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Unravelling the step-by-step process for farming system design to support agroecological transition

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Abstract

Given the huge challenges agriculture has to face, both in Northern and Southern countries, a radical change in farming practices towards agroecology is required. Most scientific literature on the design of new farming systems describes *de novo* approaches, which focus on disruption and novelty, without any concern for the way to move from the current system to the innovative one. In this study, we highlight, for the first time, the particular traits of what we will call the *step-by-step design* approach. In this aim, we disentangled 9 case studies of practice change in commercial or experimental farms through the lens of theoretical frameworks derived from three scientific fields: design sciences, farming system research, and change pathways analysis. From data collected in each case study, and collective interactions among the authors of this paper, we identified commonalities across cases, in the aim to produce guidelines for actors willing to engage, characterize or support such design processes in the future. We thus show that *step-by-step design* appears as (i) a situated design process fueled by action, (ii) structured by iterative loops diagnosis – exploration – implementation – assessment, fostered by learning, (iii) progressively shaping a desirable unknown, (iv) supported by specific tools, and (v) intertwining individual and collective dimensions. This approach is well adapted to manage the agroecological transition: by its temporality, by its capacity to overcome knowledge gaps through learning, by its contribution to farmers' empowerment, and by its capacity to tailor solutions to local specificities. By doing so, it allows the progressive implementation of profound systemic changes. Finally, this article provides benchmarks to encourage increased Research & Development investment in this type of approach, contributing to open innovation, to enhance the agroecological transition.

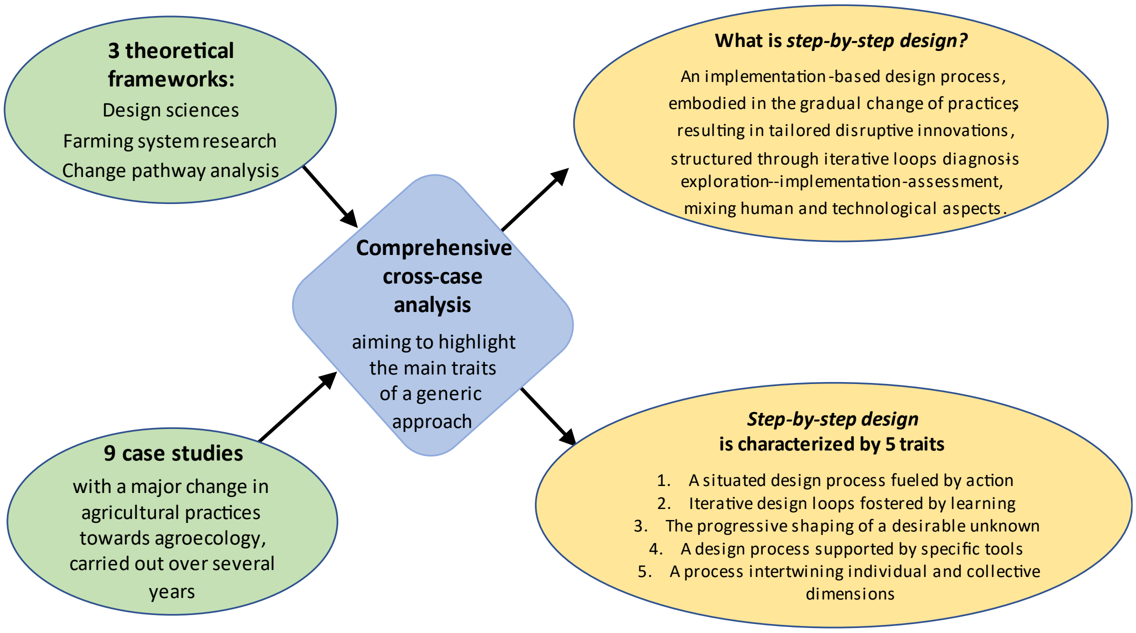
Key-words

Cropping system, change pathway, practices, farmer-designer, learning, open innovation.

Highlights

- *Step-by-step design* is a process resulting in a gradual change of practices
- We shed light on five traits of *step-by-step design* derived from 9 case studies
- *Step-by-step design* relies on the progressive shaping of a desirable unknown
- It is a situated design process fuelled by action and fostered by learning
- Specific resources and collective exchanges support a *step-by-step design* process

Graphical abstract



Tables and Supplementary Material are at the end of the document.

