protein production for food and feed, Cases 9 and 10);
(iv) each experiment included a dedicated data collection and analysis process (e.g. study of farmers' practices, Case 9; statistical analysis of IC behaviour and performance, as well as informal conversations with farmers, Case 11);
(v) each experiment had its own spatial organization, with one to nine plots, with experiments in whole fields, on strips or on microplots.

Second, *the actors involved in the management of the experiments varied, and they took on different roles*. They contributed to (i) the design and implementation of the ICs, (ii) crop management, (iii) actions surrounding the integration of the ICs into socio-technical environments (e.g. marketing), and (iv) the data collection and analysis processes. These actors had different levels of experience with both the management of MAENs and the design and practice of ICs. In some networks, the pilots controlled nearly all the interventions, and the farmers involved mainly followed advice or protocols formulated by the pilots (Cases 1, 2, 5, 6 and 11). By contrast, in Cases 4, 8 and 9, the farmers experimented as they wished with ICs they had designed themselves. The pilots only controlled the process in consultation with the farmers: they proposed experimentation parameters, supported the data collection and analysis processes, and facilitated collective meetings (Case 8). Finally, in MAENs 3, 7 and 10, the pilots and farmers each performed their own experiments and mutually enriched one another. For example, when the farmers asked to collect data of interest to them, the pilots promptly assisted them with the analysis of their experimental results; conversely, the farmers participated in field visits or meetings to share their ideas, and sometimes to help the pilots in their analysis.

Other actors, such as advisors (e.g. Cases 5, 9 and 10) or agrifood system actors (e.g. Cases 3 and 7 – supply chain, food processing, machinery industry), also took part in the process on occasion, often during field visits or collective meetings. We observed that the actors (farmers, food system actors) involved in the networks changed from one year to the next (some became involved while others left), as did their roles in the process (e.g. Case 6: in 2018, the pilots were the only ones collecting and analysing data when experimenting with a pea + wheat IC on station, and in 2019, they invited farmers to contribute to these analyses during field visits).

Third, all *the MAENs evolved from one year to the next*, based on developments in the design process, the results of the experiments, and the collective dynamics at play. For example, we observed the removal or addition of certain experiments (e.g. Fig. 1) and the adaptation of data collection and analysis processes, as well as reorientations or clarifications of the design targets and the arrival or departure of actors in the collective process, or changes to the actors' roles.

3.3. Data collection

The data collection took place between January 2017 and October 2020, and combined:

1/ The collection of documents produced as part of the design-experiment process. For each MAEN, we collected available documents presenting the initiatives, their objectives, and their progress (slideshows, websites, minutes of meetings, press articles), as well as written material presenting results (fact sheets, testimony booklets, articles) and videos that had been produced. We also collected the posters and narratives produced by the pilots each year to present major developments in the management of their respective networks, for the annual Work Package 1 meetings of the ReMix project (February 2018 in Paris, France; February 2019 in Krakov, Poland; January 2020 in Witzenhausen, Germany). As for the narratives, their content was guided by questions asked to the pilots to make them clarify the experimental and design processes (e.g. "*could you write up the story of how the design process of your MAEN was conducted from the beginning of the project, why you carried it out, the way you did and with whom, and the outputs obtained during the process?*").

2/ *Individual interviews.* A total of 11 semi-structured interviews were carried out with the pilots of each network between December 2019 and October 2020, each lasting between one and three hours. Each interview was recorded and transcribed in full. In the interviews, the pilots explained which experimentation methods they had deployed, for what reasons, in what situations, what this had helped to design, and in what way. The following types of questions were discussed: how did the experimental network come into being? Did you have any previous experience with crop mixtures and managing an experimental network with farmers? What were the objective of the network and the desirable unknown? Who became involved, when, why, where, and to what end? How did you gather and analyse data? How did you valorize these data? What were the main learnings? Did you obtain unexpected results or encounter unexpected events, and how did you respond? How did the ICs trialled evolve from one year to the next? What evolved, and why? Etc. All the interviews were prepared and triangulated with the available written data on each network, using posters and narratives from each MAEN, and the co-authors of this article – most of whom have managed MAENs – also agree with the content of this article.

3/ Collective interviews. In January 2020, during one of the ReMix project workshops, we organized three collective working sessions with all the pilots of the networks to discuss the management and evolution of their networks. The three questions addressed by the respective sessions were:

(i) What are the different experiments being carried out in your network and what is their role in the network?
(ii) Have you encountered surprises during the experiments, how did you manage them, and what have you learnt from them?

Table 1
Characteristics of the 11 Design-Support Multi-Actor Experimental Networks. Column 3 presents the main objectives of the network: "S" stands for "Scientific production of knowledge", and "D" for "Development of IC practices on farm".

	Case no.	Main objectives (S/D)	Geographical area of the experiment	Initial target of the design process	Background of the pilot (s) surrounding crop mixtures (B)/work with farmers (W)	Objects under experimentation / design	Roles of the farmers (F) and pilots (P)	Spatial organization of the network	Data collection and methods of analysis
1	Poland – Centre for Agricultural Advisory Services	S+D	Country-wide	IC to limit nitrogen and herbicide use in cereal/ legume production	(B) Various previous experiences / (W) Used to experimenting on farm	3–4 ICs; 1–5 ICVs	P: perform most interventions in the experiments F: follow advice / pilots take measurements	11 sites / 1–4 plots/sites/ strips / on station + on farm under contract, in three regions	Statistical analysis of IC behaviour & performance / informal conversations with farmers
2	Greece – Aristotle University of Thessaloniki	S+D	Country-wide	IC to increase legume species production and boost the local supply of proteins for human nutrition	(B) Numerous experiences with various kinds of ICs / (W) Used to carrying out experimentation with farmers	2–4 ICs; 1–5 ICVs	P: perform most interventions in the experiments F: follow advice	1–4 sites / 1–4 plots/sites/ whole fields, replication on microplots / on farm + experimental station, in one region	Statistical analysis of IC behaviour & performance / informal conversations with farmers
3	Switzerland – FiBl	D	Country-wide	IC for local protein for feed in organic farming, with lupin	(B) Various experiences with different ICs / (W) Always work with local farmers (experiments on their farms)	5–6 ICs; 1–4 ICVs	P & F: experiment independently, and occasionally enrich each other	7–10 sites / 1–5 plots/sites/ whole fields and strips / on farm + on farm under contract, in one region	Comprehensive analysis of IC behaviour & performance / study of farmers' practices
4	France – INRAE	D	One region	IC tailored to farmer's own design target	(B) Numerous experiences with different kinds of ICs (scientific production, on-station experiments, on-farm experiments, etc.) / (W) Used to working with farmers	25 ICs	F: experiment P: support the farmers	13 sites / 1–3 plots / on farm, in one region	Study of farmers' practices
5	Spain – INTIA	S+D	One region	IC in organic farming, for food and local supply chain, with wheat for baking and pulses	(B) One experience with ICs (for feed in organic farming, on-station experiment) / (W) Used to working with farmers (communicating and sharing results)	4–9 ICs; 1–8 ICVs	P: perform most interventions in the experiments F: follow advice	1–5 sites / 1–9 plots/sites/ whole fields and microplots / on farm + on farm under contract, in one region	Statistical analysis of IC behaviour & performance / informal conversations with farmers
6	Germany – University of Kassel	S+D	One region	IC for food, previously unknown in Germany, which increases wheat protein content	(B) Few experiences with ICs / (W) Little experimental work with farmers	1 IC; 4–8 ICVs	P: perform most interventions in the experiments F: follow advice	1–5 sites / 1–8 plots/sites/ strips and microplots / on farm and on station, in one region	Statistical analysis of IC behaviour & performance / informal conversations with farmers, qualitative interviews
7	Netherlands – Louis Bolk Insttitute	D	Country-wide	IC for food, to increase wheat protein content and facilitate legume production / IC with legumes tailored to farmer's own design target	(B) Few experiences with ICs / (W) Always work with farmers (experiments on their farms)	9–12 ICs; 1–7 ICVs	F & P experiment independently, and occasionally enrich each other	7–11 sites / 1–4 plots/sites/ strips, microplots and whole fields / on farm and on farm under contract, in one region	Statistical analysis of IC behaviour & performance / study of farmers' practices
8	Denmark – Roskilde University	S+D	Country-wide	IC tailored to farmer's own design target	(B) Numerous experiences with different types of ICs (scientific production, on-station	3–15 ICs; no ICV	F: experiment P: support the farmers	13 sites / 1–3 plots/sites/ whole fields / on farm, scattered	Study of farmers' practices, farmers' own data collection and evaluation and knowledge

(continued on next page)

Table 1 (*continued*)

	Case no.	Main objectives (S/D)	Geographical area of the experiment	Initial target of the design process	Background of the pilot (s) surrounding crop mixtures (B)/work with farmers (W)	Objects under experimentation / design	Roles of the farmers (F) and pilots (P)	Spatial organization of the network	Data collection and methods of analysis
					experiments, on-farm experiments, etc.) / (W) Used to carrying out experimentation with farmers			around the country	sharing / discussions on results with researchers and farmers
9	Sweden – Swedish University of Agricultural Sciences	S+D	Country-wide	IC producing self-sufficient protein feed (both as grains and as silage) for organic livestock farmers	(B) Few experiences with ICs / (W) Little experience working on experiments following a multi-actor approach	2–4 ICs; 1–4 ICVs	P: perform most interventions in the experiments F: follow advice	2–3 sites / 1–4 plots/sites/ whole fields, strips and microplots	Visual and statistical analysis of IC behaviour & performance / informal conversations with farmers
10	UK – Scotland's Rural College	S+D	Country-wide	IC to increase protein production, for food and feed	(B) Numerous experiences with different types of ICs (scientific production, on-station experiments, on-farm experiments, etc.) / (W) Used to interacting with farmers	1–9 ICs; 1–2 ICVs	F&P: experiment independently, and occasionally enrich each other	One to 7 sites / 1–5 plots/sites/ whole fields, strips and microplots / on farm, both under contract and without contracts	Statistical analysis of IC behaviour & performance / informal conversations with farmers
11	France – Terrena cooperative	D	One region	IC to manage pests while limiting pesticide use, and which can be sold by the cooperative Terrena	(B) Numerous experiences with various kinds of ICs / (W) Used to experimenting on farm	2–8 ICs, 1–2 ICVs	P: perform most interventions in the experiments F: follow advice	1–8 sites / 1–5 plots/sites/ microplots – strips / on farm under contract, in one region	Statistical analysis of IC behaviour & performance / informal conversations with farmers

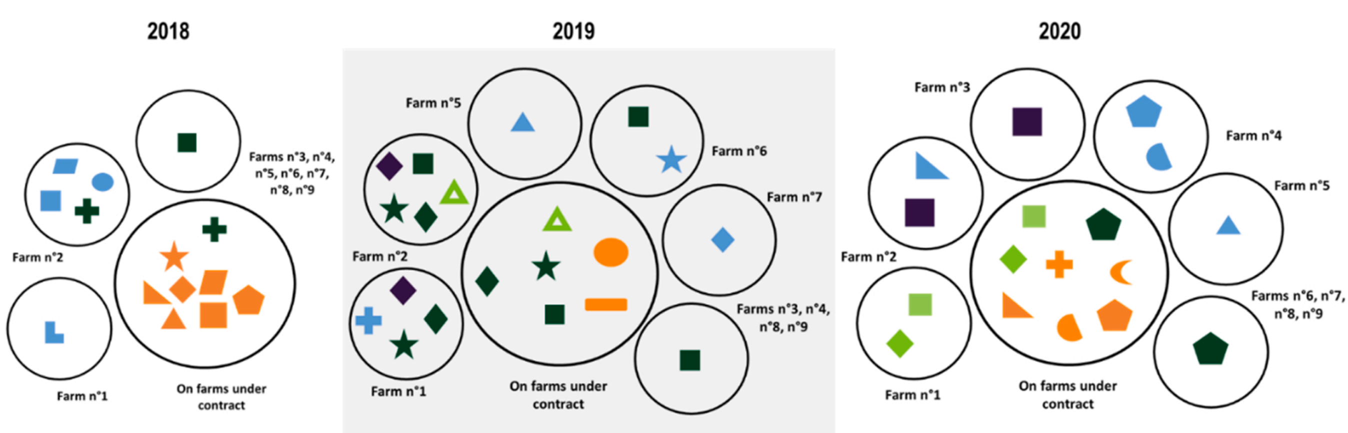

Fig. 1. Evolution of MAEN 3 over the three years of the ReMix project. Each coloured shape represents a specific IC (e.g. dark green squares are an IC combining lupin + oat). Circles represent sites (one to seven different sites) where experimenting with the same IC or ICV has been carried out.