1. Introduction

Given the huge, numerous and various challenges agriculture has to face, all around the world, a radical change in farming practices towards the ecologization of agricultural systems is required (Darnhofer, 2015; Tittonell et al., 2016). Such an agroecological transition calls for a large range of disruptive innovations, regarding among others farming systems (including cropping and livestock systems), machinery, decision-support tools or collective organizations (Côte et al., 2022). To bring out such disruptive innovations targeting sustainability, innovative design processes (Le Masson et al., 2010) have proven to be efficient (Meynard et al., 2012).

Most scientific literature on the design of new farming systems describes two main approaches: prototyping in workshops and model-based design (Le Gal et al., 2010; Schaap et al., 2013; Prost et al., 2017a). Prototyping consists in designing, during workshops involving experts with diverse and complementary knowledge, a few virtual prototypes of farming systems, tailored to farmers' aims and resources (Vereijken, 1997). Some of these prototypes are then implemented on commercial or experimental farms to assess their performances (Colnenne-David et al., 2015). Model-based design consists in using computerized simulation models to generate, simulate and assess a large number of technical options to identify those reaching targeted performances (Rossing et al., 1997; Keating and Thorburn, 2018). Both approaches have been formalized in various operational methods, such as designing crop management systems by simulation (Bergez et al., 2010), or methodological lessons for design workshops (Jeuffroy et al., 2022). Most often, in these approaches, the designer is an agronomist (researcher, engineer, advisor) whose aim is to provide prototypes of innovative systems to farmers. However, all these approaches only focus on the invention of original virtual systems (what they will look like), without considering the pathways enabling the evolution from current systems to the new ones. In the aim of enhancing agroecological transition, supporting farmers in the definition of virtual systems is not enough: helping them in the management of change pathways is also essential (Prost et al., 2023).

Various studies have described and analyzed *a posteriori* the processes of change of farming practices, emphasizing dynamic and long-term transitional pathways (Wilson, 2008; Garcia-Martinez et al., 2009; Ingram et al., 2013). Such pathways have been described as successive agronomic-coherent phases, characterized by stable practices, separated by periods during which the process of change takes shape (Chantre et al., 2014; Mawois et al., 2019). In all these studies, the management of change by farmers appears as a long and non-linear process, a trajectory along which they have progressively made their practices evolve. At each step of this pathway, farmers acquire new knowledge, implement new practices, adapting their practices to their local situations (Chantre and Cardonna, 2014; Aare et al., 2021). Yet, these studies do not describe how, in such a *step-by-step* change, the design process is managed, all along the pathway. In the aim of developing and supporting farming system design for enhancing agroecological transition, the two dominant design approaches described above are not sufficient, as they do not consider long-time span and learning processes.

In this article, by studying several past cases, we propose to highlight the particular traits of what we will call the *step-by-step design* approach (in line with Meynard et al., 2012). We assume that the potential users of such an approach could be not only farmers, but also experimenters, advisors, and more generally all kinds of actors engaged in supporting or implementing change pathways of agricultural practices. While step-by-step design is increasingly used and mentioned in the litterature (e.g. Toffolini et al., 2017; Leclère et al., 2018; Salembier et al., 2020; Perinelle et al., 2021), our objective is to produce guidelines and benchmarks for actors willing to engage in, or support such design processes in the future. To do so, we analyzed in-depth 9 cases studies of three types: a/ several retrospective analyzes of farmers' experiences, during which they managed over time a step-by-step change process in their own farms; b/ studies in which the authors of this article contributed to the design and management of practice change in real farms, by supporting farmers, or by providing them with design-support tools; and c/ studies in which scientists, authors of this paper, implemented themselves, in experimental farms, a *step-by-step design* process for agroecological cropping or livestock systems.

2. Theoretical framework

Our study is based on three theoretical frameworks derived from three scientific fields: design sciences, farming system research, and change pathways analysis.

Design is a process driven by a wish to generate something that does not yet exist (Simon, 1969). The designers consider that what exists does not fulfil their expectations. They want something new to emerge (it is “desirable”), but do not yet know what (it is “unknown”). Every design process thus begins with the formulation of a desirable unknown, which is the design target (Le Masson et al., 2017). Design is thus a goal-oriented exploration-based process. In that way, « *design is different from decision, that consists in selecting the best option(s) among known solutions, whereas design aims to generate alternatives beyond an existing set of solutions* » (Berthet and Hickey, 2018). As emphasized by Hatchuel and Weil (2009), design relies on the progressive specification of the properties of a new “object”, i.e. what it will be, what it will do, and what use will be made of it, by whom, when, and in which conditions. The progressive emergence of these properties is fed by various kinds of knowledge, some already existing before the design process, and others generated during it. In a process of innovative design (Le Masson et al., 2010), the exploration of a new object aims at meeting completely new expectations. As a consequence, neither the required knowledge, nor even the expectations concerning the object to be designed, can be entirely defined before the design process, but they become clearer as the object takes shape. Moreover, Schön (1983) underlined the major role of the implementation of prototypes during the design process: some properties of the object under design only emerge in and through action (“designing by doing”).

The second scientific field supporting our theoretical framework is Farming System Research (FSR). It focuses on cropping systems, livestock systems, or farming systems, i.e. combinations of practices implemented, respectively, on a field, a herd, or a farm, for plant or animal production (Sebillotte, 1974; Zandstra, 1979; Byerlee et al., 1982; Darnhofer et al., 2010). By using these concepts, the scientists involved in the FSR movement underline the importance of considering practices in a systemic way, to reason and manage them coherently. For cropping systems, that means considering the consistency between practices, e.g. crop sequences, sowing, fertilization, crop protection, harvest; and, for farming systems, the consistency between cropping systems, livestock systems, fodder systems, working force, equipment, at farm scale. This systemic coherence between the technical choices is linked both to the interactions between techniques in the functioning of the agroecosystem, and to the farmers’ logics of action. Designing cropping systems, livestock systems, or farming systems thus involves considering the interactions between techniques, and between techniques and their ecological and socioeconomic contexts of application. Moreover, agricultural system design should consider the unplanned effects of technical options, and take into account the interconnections between scales and along time (Meynard et al., 2012). One main feature in agriculture is that practices have to be tailored to each situation because of the large diversity of soils, climates, farm resources (equipment, labor force, cash, etc.) and socioeconomic conditions (e.g. market outlets). Thus, most cropping or farming systems are designed for one location, one farm and one environment, and differ from the ones designed elsewhere: farming system design is situated. To fuel such a situated design process, several authors stress the importance of mobilizing local knowledge of farmers, combined with scientific and technical knowledge (Leclère et al., 2018; Girard and Magda, 2020; Quinio et al., 2022), in a dynamics of open innovation.

Change pathway analysis is the third scientific field supporting our theoretical framework. It involves identifying (i) the drivers of change, i.e. the factors, external or internal to the farm, that have triggered the decision to change (Coquil et al., 2018), (ii) the process of change, i.e. the procedures and instruments used by farmers to implement the changes, and (iii) the learning process leading to stabilizing a new coherence phase (Lamine, 2011; Chantre et al., 2014). These studies show constant iterations between the changes implemented by farmers, and what they learn from them. They change because they have learned, and they learn from the changes. As shown by Darnhofer et al. (2010), the evolution of farming systems goes hand in hand with a continuous learning process, not only opening new perspectives for action, but also sometimes renewing or specifying targets. Consistently, Argyris (1976) highlighted two types of learning: single-loop learning enhances farmers' knowledge, allowing to improve their practices and to imagine others, whereas double-loop learning refers to learning that revisits and reshapes targets, values, standards and patterns of thinking. This iterative process between learning and change is also put forward in the literature on Adaptive Management, referring to the management of natural resources. Despite uncertain and incomplete knowledge, managers act, thus increasing knowledge through a structured feed-back process from doing (Biggs et al., 2010; Allen et al., 2011). Uncertainty is thus reduced through action enhancing learning.