(iii) What kind of results have you shared with other people, and how?

The discussions were recorded and transcribed.

3.4. Data analysis

The analysis began during the collective and individual interviews and the study of the written documents. It consisted of successive rounds of analysis specific to each MAEN as well as cross-cutting analyses to shed light on and categorize the convergences and divergences between MAENs following the multi-thematic coding approach (Dumez, 2013). For each MAEN, we performed a retrospective analysis of the evolution of the experimental network, the crop mixtures under design, and the collective actions undertaken. This retrospective analysis was then further developed across three complementary analytical subcategories:

1/ *The generative functions (GFs) of the experiments in a network.* Focusing on the scale of each basic experiment within the networks, and based on our conceptual framework, we analysed and shed light on generative functions, which Hatchuel et al. (2013) define as the mechanisms underpinning the experiments' contributions to intercrop design (i.e. how the experiments support the emergence of new intercrops and their integration into new socio-technical and ecological environments). To capture these contributions as perceived by the respective pilots, we traced the evolution of i) the emerging ICs (ICs abandoned, the specific properties of emerging ICs, changes in their crop management, etc.), ii) collective dynamics (farmers joining or leaving an experiment, evolution of their roles, etc.), and iii) the evolution of the experimental process (e.g. addition of new data collection methods). The analysis then consisted in identifying relationships between "the experiments" (e.g. what had been tested and analysed, the events encountered) and how they contributed to collective dynamics and the acquisition of knowledge and know-how by the actor-designers to foster the development of emerging ICs. This enabled us to highlight different generative functions in each case study, and a cross-analysis shed light on convergences and divergences between generative functions, which we categorized and named.

2/ Challenges in the management of experiments in a network, in support of IC design. For each network, we then analysed the ways in which the pilots coordinated experiments with different GFs (cf. results from the previous analysis), over time and in space, to support the design of ICs. A cross-cutting analysis of the 11 networks allowed us to identify and categorize the different logics underpinning the coordination of experiments to enhance their complementarity and synergies and, in some cases, to organize the design of different ICs within the same network. Each of these categories captures a challenge in the management of MAENs.

3/ *Different MAEN management strategies*. This third area of analysis builds on the results of the two previous areas: we characterized network management strategies for supporting design processes, on the scale of a whole network, and over the three years of the project. To this end, for each case, we analysed the consistency between: (i) the way experiments and interactions between the experiments were managed within the network; (ii) the ways in which the network as a whole contributed to the design of crop mixtures, relying on combination of GFs (e.g. design of new intercrops on farm, circulating agronomic knowledge to a wide audience); and (iii) the roles of the different actors involved. We then situated these results in relation to (iv) the particular situations of the pilots (e.g. past experience with ICs, purpose of implementing a MAEN, type of R&D organization to which they belong) and the characteristics of the network (e.g. number of ICs under experimentation, Table 1). After characterizing each network according to these four dimensions, we conducted a cross-analysis and identified strategy types.

4. Results

The results are organized into three subsections: (4.1.) the different contributions of the basic experiments to IC design; (4.2.) the range of ways in which diverse experiments were managed across networks to support design; and (4.3.) three strategies for managing MAENs to support IC design.

4.1. *Experiments' contributions to IC design: nine generative functions*

Over the course of the ReMix project, in all the MAENs studied, new ICs were designed. This design was enabled by and stimulated the evolution of the experiments carried out within the network as well as the collective action dynamics. Through a longitudinal study, by unpacking the evolution and functioning of each network over a three-year period (Fig. 2), we were able to shed light on how each experiment contributed to the design of new ICs. This analysis identified nine generative functions, presented below, along with the way in which they were implemented in the MAENs studied (Table 2). We focus here on the general description of each GF, we do not specify the actors involved in the GF processes (who were farmers and/or R&D pilots). We distinguish between three main categories: (4.1.1.) scheduled experiments for validation, appropriation, optimization and decision making; (4.1.2.) surprises encountered during the experiments that contributed to the definition and evolution of design targets and to the discovery of new properties of the ICs; and (4.1.3.) experiments to foster different actors' desire to get involved and support the emergence/maintenance of collective actions.

We outline different drivers of these generative functions, some intentional and planned, others resulting from unforeseen events. These unexpected events occurred either on one site or on the scale of the network (e.g. the 2018 drought across the entire area, Case 9). They can relate to unexpected bio-climatic hazards (e.g. aphid infestations on radish crop, Case 11), to the unexpected behaviour of a crop in a routine context (e.g. pea killed by frost during a "normal" winter, Case 6), to mistakes or difficulties in performing certain actions (e.g. a farmer sowed two species in one row instead of two separate rows, as planned, Case 3), to the socio-technical context (e.g. the inability to commercialize harvested seeds without sorting them, which could only be overcome in the last season, Case 6), or to the vagaries of everyday life (e.g. due to a family event, a farmer did not tend to the weeds in his fields, resulting in very high weed pressure on the IC in the following

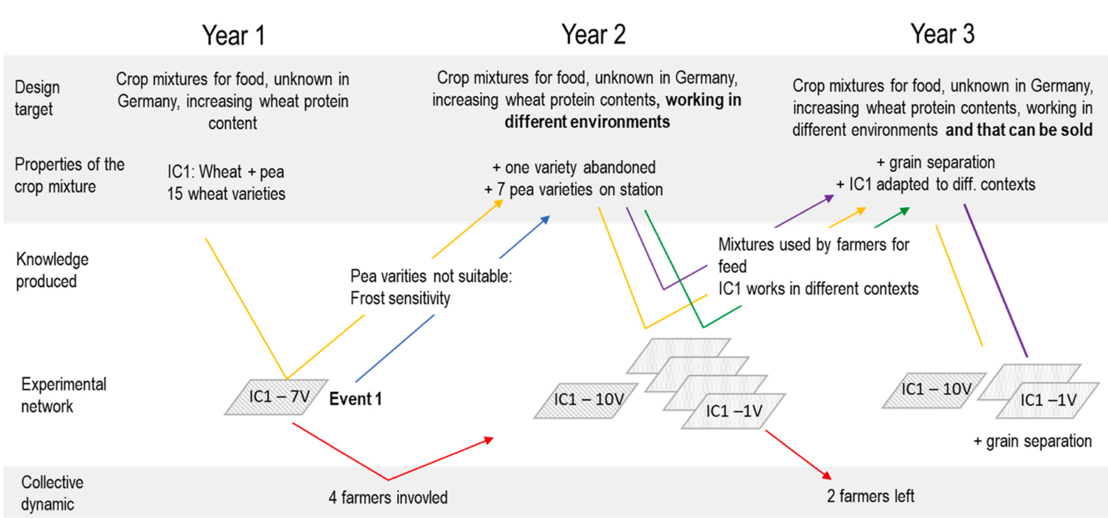

Fig. 2. Modelling of an experiment-design process, illustrating the experiments' contributions to the design of new ICs in Case 6. Each arrow refers to a generative function: yellow ones to "Exploring, verifying or validating the benefits of a crop mixture"; purple ones to "Highlighting the conditions required to achieve certain effects"; green ones to "Highlighting the feasibility of an IC"; blue ones to "Building on unexpected events to highlight new properties of the IC under design"; and red ones to "Fostering the involvement of different actors in the collective experiment". "V" stands for "IC Variants".

Table 2
Characteristics of nine generative functions highlighted in the 11 networks studied.

Type of GF	Name of the generative functions (GF)	Main characteristics of the experimental network concerned	Type of knowledge produced	Contributions to IC design and collective dynamics	Cases
Scheduled experiments for validation, appropriation, optimization and decision making	**GF1. Exploring, verifying or validating the benefits of a known IC**	One known IC was trialled on one site, on farm (contracted or not) or on station, on one or two whole fields or strips (for comparison with a pure crop), with a view to building evidence on the links between the behaviour of an IC and its effects/performance (comprehensive or statistical analysis).	Effects, performance, and behaviour of an IC, sometimes in comparison with a reference (e.g. sole crop)	Validating the IC, abandoning an IC, fostering IC adaptation	1, 2, 3, 5, 6, 7, 9, 10, 11
	GF2. Finding one best option or highlighting contrasts between different ICs	A range of poorly known ICs or ICVs were compared. They were tested either on one site with strips or on one site across different whole fields; alternatively, different mixtures were implemented on different sites. Homogeneous data were collected on each IC to compare the behaviour of different ICs and their effects/ performance.	Comparison of performance/ effects across the ICs or ICVs trialled, and the reasons for differences	Identifying an optimal IC or ICV, ranking ICs to support decision making, fostering IC adaptation	1, 2, 3, 5, 6, 7, 9, 10, 11
	GF3. Highlighting the conditions required to achieve certain effects (validity domain)	One IC was trialled on different sites (different contexts, crop management approaches). Homogeneous data were collected to identify the validity domain in which the IC reaches certain effects/a certain performance level, and to understand the reasons for this.	Conditions required to achieve certain effects/ performance levels	Abandoning the IC in some contexts, fostering the development of the IC in new contexts, fostering IC adaptation to better fit a context	All
	GF4. Highlighting the conditions for developing an IC (feasibility)	One IC was trialled on one or several sites. Data collection focused on highlighting the difficulties of, obstacles to or favourable conditions for the implementation of the IC in different contexts.	Difficulties, obstacles and conditions favourable to the cultivation of ICs	Abandoning the IC in some contexts, fostering IC adaptation / fostering the involvement of new actors	All
	GF5. Gaining know-how on ICs	Introducing an IC during the experiment contributed to the acquisition of know-how.	Know-how on an IC or ICV	Know-how on IC management	1, 2, 3, 5, 6, 7, 9, 10, 11
Surprises encountered during the experiments	**GF6. Giving rise to, adjusting or specifying new design targets for ICs**	Unexpected events encountered during an experimental process led to new discoveries, and often to additional data collection and analysis processes to understand what was happening.		New or enhanced design targets	
	GF7. Discovering new ICs or properties of ICs	Unexpected events encountered or farmers' practices discovered during an experimental process led to new discoveries, and often to additional data collection and analysis processes to understand what was happening.	New properties of the ICs under experimentation	Fostering IC adaptation, abandoning an IC, fostering awareness of the new properties of the IC	All
Experiments to encourage involvement and support collective actions	**GF8. Fostering farmers' desire to experiment with ICs**	Organization of field visits and collective meetings / distribution of seeds to farmers / management of equipment sharing.	Knowledge provided by actors from different backgrounds and professions	Evolution of the design target, involvement of new actors in the network	All
	GF9. Fostering the emergence/ continuation of collective actions around IC design	Sharing of experimental results, support for the data collection and analysis process, implementation of communication tools, circulation of agronomic content.	/	Implementation and evolution of an IC to fit farmers' contexts	All

year, Case 3).