3. Materials and methods

3.1. Case studies selection

The article is based on 9 case studies (**Table 1** and **Supplementary Material**), in which major changes in cropping or farming systems towards agroecology were carried out over several years. We focused our analysis on the design process carried out in these cases. In each case, new cropping or farming systems were implemented (from 1 to about 50). We call "pilots" the persons who coordinated the entire *step-by-step design* process and, most frequently, made the choice of practices for each cropping or farming system designed. In order to highlight generic traits of *step-by-step design*, whatever the situation of its implementation, and generic ways of supporting this process, we have chosen cases that contrast on several features (**Table 1**):

- **Diversity of the pilots**: in 6 case studies (1 to 6), pilots were farmers (farmer-designers) willing to change their practices to make their systems more consistent with their values or with the performances they hoped to achieve. In the other 3 case studies, pilots were scientists working in experimental farms with the aim to develop prototypes of sustainable, highly innovative but realistic, agricultural systems. In all cases, the pilots have imagined changes and decided their implementation in strong interaction with other actors: farmer-pilots interacted with advisors and other farmers; scientist-pilots did so with other scientists from different disciplines, experimentation technicians, and a few innovative farmers.
- **Diversity of targets for practice change**: in all case studies, as soon as the beginning of the change process, an ambitious target was defined by the pilot. All targets were part of an agroecological transition perspective. They focused either on a reduction in environmental damages (cases 2, 4, 6), or a low or no-pesticide use (cases 7 and 9), or a high autonomy regarding synthetic inputs (cases 1, 3, 5, and 9), or a better answer to their customers' expectations (cases 6 and 7), or a synergy between agriculture and biodiversity (case 8). In 6 out of 9 cases, the target for practice change focused on the field level (cropping system), and on the farm scale (farming system) in the 3 other cases.
- **Diversity of situations of production**: the 9 case studies covered a wide range of production types: arable crops (cases 1 to 6), mixed crop-livestock systems (cases 8 and 9), market gardening (cases 2 and 7). They also concerned various types of agriculture: conventional agriculture (cases 1, 3, 4, 5, 6), or organic agriculture (case 8, 9), and sometimes both (cases 2, 7). Most cases were located in France, covering highly diverse pedo-climatic conditions, and one case was in West Africa (Burkina Faso, case 3).

- **Diversity of the scientists' positions**: The contributions of the scientists, authors of this paper, in the various case studies were diverse. In some cases, they performed a retrospective analysis of the trajectories of practice changes on commercial farms (cases 1, 2). In other cases, they were involved in participatory research, supporting the design of the systems on commercial farms by providing farmers with knowledge and/or tools (cases 3, 4, 5, 6). In the last cases (7, 8, 9), the scientists were themselves the pilots of the design and implementation processes on experimental farms.

The characteristics of the 9 case studies, underlying their selection, are detailed in **Table 1**, and complementary information can be found in the articles linked to the cases. A more detailed presentation of the 9 case studies is provided in **Supplementary Material**.

3.2. Data collection and method of analysis

As all case studies have already been published, we do not describe here all the data collected on each case, but only data that have been used in our cross-case analysis. For all cases, they cover: chronology of the practices evolution over the period under study, reasons for changes (according to the pilots), experiments carried out by the pilots over time to support changes, knowledge and know-how acquired by the pilots following the implementation of a new practice, indicators and tools used in the course of the change, other people who influenced the choice of the new practices implemented. On the farms where a retrospective approach was performed (cases 1, 2), this data was collected through semi-directive interviews with the farmers (see Chantre et al., 2014, 2015; Catalogna et al., 2018, 2022, for more details). In participatory research on commercial farms (cases 3, 4, 5, 6), data was collected in real time by the research team from the farmer-pilots of the design and, sometimes, from the advisors supporting the change of practices, through semi-directive interviews and participatory observation of the meetings gathering farmers undergoing change. In participatory research on experimental farms (cases 7, 8 and 9), data was collected in real time by the team in charge of designing and implementing the new systems.

A cross-case analysis was performed to identify some generic traits among the various cases, through iterations between the in-depth analysis of each case and the comparison with all other cases (Yin, 2003). The *three theoretical frameworks* described above (section 2) allowed us to compare the cases on:

- the systemic consistency between the pilot's target, the production situation and the implemented changes, at each step of the change process (*Farming System Research and change pathway analysis*),
- the consequences on the design process of implementing, in real conditions, the system under design (*designing by doing)*,
- the various kinds of knowledge and know-how acquired by the pilots during the design process, and remobilized to fuel the design process over time (*learning process)*,
- the nature, formulation and evolution of the design target (*desirable unknown*),
- the resources (material, social and cognitive) used by the pilots and their partners to fuel the design process (*change pathway analysis*),
- the role of the different people participating in the design process.

The traits of *step-by-step design*, described from the cross-case analysis, as well as avenues for stimulating design in other situations, were then discussed during several collective meetings, gathering all the authors of the article.

4. Results

4.1. Overview of the design dynamics across the 9 case studies

In all cases, at the end of the period of study, the agricultural practices were highly different from the initial ones. The cropping or farming systems resulting from these changes were not known at the beginning of the process. The changes of agricultural practices usually spread over about ten years, sometimes more (until 20 years for case 1), sometimes less (only 3 years in the case 3). In most cases (2 to 9), the process of change continued beyond the period under study. The design process underlying these changes appears as a long process, during which the pilots developed, year after year (*step-by-step*), their new systems, resulting in a pathway progressively built.

Across all cases, design concerned a large diversity of objects (**Table 1**): the cropping systems of one commercial or experimental farm (e.g. cases 4 and 7), or those of several farms redesigned together (e.g. case 5), or both the cropping and livestock systems (e.g. case 9). In case 6, the design process concerned all the cropping systems of a catchment area of 2,000 ha, i.e. those of 58 farmers. In all cases, several techniques were consistently changed: e.g., in case 8, the desire to be self-sufficient regarding animal feed has led to a change in the feeding of suckler cows, which has resulted in the cultivation of cereal-legume mixtures, an experiment of over-sowing of legumes on hay meadows, but also in a change in the calving periods to better match forage supply with animal requirements.

In numerous cases (e.g. 1 to 6), the new elementary practices were not totally unknown to the pilots, but the design and the resulting novelty were centered on their combination, and their adaptation to the farms. However, using the terms cropping or farming system to describe the systemic objects designed is not sufficient, as the design was not limited to these objects. Indeed, the design of cropping systems was often linked to a change in work organization (cases 1, 5, 6), equipment (case 2), field surroundings management (case 7), or crop monitoring (cases 1, 6, 7), thus impacting several components of the farms. In case 4, the design, which initially concerned only 2 plots of each farm to limit risks, was quickly extended to all plots on their farms, on the farmers' initiative. In case 6, some farmers have only changed their practices on the fields located in the water catchment area, while others have changed their whole farming systems (e.g. by converting to organic agriculture). In some cases, the design at the farming system level not only led to strengthening the links between cropping and livestock systems (cases 8, 9), but also to the inclusion of landscape elements favorable to biodiversity (e.g. grassy or flower strips, hedgerows and ponds, case 8).

Among the outputs of the design process, the pilots also mentioned learnings (all cases), generation of new knowledge (cases 1, 2, 3), new assessment criteria (cases 2, 4, 5, 7), new tools to monitor change (case 6), and the renewal of the pilots' relationship network (cases 1, 6, 7, 8, 9).

4.2. The main traits of step-by-step design

We highlighted 5 traits of a *step-by-step design* process, common to the 9 case studies: (i) a situated design fueled by action; (ii) iterative design loops fostered by learning; (iii) the progressive shaping of a desirable unknown; (iv) a design process supported by specific tools; (v) a design process intertwining individual and collective dimensions.