4.1.1. Scheduled experiments for validation, appropriation, optimization and decision making

GF1. Exploring, verifying or validating the benefits of a known IC. In nine cases, pilots, sometimes together with farmers, experimented with an IC of which the performance/effects had already been proven elsewhere, in order to explore, verify or validate its benefits in their own context. They did so on one site, either on an experimental station or on farm (under contract). Most of the time, the IC of interest was compared to sole crops, in strips or in whole fields. Sometimes, however, the experimentation did not involve any comparison, and simply sought to "see what happens". Data collection and analysis was always geared towards quantifying and understanding the effects/performance of the IC. Regarding design processes, the results led either to validating the IC – which often involved trialling it again to observe the "year-on-year effect" – or to abandoning or adapting it. For instance, in Case 3 (Table 3), the pilots experimented with a lupin + oat IC (80%/40% densities), already known to be beneficial in their context. Still, the first-year experiment revealed that the oat was too competitive. The lupin was unable to develop, which led the pilots to adjust the sowing densities and to experiment with staggered sowing dates.

GF2. Finding one best option or highlighting contrasts among different ICs. In these experiments, the pilots knew various ICs or ICVs, and wished to compare their behaviours, effects or performance in their own contexts. To this end, the pilots either grew (i) the various ICs in strips on a plot and followed the same observation process / took the same measurements for each IC iteration, or (ii) they carried out

Table 3
Quotes illustrating generative functions across the 11 networks. We refer to quotes from interviews with (*) and to document excerpts with (**).

Name of the generative function	Quotes
GF1. Exploring, verifying or validating the benefits of a known IC	Case 3 * - "we started with 40% oats (.) it had worked the years when my colleague had done it, and then it stopped working. **We've reduced the amount every year, now we're hoping to arrive at the right proportion**"; Case 11 * - "last year, with lentil-wheat, we went to measure the height of the canopy, **to see whether or not the wheat had a stake**"
GF2. Finding one best option or highlighting contrasts among different ICs	Case 5 * - "The first year, we used two different varieties of chickpea. However, **we saw that one variety was not beneficial, so we removed one** (.) we can also compare the different mixtures, in the same year, using statistical analysis"; Case 9 * - "we expect different interactions, depending on the mixture and spatial arrangements, and that is what we wanted to evaluate"; Case 6 * - "**we see some variation in the protein** in the varieties, the level increases between one and two percentage points, for instance if you have say 10% protein content, then the increase could be from 11 to 12. **This increase seems to be lower for some varieties**; with one year…"; Case 1 * "our central field is organic, so we tried to use the best mixture from our point of view (…) on one hectare (…) **we used two types of pea, with one more leafy** (…) t**o see how it works in the mixture** (…) we wanted to show what is better for the mixture"
GF3. Highlighting the conditions required to achieve certain effects (validity domain)	Case 3 * - "Lupin is sensitive to limestone, **so the idea was also to have the same IC everywhere to try to set the sensitivity thresholds**, because in the literature you can find all kinds of thresholds and we didn't know exactly how far we could go in terms of the pH level and limestone, or if it still worked, so the idea was to do this everywhere and see where it works and where it doesn't and see whether it comes down to the limestone (…) [repetition of the IC] **to multiply the sites and not just have one test site**, **to see if it was reproducible** (.) to see if it worked in several conditions"; Case 11 * - "**the robustness is also owed to the fact that it will be generalized, irrespective of the type of soil, climate, previous crop or rotation, of the type of tractor and sowing density** (…) And well, we know what will happen, **we know what advice to give**, and the farmer knows what risk he is taking, and so that's where the idea of gradually expanding it geographically is also to cater to diverse types of farming systems"
GF4. Highlighting the conditions for developing an IC (feasibility)	Case 9 * * - "The farmers also **did not have the required machinery** to perform 3:1 alternate row sowing as well as the later/delayed sowing of wheat in the rows between legumes"; Case 2 * - "we try to experiment outside the university farm, it's important for us **to demonstrate that all these experiments work in the farmers' fields**, to get feedback from them"; Case 3 * - "we had started with the reference mix with one variety, which could be found everywhere. After the first year **some people had problems finding seeds**, so they turned to the other variety"
GF5. Gaining know-how on ICs	Case 5 * - "**we didn't have any experience** with these mixtures, so we decided to try different densities of wheat"; Case 6 * - "having the mixture and a place where I can often really observe, see what is happening, [it means] **I can really learn about it**, and I cannot do this on a farmer's field because it is too far away, so [I get] to know the crop, [I get] into the results, and also it's a bit controlled, [I get] a good starting seed, and then I can go out and invite people"
GF6. Giving rise to, adjusting or specifying new design targets for ICs	Case 5 * - "observing weed density (.) the first year we saw differences, so we decided **to add a measurement** (.) we saw visual differences in weeds, which is why the second year we also evaluated the weeds"; Case 9 * [after a very dry season] – "if you grow only one crop, faba bean or vetch, and the weather is too dry, all the crop will be destroyed, if you grow crop mixtures, the faba bean or the vetch will die, but at least, you get cereals, **it's a security or a way to manage risk**. In normal weather conditions, the yields from crop mixtures is likely to be better than sole crops"; Case 6 * - "most of the farmers, **in the end, they all sold it as fodder, they did not separate** and all…"; "I interviewed a farmer, he said that mixing wheat with pea is very good for fodder, because if you separate it, when you have wheat with half peas it is not a problem for fodder, but when you want baking wheat, it is hard to separate out the peas, **so then it becomes a question of whether it's worth it**. This farmer was not convinced it was worth it"; "I saw that they were not doing it, it obviously requires effort for them to do it because most of them don't have the infrastructure to separate"; "there have been so many mixture experiments, the literature on mixtures is like (…) most of [the experiments] **do not even consider these practical things**, the goal is often to produce baking wheat but there is not a word about separation and so on"
GF7. Discovering new ICs or properties of ICs	Case 3 * - "He told me that his daughter got married the previous year and so weeding the maize wasn't his priority and the problem is that we inherited the weed pressure from the maize and so actually even the sole crop was an associated crop [with weed] (…) **it was in a context of strong weed pressure**, and **we saw that lentil-chickpea was useless**, and flax seemed to have a small effect [on weeds] but the intercrop still needed improving, and on the other hand, he [the farmer] was quite happy with the oats"; Case 11 * - "Well **we realized that the radish cover crop was attracting aphids rather than repelling them**, so we wanted to test a sole crop the following year"; Case 3 * - "[Lupin + camelina + oat] – it does that (…) it's something that suits it well, and actually **lentils and camelina are quite lucrative**, he'll make a good gross

(*continued on next page*)

Table 3 (*continued*)

Name of the generative function	Quotes
	margin and even if those ones don't work, he'll still have lupin to fall back on if ever it's the lupin that grows that year; Case 3 * - "We recommended the unbranched [variety], but then **he saw that it yielded far less than the branched one**, and actually, the problem with the branched one is that **it easily tends to spill over**, especially as a sole crop, so he thought maybe if I mix the two, I'll solve my spilling problem, but I'll still improve the yield; because the branched variety yields far more than the unbranched one, so he thought 'I'm going to mix the two'"; Case 4 * - "another intercrop that I found brilliant was Mr X who sowed lentil-barley. **Normally lentils are sown in the spring around March and so we often do wheat-lentil; his idea was to sow his lentils in November**, except that lentils are sensitive to frost so there is a risk of freezing, so he sowed them in barley, and **what really surprised me** is that when you see the plot at the beginning, you think there is only barley and actually the lentils managed to grow in the barley! Normally lentil is very small, 30–40 cm long, but here I have photos of lentils that are 60–70 cm long. I've never seen lentil that big, and actually it's as if the lentil had managed to follow the growth of the barley, whereas my agronomic expertise would have led me to conclude that that doesn't work because the lentil will be completely smothered by the barley. Still, we'd have to confirm whether there's a risk of it freezing in other years, and whether lentils will systematically develop concomitantly with barley. I find it really interesting"
GF8. Fostering farmers' desire to experiment with ICs	Case 11 * - "there are bits of fields, **with visits to plots to show the other members**, 'here is the result of the intercrop', or in the case of lentil-wheat, whereas lentil on its own will tend to spill and will get overrun by weeds, with lentil-wheat the wheat will have a killing effect, there will be fewer weeds (…) **it gives security to the farmer**, and also to the technician (…) there is an intermediary: field technicians, technical salespeople, who will go and deliver the advice to all their clients"; Case 8 * [testing the same intercrop across several farms] – "about the mixture of seven species, all the satellite farmers tried it the first year, the idea with this was to ensure that every farmer who had signed up for this – participating in ReMix – would **have some kind of experiments to actually go and see**; even though it is intercropping in the sense of mixing main crops, it still maybe serves some of the same functions you would be able to see in catch crops and it is not as risky as trying a catch crop"; Case 5 * - "the first year, we did a repetition of two mixtures **to visit the field with farmers and ask them to be satellite farmers** (…) it's not scientifically proven, this is just an observation, they were in the field visit so they also saw the differences"; Case 9 * - "also **we had to convince the farmers** that with crop mixtures the productivity should be higher than when growing sole crops, because growing mixtures can require extra time and extra machinery, so in order to make up for all those things, you need higher productivity"
GF9. Fostering the emergence/ continuation of collective actions around IC design.	Case 8 * - "the **learning by doing**… I think that's the way they [farmers] like to learn, and they reflect a lot, and that is also when they discuss things, they mostly say 'I tried this', 'I have also seen this', all of them, **their input in the discussion is almost always based on something they have tried out at home**, or have seen other people trying out"; Case 5 * * - "the best learning process for farmers is **to visit trials and see** in the field that mixtures work well"; Case 9 * - "if you do things by yourself, then you see the crop or the challenges, so for them, the idea with adopting it was also to see how it works, and if it works well **then they can scale it up, the farmer will develop the mixture on the whole farm**, because he already has experience from this trial"; Case 9 * - "[during visits] another farm had pea and wheat, and wheat as well for comparison, he was delighted, he looked around and found a lot more earthworms in the pea mixture, half the field had wheat and the other half had wheat-pea mixture, one of his big drivers was soil health, he was definitely very keen on that and he was delighted with what he found"

randomized trials on microplots in order to collect enough data to use statistical tools (e.g. Anova), or (iii) they experimented with and qualitatively compared ICs grown in whole fields, on one or several sites. Regarding IC design, these experiments helped to identify optimal options and prioritize or choose between variants, and sometimes led to ICs deemed unsatisfactory being abandoned. For instance, in Cases 1, 2 and 9 (Table 3), the pilots compared variants – different cultivars, spatial layouts, and/or sowing dates – of a same intercrop (wheat + oat + barley + pea and wheat + faba bean).

GF3. Highlighting the conditions required to achieve certain effects (specifying the validity domain). In all cases, the experiments highlighted the conditions under which an IC achieved certain effects. The ICs were implemented across different sites (two to seven), on station or on farm (plots under contract or not), to observe their behaviour in different biophysical and socio-technical conditions. As regards the IC design process, this knowledge sometimes led the pilots to abandon an IC deemed unsuitable for a particular context, while fostering its development in others or adjusting it to better suit a particular situation. Most experiments helped enhance the pilots' recommendations. For instance (Table 3), in Case 3, the pilots wished to define "terroirs" in which ICs with lupin could be successfully grown. By replicating an IC with lupin on different sites over a three-year period, they were able to identify the maximum amount of limestone in the soil beyond which lupin no longer develops. In Cases 1 and 11, the pilots repeated ICs on various sites and, drawing on a homogenous body of collected data, they performed statistical analyses to characterize the validity domain of the IC (defined as the situations in which the performance of the IC was satisfactory/sufficient).

GF4. Highlighting the conditions required for developing an intercrop (feasibility). For all the pilots, the experiments also contributed to highlighting the conditions required for implementing an IC. They gained knowledge on the IC's feasibility through interviews or informal conversations with farmers (e.g. difficulties encountered, drivers for developing the IC in their area). As regards IC design, this knowledge led either to the involvement of new actors, called upon to help solve feasibility issues (e.g. supply-chain and food-processing actors, Case 7), or to adjusting the IC and the experiment (e.g. adding new experiments with grain sorting, Cases 5 and 6). In some cases, it also contributed to the reformulation of the design target to better account for issues encountered in real contexts.

GF5. Gaining know-how on IC management. Experimenting afforded an opportunity to implement and monitor ICs, and to collect and analyse data on them in a real-life environment. This always led to the acquisition of know-how, a key dimension of IC design processes (e.g. know-how to use an equipment to implement an IC, Case 3; know-how to observe crop development in order to determine at which point to trigger an action, Case 6). For instance, in Cases 5 and 6, the pilots explained that the first year of experimentation had allowed them to "get comfortable" with IC as a technique, which they had never applied or studied until then.

4.1.2. Surprises encountered during the experiments that contributed to the definition and evolution of design targets and to the discovery of new properties of the ICs

Unlike the previous generative functions, GFs 6 and 7 involved little to no planning on the part of the pilots: discoveries across the network resulted from unforeseen events and from what farmers had decided to explore in their own contexts.

GF6. Giving rise to, adjusting or specifying new design targets for ICs. In five cases, during the three years of the project, the experiments contributed to the emergence, adjustment or specification of new design targets. In some cases, unforeseen events or the discovery of farmer practices previously unknown to the pilots led the latter to start designing new objects that complemented earlier ICs and could support their introduction or development in a new context (e.g. food processes, farming equipment). For example, in Case 7, following the on-farm experiment with wheat + faba beans in Year 1, the farmers and pilots identified the need to develop new food processing tailored to food-oriented ICs (i.e. dedicated to human consumption), so as to valorize the increased wheat protein content and facilitate pulse production. In other cases, the experiments contributed to the evolution of the design targets initially defined by the pilots and/or farmers. For instance, in Case 6, in the first year, when the farmers implemented a wheat + pea IC chosen by the pilot, he discovered that no farmer involved in the network had sold the IC they had grown: they had all used it for feed, whereas the pilot had expected them to implement it for food. Through interviews, the pilot realized that he had not taken into account the limited resources of involved farmers for separation for baking quality wheat. The design target thus evolved from "crop mixtures for food" to "crop mixture for food that can be sold locally, thanks to grain sorting".

GF7. Discovering new ICs or properties of ICs. In all cases, the pilots and farmers discovered new ICs or IC properties during the experiments. In some cases, unexpected events helped to reveal these, as in Case 11 where the radish crop attracted aphids instead of repelling them, which led the pilots to test other repellent crops the following year, or in Case 7, where a farmer decided to sell his forage locally through a supply chain that the pilots had not considered. In other cases, the pilots discovered ICs that the farmers themselves had imagined and implemented on their farms, through interviews with them, observations or measurements in their fields. In all cases, these discoveries increased the range of ICs known to the pilots and the farmers (e.g. Case 7, maize + faba bean for feed; Case 3, lupin as a relay crop, lupin + camelina + lentil to reduce climate and economic risks, Table 3), and also led to the formulation of new research questions (e.g. in which conditions can lentil sown in autumn with barley develop and achieve satisfactory yields, Case 4).

4.1.3. Experiments to encourage involvement and support the emergence/continuation of collective actions

GF8. Fostering farmers' desire to experiment with ICs. In all cases, the pilots set up experiments with the aim of making new actors want to participate in the collective experiment (e.g. supply chain actors, Case 7; students, Case 9; farmers, Case 1). For this purpose, pilots developed methods to "convince", "enable" and "instil a desire" in people to engage in the network. For instance, as a physical place, the site of the experiment, whether on station or on plots under contract, served to organize field visits or collective meetings (Cases 1, 2, 3, 5, 7, 9, 10 and 11). Pilots often used strips and microplots to provide visual demonstrations of the results obtained and compare ICs, sometimes with a sole crop. These visits were also often coupled with indoor meetings, to present results, discuss difficulties encountered, interpret results, discuss participants' projects, etc. The farmers involved in the network often played a key role, particularly by sharing their respective experiences (e.g. acting as "farmer-ambassadors" of an IC, Case 7). Another example is the organization of equipment sharing (e.g. grain separation equipment, Case 5) and seed access (e.g. Case 8). Sometimes, the pilots also paid the farmers to experiment with ICs free of risk (e.g. Case 1), or suggested that they experiment with ICs they knew, so as to facilitate implementation (e.g. Case 3, barley + lupin; Case 9, wheat + faba bean). Some pilots also offered to support the farmers in their technical choices, in the implementation of an IC, and/or with data collection and analysis (e.g. in Cases 7 and 8, the pilots suggested that the farmers implement strips, to be able to compare their results with sole crops; in Cases 3, 4 and 8, the pilots supported the farmers with the interpretation of their results).

GF9. Fostering the emergence/continuation of collective action around IC design. The experiments also supported the emergence of collective action or served as a medium for such action. The pilots organized the collective sharing of experimental results during field visits or collective meetings, they circulated meeting minutes (Cases 1, 2, 3 and 11), and provided farmers with interactive tools such as WhatsApp and Facebook groups (e.g. Cases 8, 9 and 10) to facilitate and enhance discussions on results. Beyond the network, most pilots generated a range of agronomic content (e.g. farmers' testimonies, Cases 4, 5 and 8; action rules, Cases 2 and 11; IC portfolios, Case 3), and circulated them through videos (e.g. Cases 5 and 11), physical presentations (e.g. training courses, Case 6), or written material (e.g. leaflets, websites, Cases 3, 6, 7 and 8).

4.2. Coordinating several experiments in a network to support IC design

The cross-cutting analysis of the MAENs reveals that pilots simultaneously manage both the implementation of several experiments and the design of several ICs, and that they invent ways of managing this diversity. We here describe four categories of processes:

1/ Coordinating several objects under design in a network of experiments. All the MAENs comprised several experiments, each spread across 1–13 sites, either in a single region or country-wide, with each site consisting of one to nine plots. In all the MAENs studied, the pilots simultaneously experimented with two to seven ICs, and different ICVs. They coordinated the exploration of these objects in different ways. In some cases, all the ICs shared a common characteristic, which made it possible to organize or even orient exploration from the outset, based on a target shared throughout the MAEN (e.g. fostering the development of lupin in an area, Case 3). In these cases, the differences between the ICs under design related to the specific design targets of the farmers involved. This was the case of MAEN 3, with an IC on farm combining camelina + lupin + oat, to reduce climate and market risks, diversify the crop rotation, and limit the use of synthetic inputs. In other cases, the only feature shared by the whole MAEN was the desire to grow an IC, without there being any precise coordination of targets or technical choices (e.g. designing an IC tailored to different farming situations, Case 8).

2/ Managing the coexistence of experiments with different logics in the *same geographical area.* The analysis of each network shows that on a same site or plot, pilots have to manage the coexistence of experiments. This means contending with different technical parameters, data collection and analysis processes, forms of spatial organization of the experiments (e.g. whole fields, microplots, strips), several actors playing diverse roles in this process, and unexpected events with repercussions for various experiments at the same time. For instance, as illustrated in Fig. 3, one plot on an experimental station, which hosted wheat + faba bean, contributed simultaneously and in combination with other plots (i) to exploring the value of an IC in a particular context (GF1), (ii) to identifying the best cultivars for the local context (GF2), and (iii) to establishing its validity domain, by comparing crop management approaches and production contexts, on station and on farms (GF3). Such coexistence commonly involves trade-offs and, often implicitly, pilots choose experimental designs based on the GFs they consider to be of priority to the whole network.

3/ Developing interactions between experiments at a given point in time to support the design of ICs. MAEN pilots manage the interactions between experiments at a given time in different ways: (i) some pilots in the networks studied took advantage of the diverse range of experiments to simultaneously explore different facets of an IC in a complementary way (e.g. Cases 3, 6 and 11). In Case 3, for instance, the lupin + oat IC was trialled on six sites in the same year to simultaneously explore the behaviour of different cultivars in different contexts, with different spatial layouts, sowing dates and tillage. (ii) In other cases, pilots leveraged the diversity of experiments to make their analyses more robust. For instance, in Case 6, the replication of the pea + wheat IC across several sites, on farm and on a station, confirmed its performance in different contexts. (iii) In some cases, pilots repeated an experiment with one IC on several sites in the same year, in order to limit risks and ensure that at least one site would provide usable results (e.g. Case 7). (iv) Finally, the networks provided an arena for dialogue between farmers with different levels of experience with ICs, as some were beginners and others had been practising them for several years.

4/ Managing interactions between experiments over time to support IC design. The networks were not rigid, they evolved over time along with the design process. We identified four ways in which pilots organized the interactions between experiments over time: (i) in several cases, the first year, pilots experimented with a little-known IC on one site on station to minimize risk taking, and if it proved beneficial, they then extended its implementation to the whole network. For instance, in Cases 2, 5 and 6, the pilots first experimented with pea + wheat and lentil + wheat on station, and suggested these ICs to farmers the following year. (ii) Over time, we observed that some pilots first sought to understand the functioning of an IC before exploring its validity domain. In Case 11, for example, the oilseed rape + cover crop IC was first tested on microplots on station to demonstrate its effects on flea beetles, and then on farms on plots under contract to explore its validity domain. (iii) Sometimes, the experiments on station in the first year provided a physical place to invite and involve farmers who, once they had engaged with the network, started to experiment on their own farms (Cases 2, 5 and 8). (iv) We also observed cases where an IC introduced on a site – either by pilots or by farmers – inspired other members of the network to trial it in the following year (e.g. Cases 3 and 8).

4.3. Strategies for managing MAENs to support IC design

Based on the previous results, we identified three strategies for managing MAENs to support IC design (Fig. 4) and we characterized their main features (Table 4), namely the relationships between the characteristics of the MAENs and their management, contributions to IC design processes (through combinations of GFs), the roles of the actors involved, and particular R&D situations.

4.3.1. MAENs supporting R&D-led design

The first group comprises most of the MAENs (1, 2, 5, 6, 9 and 11). The pilots set up these networks for the in-depth exploration of one or several ICs and their different facets. Their main objective was to produce statistically robust knowledge on one or several ICs, to formulate general and low-risk recommendations to be disseminated and locally adapted, and often to publish this knowledge in scientific journals.

In the "core experiments", on station or on farm, during the three years of the project, only one or a few ICs were repeated over time, often on microplots (e.g. Case 5, lentil + wheat, chickpea + wheat). In these experiments, the pilots controlled crop management, data collection, and data analysis. In most cases, the protocols remained the same from one year to the next. The pilots often sought to identify optimal IC management approaches, or to gain knowledge on a range of options so as to enhance their recommendations, for instance on the effects of different cultivars, or sowing dates (GF2). Sole crops were systematically implemented in the trials to determine the value of the IC or ICV tested (GF1). These sole crops also aimed to demonstrate the benefits of the IC to farmers during field visits, and to foster their engagement in the network (GF8). In Cases 5 and 6, the pilots had little to no experience with ICs, and used the first year to develop know-how (GF7).

Beyond these "core experiments", the networks also included on-farm "satellite experiments" that were carried out in the first or second year (Cases 5, 6 and 9). Most farmers experimented with the IC co-designed and further refined by the pilots (e.g. replicating what the pilots had done on station in the first year – Fig. 2, Cases 2, 5 and 6; or implementing an IC known to the pilots, Case 1). In these experiments,

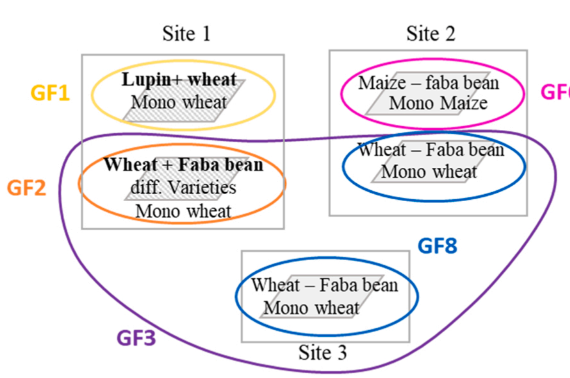

Fig. 3. Contributions of different experiments to IC design in MAEN 7, in 2018. The grey rectangles represent three different the striped parallelograms are farm plots managed by R&D, and the plain parallelograms are managed by farmers. "Mono" refers to plots with the monospecific crops from the IC. The coloured shapes refer to the generative functions (GFs) described in Table 2: yellow for GF1, orange for GF2, purple for GF3, pink for GF6, and blue for GF8.

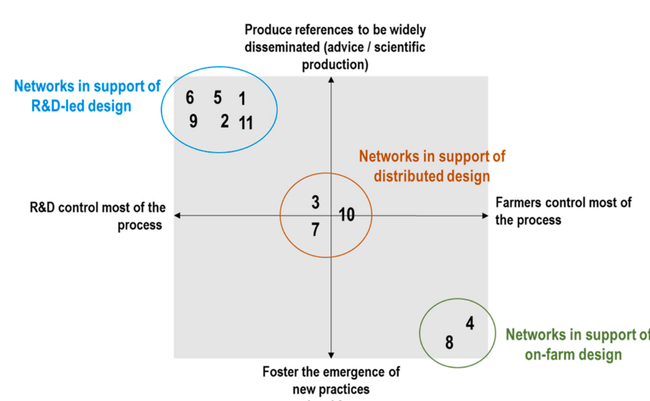

Fig. 4. Different strategies for managing MAENs to support IC design processes. The strategies are presented in different colours and positioned along the coordinates of control (x-axis) or objective (y-axis) of the processes. The numbers refer to the case studies presented in Table 1.

Table 4
Main features differentiating the three strategies for managing MAENs to support IC design.

MAEN strategies	Main pilots' intentions when developing the MAEN	Roles of the pilots (P) and farmers (F)	Main traits of the experimental network	GFs common to the cases concerned	Main outcome of the design-experimentation process
Supporting R&D-led design	Producing statistically robust knowledge and references on one or several ICs, with a view to disseminating advice to be applied by farmers	P: perform most interventions in the experiments, analyse and interpret the results F: follow advice	Core experiments conducted on station or on farms under contract, and satellite experiments on farm	GF1, GF2, GF3, GF4	Formulation of generic and low-risk recommendations for IC management
Supporting farmer-led design	Strengthening farmers' skills and supporting them in the design of ICs tailored to their own situations	F: design and manage the experiment, draw conclusions from the results for future IC management P: support farmers in their activities (described above)	Experiments are implemented on farm	GF1, GF3, GF4, GF5, GF6, GF7, GF8, GF9	Design and development of new ICs on farm
Supporting distributed design	Combining the ggeneration of agronomic knowledge dedicated to being widely disseminated and support to farmers in the design of ICs tailored to their own situations	F&P: experiment independently, and occasionally enrich each other	Mixture of experiments on station, and on farm (with or without contract)	All the GFs	Production of agronomic content to be widely shared, and new ICs designed and implemented on farm

the farmers were free to choose how they managed the IC, or to follow the pilot's guidelines (e.g. Case 11). For the pilots, these experiments were an opportunity to observe the behaviour of an IC in a "farming context" (Cases 5 and 9) and to develop their knowledge on the validity domain of an IC (GF3) and its feasibility (GF4). In some cases, when observing the farmers' own practices, the pilots had to adjust the design target (e.g. to include harvesting, sorting and marketing, Cases 5 and 6).

4.3.2. *MAENs supporting on-farm design*

This strategy was observed in Cases 4 and 8. In these MAENs, the pilots had great expertise on ICs. They implemented these networks with a view to supporting farmers and strengthening their skills to enable them to design ICs tailored to their own situations and expectations. The scope of exploration was not imposed by the pilots from the outset, such that each farmer was free to envisage an IC tailored to their situation.

The on-farm experiments were therefore central to the networks, strengthening the skills of farmers to design locally tailored ICs (GF9). The farmers managed the ICs themselves and carried out most of the data collection and analysis, and when necessary, they requested advice and support from the pilots. In the two cases, the pilots carried out interviews with the farmers before, during and after the implementation of the IC, in order to find out what they had done, how, in which conditions, why, the results obtained or whether they were satisfied, etc.

In Case 8, the pilots implemented a particular experiment in the first year and suggested that all the farmers experiment with the same IC. The aim was to encourage the farmers to get involved in the network, enhance group cohesion (GF8), foster learning to help the farmers familiarize themselves with the IC, to obtain homogeneous data across the different farms to be able to collectively discuss and develop their understanding of the relationships between different IC management approaches and results (GF9).

In the two cases, the pilots observed ICs that they already knew in new farming contexts and evaluated their performance, the conditions in which they were effective, and their feasibility (GF1, GF3 and GF4). They also discovered ICs they did not know (GF6), and formulated new research questions. In Case 4, the pilot used what he had learnt through interviews with farmers to write testimonies intended for other farmers (GF9). In Case 8, the pilots relied on the network to foster the sharing of experiences among farmers (beginners/experts) and to encourage them to support each other (GF9).

These networks experimented with many different ICs, and according to their pilots, the MAENs contributed to strengthening the skills of farmers to design locally tailored ICs, and helped the pilots discover new ICs and to gain knowledge about possibilities and barriers for using these practices (value chains, cultural barriers, etc.).

4.3.3. *MAENs supporting distributed design*

The experiments in Cases 3, 7 and 10 were initiated to support the distributed design of ICs. Both the pilots and the farmers experimented with ICs that they had designed. They enriched and supported each other in their explorations, for instance through joint analysis of the results obtained, and the IC trialled on farm gave the pilots ideas. These networks combined the pilots' in-depth exploration of a few ICs over a three-year period (e.g. Case 3, lupin + oat, Figure 5) with the farmers' explorations of one or several ICs they had envisaged and tailored to their own situations and objectives. At the same time, the pilots sought to generate agronomic content on a number of ICs while supporting the development of other locally tailored ICs on the farms in an area, and to discover new ICs.

In these networks, the pilots experimented with ICs that they had chosen and that they knew to varying degrees. For instance, in Case 3, the pilots trialled lupin + oat, chosen as a reference because it had performed well in past trials. In Case 10, the pilots experimented with crops they already knew in sole crops – lupin + barley, bean or field bean – and others, such as oat + lentil, which was poorly known in their context. Through the experiments, the pilots looked to produce robust knowledge on these ICs by exploring or validating their benefits (GF1) and by finding best options or highlighting contrasts across a range of ICs or ICVs (GF2). The novice farmers involved in the network often experimented with these same ICs, on the advice of the pilots, because they were considered as the best known and involved the least risk to start with ICs. Through these on-farm experiments, the pilots gained knowledge on the conditions required in order to reach certain effects (GF3) and the feasibility of these ICs (GF4).

Furthermore, from the first year, other farmers joined in the network because they were interested in growing ICs that they had envisaged. Their ICs often shared common features with those trialled in the rest of the network (e.g. in Case 3, farmers experimented with an IC involving lupin). In some cases, however, their ICs were very different, such as in Case 7, where the pilots trialled ICs for food that were relatively unknown in the Netherlands – spring wheat + faba bean, spring wheat + white lupin – while the farmers involved experimented with ICs for feed that they could easily use or sell locally, such as wheat + white clover and triticale + vetch. Through these on-farm experiments, the pilots discovered new ICs (GF6), which they often valorized through written or oral testimonies, technical articles, teaching, or field visits (GFs 8 and 9). These networks involved extensive interaction between the pilots and farmers and between experiments. For instance, we observed that ICs trialled on farm in Year 1 gave ideas to other farmers or pilots in Years 2 and 3. Moreover, farmers and pilots helped each other to interpret results, or to collect and analyse the data they both needed, and the most experienced farmers often advised the beginners and the pilots.

In these networks, the pilots and farmers independently benefited from the respective experiments they managed, while also supporting each other in different ways over the course of their implementation. These networks contributed to the emergence of new ICs on farms, and afforded the pilots a deeper understanding of certain ICs that they wanted to recommend with assurance (limiting risks) as well as allowing them to discover new ICs imagined by farmers.

5. Discussion

5.1. Lessons for implementing and managing MAENs

MAENs are a form of experimentation currently developing, which belongs to the broad and poorly defined category of on-farm experiments (Lacoste et al., 2022; Toffolini and Jeuffroy, 2022). This study shows that there is no "one right way" to manage MAENs geared towards sustainable farming system design, but a range of approaches, tailored to the ambitions of their pilots and to the situations underlying the implementation of these networks (e.g. local goals, background and skills of the pilots, geographical scatteredness of the network). The cross-analysis of 11 cases allowed us to draw lessons on the relations between MAENs' characteristics and management, expected outcomes, and R&D situations.

We show that several MAENs have been set up and managed with the aim of supporting the step-by-step design (Meynard et al., 2012) of ICs tailored to farmers' situations and preferences. In these cases (Type 2), the pilots deal with a large range of ICs at the same time within the MAEN, as every farmer designs his/her own system. To adapt to this diversity, pilots need to have a good understanding of a range of ICs (the pilots in Cases 4 and 8 worked and experimented with ICs for years), and/or be able to efficiently gather knowledge or facilitate the gathering of knowledge and the acquisition of know-how (Klerkx, 2020) in order to support farmers in the design of ICs that they have never experimented with or encountered before (crops combined, their management in a specific situation, etc.). Moreover, in this type of MAEN, it is more difficult to draw general lessons on ICs and their management that can be shared widely, as every farm has its own situation. This challenge requires particular analytical skills, to produce knowledge from unique cases (Salembier et al., 2021; Quinio et al., 2022). Such experiment-based design processes lead to several outcomes, often mentioned in earlier studies. The first are approaches developed to support on-farm design processes, and the building and management of local collectives around a common issue (Aare et al., 2020; Périnelle et al., 2021). Another outcome is the learnings achieved by the pilots, who discover new ICs on farm, and the new research questions they formulate. These learnings enrich the pilots' knowledge and competencies, which contribute to enhancing their background to support other farmer-led design processes. Finally, we observed that pilots produce leaflets dedicated to a wide audience, presenting testimonies of farmers involved in the MAEN. Such content offers a way to share farmers' experience with a wide audience (Salembier et al., 2021). In the cases we studied, the main motivation for pilots to engage in developing such networks was their desire to put their scientific expertise at the service of locally adapted on-farm IC design. These MAENs thus closely resemble the networks described by Périnelle et al. (2021) and Leclère et al. (2018), who shed light on other possible outcomes of these processes (such as the identification of innovative assessment criteria used by the farmers). In these MAENs, farmers are the core designers of innovative ICs, and the pilots' main aim is to contribute to increasing farmers' design capacities. Further researches could explore how to build on and hybridize existing agronomic methods and tools to support farmers' design activities in MAEN (such as Farmer Field Schools, Braun et al., 2006; Bakker et al., 2021; Vaarst et al., 2007); Design workshops, Jeuffroy et al., 2022; Famers' innovations tracking, Salembier et al., 2021)?

Another type of MAEN which we identified, similar to what Snapp (2002) calls the "mother-baby trials", aims firstly to produce knowledge and references on ICs dedicated to a broad range of farmers (considered as future users) and advisors, and/or to scientific applications. In these MAENs, R&D pilots are the main designers of a small number of ICs (they aim to identify the best options to be applied by numerous farmers). They sometimes discover IC candidates for the first time (e.g. Case 2), and they explore their characteristics in depth (e.g. they seek to validate the ICs' performance in different contexts as well as their feasibility), with a view to sharing robust knowledge on ICs that could be shared to scale out IC (e.g. general rules to manage IC in different situations). In most cases, R&D pilots make structural choices regarding the ICs with which to experiment: they themselves choose the species to intercrop their spatial arrangement, as well as monitor and control most of the experimental process (e.g. spatial arrangement, replicates). Farmers then mostly choose options between proposals made by R&D, and are sometimes in charge of designing and experimenting with the management of the IC. The main output of such MAENs is the knowledge produced on ICs (e.g. assessment of their performances, definition of their validity domain, identification of "best" technical options), formalized through scientific papers or documents dedicated to farmers or advisors. Another associated outcome is the adoption of IC practices by some of the farmers involved in the network. The extent to which the results can be scaled out beyond the confines of the MAEN is highly dependent on the nature of the results produced and their value for farmers, and on the media used to disseminate the knowledge (scientific papers, technical leaflets, farmer- or advisor-oriented journals or websites). In three cases, the MAENs were created in connection with advisory networks (Terrena cooperative network in France, an advisory network in Poland, Fibl network in Switzerland), and future studies could further explore the connection between the formalisms used to share the content produced in these MAENs and the development of ICs elsewhere.

Finally, several MAENs are run to both produce knowledge on ICs for wide dissemination and support the local design of ICs. In these MAENs, both pilots and farmers are considered as designers of the ICs that they want to create and which the pilots wish to see widespread in a region. In these MAENs, ICs emerge from co-design processes, where the "co" can take various forms (Lacombe et al., 2018). Pilots sometimes propose that novice farmers try less risky IC options which the pilots already know, to help them get familiar with this technique. Other times, they design ICs to produce knowledge to be shared widely and to get the support (ideas, knowledge) of experienced farmers involved in the network. Experienced farmers can also ask the pilots for support in the step-by-step design of poorly known ICs adapted to their own context and expectations. We refer to these MAENs as "distributed" (to borrow the term used by Prost, 2021), as the design effort is distributed among actors: both pilots and farmers contribute to the design of each other's objects of interest (local ICs, experimental ICs to produce general knowledge). Our characterization of this type of network adds to the descriptions provided by Navarrete et al. (2018), and we show that one way to coordinate the various explorations in a network is to structure it around a shared design target (e.g. "ICs with lupin"). For the R&D pilots, these networks afford deeper knowledge on a few ICs, to produce and widely share agronomic content while exploring a range of poorly known ICs thanks to the farmers involved. This kind of MAEN thus aims to reach two objectives, very often disconnected: knowledge production dedicated to a wide audience, and local co-design activities. Further researches could explore: in which conditions do the pilots of these networks can deal with these two objectives? And what are the background and the competencies necessary to manage such network?

This work also enriches the descriptions and typologies of experiments mentioned in the literature (e.g. Caniglia et al., 2017; Lechenet et al., 2017; Snapp, 2002; Ansell and Bartenberger, 2016), focusing on the particular case of MAENs. We show that MAENs differ from the "farmers' field networks" and "experimental networks" described by

Doré et al. (2008) and Lechenet et al. (2017), developed to "*represent the diversity of existing systems and environments (soil and climatic types) in the studied area*", and which aim to detect the causes of problems or to produce knowledge on natural processes, without explicit links to design processes. Numerous concepts have been used to describe experimental networks aiming to support design processes and involving diverse actors participating in the process: participatory prototyping trials (Périnelle et al., 2021), collective on-farm experimentations (Navarrete et al., 2018), mother-baby trial networks (Snapp, 2002), etc. In this work, we proposed to call them MAENs, to identify and name this particular kind of experiment with a unified vocabulary, without however obscuring the diversity of management practices at stake. Further research could explore the value of such networks and their limits, as well as adaptations necessary to implement MAENs around other innovative objects beyond the field level (e.g. cropping system mosaics, territories, supply chains), and the roles and contributions of actors beyond the R&D pilots-farmers pair (e.g. equipment industry, supply chain actors).

Besides the differences between the MAENs we studied, we also shed light on common challenges for their management: coordinating several objects under design in the network of experiments, managing the coexistence of experiments with different logics in the same geographical area, developing interactions between experiments at a given point in time to support the design of ICs, managing interactions between experiments over time to support IC design. And further researches could deeply explore ways to keep participating actors motivated and engaged throughout a long-term process characterized by unpredictable evolutions (as Aare et al., 2021 started to do), and how the interactions between research and development actors are set and can evolve. These first results also call for further refining our understanding of these challenges, and for creating tools and methods to support the establishment of MAENs (e.g. digital tools to facilitate the collective collection, sharing and analysis of different types of data, and tools to map the complementarities between experiments as well as their interactions). Future studies could also take this analysis further by exploring the skills required by MAEN pilots (e.g. Fiorelli et al., 2014), as well as these networks' connections or potential synergies with other kinds of design-oriented experiments (e.g. living labs, Gamache et al., 2020).

5.2. Experimentation to support the design of sustainable farming systems

The pilots of these MAENs stated that their aim was to support IC design. This article has explored in what way they go about reaching this goal. We here discuss our findings from three different perspectives.

1. The longitudinal study of interconnected experimentation and intercrop design processes allowed us to identify a range of functions, served by experimentation in design processes, which have rarely been presented together. As outlined by Navarrete et al. (2021) and Lacoste et al. (2022), four of these functions are well known and are most frequently cited to justify experimental agronomic work: experimenting to validate technical proposals (GF3), to optimize a technique or find the best option and choose alternatives (GF4), and to identify validity domains (GF5) or feasibility domains (GF6). As we have shown, these functions help designers to choose between options (decision-making process), to select or exclude certain options, and to know which option would achieve the desired result, where and why. Historically, these experimentation functions have guided R&D actors in formulating decision-making or action rules, which are then shared with farmers to help them tackle the problems they encounter in their fields (Salembier et al., 2018). Our results shed light on other generative functions of experimentation that have received little attention in agronomic research: beyond the processes surrounding validation, decision making and understanding, experimentation also contributes to the exploration of alternatives, to challenging designers by giving rise to surprises, and to developing collective action dynamics – all of which contribute to the implementation of "design" processes (see Section 2). For instance, our results show that, in all cases, the experiments enabled the pilots to discover new ICs or unknown properties of ICs (GF8), which led them to reorient or broaden their explorations. These discoveries were especially afforded by surprises resulting from unexpected events or from the exploration of what farmers were doing in their respective situations. The generative power of putting ideas to the test of real contexts, particularly through experimentation, is a mechanism that has already been widely discussed in the literature on experimentation and design processes. For example, Schon and Wiggins (1992) speak of a "reflective conversation with the materials of a design situation", de Ansell and Bartenberger (2016) talk about "generative experiments", Caniglia et al. (2017) discuss "out of control experiments", and Toffolini et al. (2020) mention that "putting into action the object under design enriches and even re-orientates the design process, as well as the associated knowledge generation". Irrespective of the experimenter's level of control, experimentation, by its very nature, is therefore a source of surprise and discovery (see Section 2), and this process appears to be amplified in the context of a network involving a range of actors. Although a growing number of studies describe or mention the implementation of experimental processes that are flexible (Lechenet et al., 2017), open-ended (Navarrete et al., 2021) or uncontrolled (Caniglia et al., 2017), methodological processes still need to be developed to collectively learn to manage these surprises on the scale of a network, so as to no longer endure them but harness their generative power to feed design processes (e.g. to help reformulate the design target; to detect, trace and valorize the emergence of new properties).

2. Our results also show that generative functions are closely linked and interconnected, with each other and with the characteristics of the management of the MAEN. We observed that functions complement and enhance one another in time and space, and their combination is instrumental to step-by-step progress in design processes (Meynard et al., 2012). For example, we show that some pilots use the MAENs to explore different facets of the same IC, to validate the benefits of ICs in certain contexts before suggesting that farmers experiment with them, or, as Navarrete et al. (2018) and Aare et al. (2021) have shown, to enable farmers and R&D actors from diverse backgrounds to share their experiences and know-how over the course of experiments. The typology of MAENs that we developed reveals that different approaches exist for fostering complementarity between experiments. These strategies specifically depend on what has to be designed in the network (e.g. ICs tailored to each farm, or generic IC rules recommended to a broad panel of farmers). They also vary depending on the pilots' visions and understanding of innovation in agriculture (e.g. from their perspective where does innovation come from? What is the role of farmers in innovation processes?), which is deeply related to the role they assumed in this process, which can range from helping farmers to design by themselves, to designing general management rules ready to be widely shared. Our characterization of the interactions between experiments is informed by a longitudinal study, and thus enriches studies focusing on a given moment in time, which distinguish between types of experimentation without studying their complementarities (e.g. Lechenet et al., 2017). Our findings confirm the need, already identified by Navarrete et al. (2018), to further develop the characterization of approaches to fostering complementarity between experiments. Moreover, MAENs are just one of a number of approaches mobilized in co-design processes. In line with the work of Aare et al. (2021), this work calls for further research on the complementarities between experimentation and other approaches (innovation tracking, serious games, socio-technical diagnosis, etc.) to better foster synergy when implementing them in support of design and transition processes more broadly.

3. Studying experiments that support design processes calls for discussing evidence gathering through experimentation. In most previous research studies, the robustness of evidence of causality or effectiveness hinges on the ability to predict, with the greatest possible certainty, the effects of actions under certain conditions, to limit all risk taking by a farmer. This evidence is often developed (as recommended in most peer-

reviewed journals) by accumulating statistically representative observations. Some of the experiments we studied followed this standard, particularly those seeking to validate the value of an IC, or to shed light on its conditions of effectiveness, often to foster the scaling out of that IC. However, other experiments we studied deviated from the standard, and involved various iterative evidence-building processes covering spatial and temporal in-field variability. Furthermore, in some cases, a single observation in the fields led to changes to the IC tested. In line with the advances made surrounding action or intervention research processes (e.g. Argyris et al., 1985; David, 2000), this calls for further formalizing the different ways of developing evidence, by investigating them through the prism of the diverse functions served by experimentation in design processes. Such evidence-building processes reflect the real-life contexts that farmers face, where evidence is also enhanced by experiential learning, always subject to surprises in their action situations (e.g. Catalogna et al., 2018; Ingram et al., 2018).

6. Conclusion

In a context where new forms of experimentation are emerging or growing to support transitions towards sustainable farming, this article specifically explored the characteristics of Multi-Actor Experimental Networks and their contributions to cropping system design processes. In this work, we studied these contributions using a theoretical framework inspired by the design sciences. The cross-cutting analysis of 11 MAENs implemented in 10 European countries, centred around intercrop design, allowed us to identify nine functions served by these networks to support the emergence of new ICs. We also highlighted several mechanisms enabling the pilots of these networks to articulate experiments guided by different logics, thereby capitalizing on their complementarities to support design processes, and three strategies to manage MAENs, tailored to different R&D contexts and expectations.

This research, which builds on the research method of and general lessons drawn by Salembier et al. (2021), highlights points of reference, mechanisms, and types of strategies that could help future MAEN pilots to reflect on the implications of their methodological choices when engaging in the development of such a network. Also, such experimental processes are shown to be of particular value for intercrops that are not widely implemented in farming practice but represent largely uncharted territory for science and practice and are characterized by increased complexity such as food grain intercrops (Timaeus et al., 2022).

Finally, this study opens up several research avenues. First, as the analysis was conducted from the perspective of MAEN pilots from R&D, further studies could enrich and explore these results from the farmers' perspectives, to assess whether and how these kinds of MAENs contribute to anchored farming system design. More broadly, future work could explore in more detail the roles of the actors involved in the participatory and social processes to enable the realization of design-experimentation processes (Koole, 2020; Fiorelli et al., 2014; Toffolini et al., 2021) Second, this work calls for further research on the skills needed to bring about and sustain such multi-actor networks, in complementarity with other existing methods and tools, to support innovation processes for a variety of transition paths (Klerkx, 2020; Källström and Ljung, 2005). Lastly, all the MAENs we studied were part of an H2020 project, and future studies could explore how to coordinate a network of MAENs across Europe, in order to support the sharing and valorization of knowledge on and experience with their management.

CRediT authorship contribution statement

Chloé Salembier: Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Ane Kristine Aare:** Validation, Writing – review & editing. **Laurent Bedoussac:** Validation, Writing - review & editing. **Iman Raj Chongtham:** Validation, Writing – review & editing. **Abco de Buck:** Validation, Writing – review & editing. **N**awa Raj **Dhamala:** Validation, Writing – review & editing. Christos **Dordas:** Validation, Writing – review & editing. **Maria Renate Finckh:** Validation, Writing - review & editing. **Henrik Hauggaard-Nielsen:** Funding acquisition, Project administration, Validation, Writing - review & editing. **Marek Krysztoforski:** Validation, Writing – review & editing. **Soren Lund:** Validation, Writing – review & editing. **Boki Luske:** Validation, Writing – review & editing. **Bertrand Pinel:** Validation, Writing – review & editing. **Johannes Timaeus:** Validation, Writing – review & editing. **Cristina Virto:** Validation, Writing – review & editing. **Robin Walker:** Validation, Writing – review & editing. **Marina Wendling:** Validation, Writing – review & editing. **Marie-Hélène Jeuffroy:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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References

Aare, A.K., Cooreman, H., Garayoa, C.V., Arrieta, E.S., Bellostas, N., Marchand, F., Hauggaard-Nielsen, H., 2020. Methodological Reflections on Monitoring Interactive Knowledge Creation during Farming Demonstrations by Means of Surveys and Observations. Sustainability 12, 5739. https://doi.org/10.3390/su12145739.

Aare, A.K., Lund, S., Hauggaard-Nielsen, H., 2021. Exploring transitions towards sustainable farming practices through participatory research – the case of Danish farmers' use of species mixtures. Agric. Syst. 189, 103053 https://doi.org/10.1016/j.agsy.2021.103053.

Adamsone-Fiskovica, A., Grivins, M., Burton, R.J.F., Elzen, B., Flanigan, S., Frick, R., Hardy, C., 2021. Disentangling critical success factors and principles of on-farm agricultural demonstration events. J. Agric. Educ. Ext. https://doi.org/10.1080/1389224X.2020.1844768.

Ansell, C.K., Bartenberger, M., 2016. Varieties of experimentalism. Ecol. Econ. 130. ⟨https://doi.org/10.2139/ssrn.2475844⟩.

Argyris, C., Putnam, R., McLain Smith, D., 1985. Action Science. Jossey-Bass.

Bakker, T., Dugué, P., de Tourdonnet, S., 2021. Assessing the effects of farmer field schools on farmers' trajectories of change in practices. Agron. Sustain. Dev. 41, 18. ⟨https://doi.org/10.1007/s13593-021-00667-2⟩.

Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., et al., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35, 911–935. https://doi.org/10.1007/s13593-014-0277-7.

Berkes, F., 2009. Indigenous ways of knowing and the study of environmental change. J. R. Soc. N. Z. 39 (4), 151–156. https://doi.org/10.1080/03014220909510568.

Bonaudo, T., Burlamaqui Bendahan, A., Sabatier, R., Ryschawy, J., Bellon, S., Leger, F., Magda, D., Tichit, M., 2014. Agroecological principles for the redesign of integrated crop–livestock systems. Eur. J. Agron. 57, 43–51. https://doi.org/10.1016/j.eja.2013.09.010.

Braun A., Jiggins J., Röling N., van den Berg H., Snijders P. 2006. A Global Survey and Review of Farmer Field School Experiences.

Brugnach, M., Dewulf, A., Pahl-Wostl, C., Taillieu, T., 2008. Toward a relational concept of uncertainty: about knowing too little, knowing too differently, and accepting not to know. Ecol. Soc. 13 (2), 30.

Caniglia, G., Schäpke, N., Lang, D.J., Abson, D.J., Luederitz, C., Wiek, A., Laubichler, M. D., Gralla, F., Von, Wehrden, H., 2017. Experiments and evidence in sustainability science: a typology. J. Clean. Prod. 169, 39–47.
Cardona, A., Lefevre, A., Simon, S., 2018. Les stations expérimentales comme lieux de production des savoirs agronomiques semi-confinés. Enquête dans deux stations INRA engagées dans l'agroécologie. Rev. D. 'Anthropol. Des. Connaiss. 12 (2), 139–170.
Catalogna, M., Dubois, M., Navarrete, M., 2018. Diversity of experimentation by farmers en-gaged in agroecology. Agron. Sustain. Dev. 38 (5), 50.
Darnhofer, I., Bellon, S., Dedieu, B., Milestad, R., 2009. Adaptiveness to enhance the sustainability of farming systems. Sustain. Agric. 2, 45–58. https://doi.org/10.1007/978-94-007-0394-0_4.
David, A., 2000. La recherche intervention, un cadre général pour les sciences de gestion? in: IXème Conférence Internationale de Management Stratégique Montpellier, 24 - 26mai 2000. Montpellier, p. 22.
Debaeke, P., Munier-Jolain, N., Bertrand, M., Guichard, L., Nolot, J.M., Faloya, V., Saulas, P., 2009. Iterative design and evaluation of rule based cropping systems: methodology and case studies. A review. Agron. Sustain. Dev. 29, 73–86.
Deytieux, V., Vivier, C., Minette, S., Nolot, J.-M., Piaud, S., Schaub, A., Lande, N., Petit, M.-S., Reau, R., Fourrié, L., Fontaine, L., 2012. Expérimentation de systèmes de culture innovants: avancées méthodologiques et mise en réseau opérationnelle. Innov. Agron. 20, 49, 7.
Doré, T., Clermont-Dauphin, C., Crozat, Y., David, C., Jeuffroy, M.H., et al., 2008. Methodological progress in on-farm regional agronomic diagnosis. A review. Agron. Sustain. Dev. 28 (1), 151–161.
Drinkwater, L.E., 2002. Cropping systems rsearch: reconsidering agricultural experimental approaches. HortTechnol. Horttech 12 (3), 355–361.
Dumez, H., 2013. Qu'est-ce que la recherche qualitative? Problèmes épistémologiques, méthodologiques et de théorisation. Ann. Des. Mines Gérer Compr. 112, 29. https://doi.org/10.3917/geco.112.0029.
Eisenhardt, K.M., Graebner, M.E., 2007. Theory building from cases: opportunities and challenges. Acad. Manag J. 50, 1. https://doi.org/10.5465/amj.2007.24160888.
Fiorelli, C., Auricoste, C., Meynard, J.M., 2014. Concevoir des systèmes de production agroécologiques dans les stations expérimentales de l'INRA: changements de référentiel professionnel pour les agents et les collectifs de recherche. Le. Courr. De. l'Environ. De. l'INRA 64, 57–68.
Gamache, G., Anglade, J., Feche, R., Barataud, F., Mignolet, C., Coquil, X., 2020. Can living labs offer a pathway to support local agri-food sustainability transitions. Environ. Innov. Soc. Transit. 37, 93–107. https://doi.org/10.1016/j.eist.2020.08.002.
Gillier, T., Lenfle, S., 2018. Experimenting in the unknown: lessons from the manhattan project. Eur. Manag. Rev. 16 (2), 449–469.
Hansen, J.A., Tummers, L., 2019. A systematic review of field experiments in public administration. Public Adm. Rev. 80 (6), 921–931.
Hatchuel A., Weil B. 2003. A new approach of innovative design: an introduction to C-K theory, in: Folkeson A, Gralen K, Norell M, Sellgren U. (Eds.), International Conference on Engineering Design. Stockholm, 109–110. ⟨https://www.designsociety.org/publication/24204/A+NEW+APPROACH+OF+INNOVATIVE+DESIGN+%3A+AN+INTRODUCTION+TO+C-K+THEORY⟩.
Hatchuel A., Reich Y., Le Masson P., Weil B., Kazakçi A. 2013. Beyond Models and Decisions: Situating Design Through Generative Functions, in: ICED13: 19th International Conference on Engineering Design. Séoul, 1–10. ⟨https://hal-mines-paristech.archives-ouvertes.fr/hal-01485144/document⟩.
Hatchuel, A., Le Masson, P., Reich, Y., Eswaran, S., 2017. Design theory: a foundation of a new paradigm for design science and engineering. Res Eng. Des. 29, 5–21. https://doi.org/10.1007/s00163-017-0275-2.
Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozat, Y., Dahlmann, C., Dibet, A., von Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S., 2009. Pea-barley intercropping and short-term subsequent crop effects across European organic cropping conditions. Nutr. Cycl. Agroecosyst. 85, 141–155.
Hauggaard-Nielsen, H., Johansen, A., Carter, M.S., Ambus, P., Jensen, E.S., 2013. Annual maize and perennial grass-clover strip cropping for increased resource use efficiency and productivity using organic farming practice as a model. Eur. J. Agron. 47, 55–64.
Henke, C.R., 2000. Making a place for science: The Field Trial. Soc. Stud. Sci. 30 (4), 483–511.
Husson, O., Tran Quoc, H., Boulakia, S., Chabanne, A., Tivet, F., Bouzinac, S., Séguy, L., 2016. Co-designing innovative cropping systems that match biophysical and socio-economic diversity: the DATE approach to conservation agriculture in Madagascar, Lao PDR and Cambodia. Renew. Agric. Food Syst. 31 (5), 452–470. https://doi.org/10.1017/S174217051500037X.
Ingram, J., Dwyer, J., Gaskell, P., Mills, J., de Wolf, P., 2018. Reconceptualising translation in agricultural innovation: A co-translation approach to bring research knowledge and practice closer together. Land Use Policy 70, 38–51. https://doi.org/10.1016/j.landusepol.2017.10.013.
Jas, N., 2001. Au carrefour de la chimie et de l'agriculture. Editions des archives contemporaines, Paris.
Jensen, E.S., et al., 2020. Diversifying European agricultural systems by intercropping grain legumes and cereals. Int. J. Agric. Nat. Resour. 47 (3), 174–186. https://doi.org/10.7764/ijanr.v47i3.2241.
Jeuffroy, M.-H., Loyce, C., Lefeuvre, T., Valantin-Morison, M., Colnenne-David, C., Gauffreteau, A., Médiène, S., Pelzer, E., Reau, R., Salembier, C., Meynard, J.-M., 2022. Design workshops for innovative cropping systems and decision-support tools: learning from 12 case studies. Eur. J. Agron. 139, 126573 https://doi.org/10.1016/j.eja.2022.126573.
Jobin C., Hooge S., Le Masson P. 2021. The logics of double proof in proof of concept: a design theory-based model of experimentation in the unknown. 23rd International Conference on Engineering Design (ICED), Aug 2021, Gothenburg, Sweden.
Johnston, A.E., Poulton, P.R., 2018. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. Eur. J. Soil Sci. 69 (1), 113–125. https://doi.org/10.1111/ejss.12521.
Källström, H.N., Ljung, M., 2005. Social sustainability and collaborative learning. Ambio 34 (4–5), 376–382. https://doi.org/10.1579/0044-7447-34.4.376.
Klerkx, L., 2020. Advisory services and transformation, plurality and disruption of agriculture and food systems: towards a new research agenda for agricultural education and extension studies. J Agric Educ Ext 26, 131–140. https://doi.org/10.1080/1389224X.2020.1738046.
Koole, B., 2020. Trusting to learn and learning to trust. A framework for analyzing the interactions of trust and learning in arrangements dedicated to instigating social change. Technol. Forecast. Soc. Change 161, 120260. https://doi.org/10.1016/j.techfore.2020.120260.
Kummer, S., Milestad, R., Leitgeb, F., Vogl, C.R., 2012. Building resilience through farmers' experiments in organic agriculture: examples from Eastern Austria. Sustain. Agric. Res. 1 (2), 308. https://doi.org/10.5539/sar.v1n2p308.
Lacombe, C., Couix, N., Hazard, L., 2018. Designing agroecological farming systems with farmers: a review. Agric. Syst. 165, 208–220. https://doi.org/10.1016/j.agsy.2018.06.014.
Lacoste, M., Cook, S., McNee, M., et al., 2022. On-Farm Experimentation to transform global agriculture. Nat. Food 3, 11–18. https://doi.org/10.1038/s43016-021-00424-4.
Le Masson, P., Weil, B., Hatchuel, A., 2017. Design Theory. Methods and Organization for innovation. Springer Nature. ⟨10.1007/978-3-319-50277-9⟩.
Lechenet, M., et al., 2017. Diversity of methodologies to experiment Integrated Pest Management in arable cropping systems: analysis and reflections based on a European network. Eur. J. Agron. 83, 86–99.
Leclère, M., Loyce, C., Jeuffroy, M.H., 2018. Growing camelina as a second crop in France: a participatory design approach to produce actionable knowledge. Eur. J. Agron. 101, 78–89. https://doi.org/10.1016/j.eja.2018.08.006.
Maat, H., 2011. The history and future of agricultural experiments. NJAS – Wagening. J. Life Sci. 57 (3–4), 187–195. ⟨http://www.sciencedirect.com/science/article/pii/S1573521410000461⟩.
Makowski, D., Piraux, F., Brun, F. 2019. From experimental network to meta-analysis. Editions Quae.
Meynard, J.M., Dedieu, B., Bos, A., 2012. Re-design and co-design of farming systems. An overview of methods and practices. In: Darnhofer, I., Gibon, D., Dedieu, B. (Eds.), Farming Systems Research into the 21st Century: The New Dynamic. Springer, Paris, pp. 407–432.
Navarrete M., Brives H., Catalogna M., Gouttenoire L., Heinisch C. et al. 2018. Farmers' involvement in collective experimental designs in a French region, Rhône-Alpes. How do they contribute to farmers' learning and facilitate the agroecological transition?. 13th European IFSA Symposium (IFSA 2018), La Canée (Crete), Greece.
Navarrete, M., Brives, H., Catalogna, M., Lefèvre, A., Simon, S., 2021. Intertwining deterministic and openended perspectives in the experimentation of agroecological production systems: A challenge for agronomy researchers. Agroecological transitions, between determinist and open-ended visions. In: Lamine, C., Magda, D., Rivera-Ferre, M., Marsden, T. (Eds.), Agroecological transitions, between determinist and open-ended visions. Peter Lang, pp. 57–78.
Papalambros, P.Y., 2015. Design science: why, what and how. Des. Sci. 1, e1 https://doi.org/10.1017/dsj.2015.1.
Pelzer, E., Hombert, N., Jeuffroy, M.H., Makowski, N., 2012. Meta-analysis of the effect of nitrogen fertilization on annual cereal–legume intercrop production. Agron. J. 106 (5), 1775–1786.
Périnelle, A., Meynard, J.M., Scopel, E., 2021. Combining on-farm innovation tracking and participatory prototyping trials to develop legume-based cropping systems in West Africa. Agric. Syst. 187, 102978 https://doi.org/10.1016/j.agsy.2020.102978.
Prost, L., 2021. Revitalizing agricultural sciences with design sciences. Agric. Syst. 193, 103225 https://doi.org/10.1016/j.agsy.2021.103225.
Prost, L., Reau, R., Paravano, L., Cerf, M., Jeuffroy, M.H., 2018. Designing agricultural systems from invention to implementation: the contribution of agronomy. Lessons from a case study. Agric. Syst. 164, 122–132. https://doi.org/10.1016/j.agsy.2021.103225.
Quinio, M., Guichard, L., Salazar, P., Détienne, F., Jeuffroy, M.H., 2022. Cognitive resources to promote exploration in agroecological systems design. Agricultural Systems 196, 103334. https://doi.org/10.1016/j.agsy.2021.103334.
Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Bachinger, J., 2020. Re-designing organic grain legume cropping systems using systems agronomy. Eur. J. Agron. 112, 125951 https://doi.org/10.1016/j.eja.2019.125951.
Salembier, C., Segrestin, B., Berthet, E., Weil, B., Meynard, J.M., 2018. Genealogy of design reasoning in agronomy: lessons for supporting the design of agricultural systems. Agric. Syst. 164, 277–290.
Salembier, C., Segrestin, B., Weil, B., et al., 2021. A theoretical framework for tracking farmers' innovations to support farming system design. Agron. Sustain. Dev. 41, 61.
Schon, D.A., Wiggins, G., 1992. Kinds of seeing and their functions in designing. Des. Stud. 13, 135–156. https://doi.org/10.1016/0142-694X(92)90268-F.
Schön, D., 1983. The Reflective Practitioner: How Professionals Think in Action. Basic Books, New York.
Silva, E.M., Tchamitchian, M., 2018. Long-term systems experiments and long-term agricultural research sites: Tools for overcoming the border problem in agroecological research and design. In: Agroecology and Sustainable Food Systems, 42. Taylor & Francis, Philadelphia PA, pp. 620–628.

Simon, H.A., 1969. The Sciences of the Artificial. MIT Press.
Snapp, S., 2002. Quantifying Farmer Evaluation of Technologies: The Mother and Baby Trial Design. In: Bellon, M.R., Reeves, J. (Eds.), Quantitative Analysis of Data from Participatory Methods in Plant Breeding. CIMMYT, Mexico, DF.
Šūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., Rios, I., des, I., Rivera, M., Chebach, T., Ashkenazy, A., 2018. Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. J. Rural Stud. 59, 232–241. https://doi.org/10.1016/j.jrurstud.2017.01.020.
Timaeus, J., Ties, R., Torsten, S., Maria Renate, F., 2022. Adoption of food species mixtures from farmers' perspectives in germany: managing complexity and harnessing advantages. Agriculture 12 (Nr. 5), 697. https://doi.org/10.3390/agriculture12050697.
Toffolini, Q., Jeuffroy, M.H., 2022. On-farm experimentation practices and associated farmer-researcher relationships: a systematic literature review. Agronomy for Sustainable Development 42, 114.
Toffolini, Q., Jeuffroy, M.H., Meynard, J.M., Borg, J., Enjalbert, J., Gauffreteau, A., Goldringer, I., Lefèvre, A., Loyce, C., Martin, P., Salembier, C., Souchère, V., Valantin-Morison, M., van Frank, G., Prost, L., 2020. Design as a source of renewal in the production of scientific knowledge in crop science. Agric. Syst. 185, 102939 https://doi.org/10.1016/j.agsy.2020.102939.
Toffolini, Q., Capitaine, M., Hannachi, M., Cerf, M., 2021. Implementing agricultural living labs that renew actors' roles within existing innovation systems: a case study in France. J. Rural Stud. 88, 157–168. https://doi.org/10.1016/j.jrurstud.2021.10.015.
Vaarst, M., Nissen, T.B., Østergaard, S., Klaas, I.C., Bennedsgaard, T.W., Christensen, J., 2007. Danish stable schools for experiential common learning in groups of organic dairy farmers. J. Dairy Sci. 90 (5), 2543–2554. https://doi.org/10.3168/jds.2006-607.
Walters, C.J., Holling, C.S., 1990. Large-scale management experiments and learning by doing. Ecology 71, 2060–2068.
Weiland, S., Bleicher, A., Polzin, C., Rauschmayer, F., Rode, J., 2017. The nature of experiments for sustainability transformations: a search for common ground. J. Clean. Prod. 169, 30–38. https://doi.org/10.1016/j.jclepro.2017.06.182.
Willey, R.W., 1979. Intercropping – it's important and research needs. Part 1. Competition and yield advantages. Field Crop Abstr. 32, 1–10.
Wynn, D.C., Clarkson, P.J., 2018. Process models in design and development. Res. Eng. Des. 29, 161–202. https://doi.org/10.1007/s00163-017-0262-7.
Yin, R.K., 2003. Case Study Research: Design and Methods. Sage, Thousand Oaks, California.