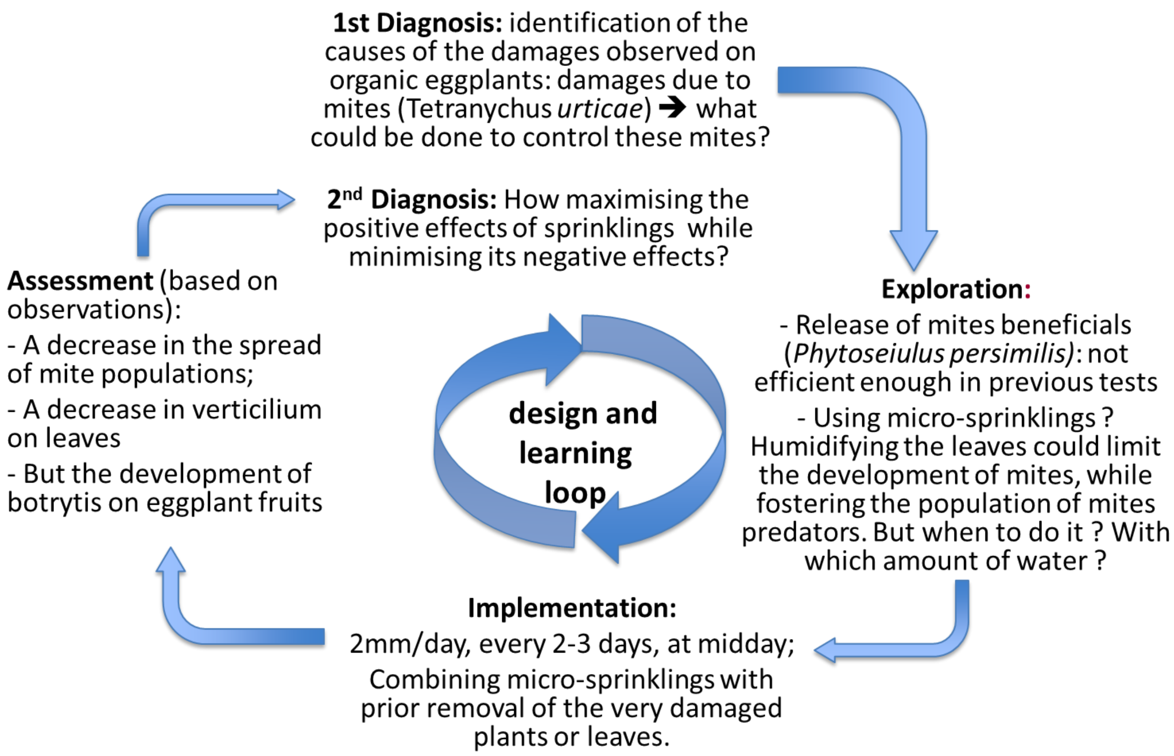
4.2.1. Trait 1: a situated design process fueled by action

In all cases studied, the pilots progressively designed their farming or cropping systems by combining practices that they adapted to their singular situations (soils, climate, farm structure, available resources, political regulations, value chain standards, commercial outlets, etc.), and to their own expectations. Therefore, no designed system is identical to another one, and, even though some practices may be similar, their combination is site-specific and therefore unique. For example, in case 5, whereas the design process was collectively managed with a shared target (i.e. to limit the amount of synthetic-N fertilizer within the crop sequence), the designed practices differed between farms. Some farmers chose to introduce crops with low N requirements (spring barley, sunflower), while others preferred to purchase organic waste products (manure, urban composts) or to grow legumes. In case 6, most farmers chose to grow a cover crop after the summer harvest of their cash crops, to foster soil mineral N uptake during autumn and reach low nitrate leaching. Yet, the cover crop management was very diverse between farms (sowing different species, or keeping volunteers of pea or oilseed rape), due to the knowledge, expectations and resources of each pilot.

In all case studies, design was strongly intertwined with the implementation of new practices, according to a dynamics that was not planned. Implementing new practices or combinations of practices for real contributed to progressively shaping the system under design (**Table 2**). For example, to increase the nitrogen self-sufficiency of his system, a farmer in case 2 chose to introduce a vetch (a legume) between wheat and maize. Observing that the maize crop lacked nitrogen, he decided, year after year, to sow the vetch earlier and earlier, to enhance its ability to accumulate N. The finally-designed system (vetch sown just before wheat harvest) therefore resulted from iterative tests over several years. In other cases, quicker adjustments were observed: in case 3, the ridging date of sorghum, grown in mixture with a legume, was decided during the crop season, according to the farmer's observation of the relative growth of the two species. The implementation of new practices plays an essential role in the emergence of new ideas, derived from the pilots' observations, which are in turn put into action. Another function of the implementation was to validate technical options that were poorly known by the pilot. For example, despite their strong apprehension regarding wheat lodging, some farmers in cases 1 and 4 dared to eliminate the growth regulator, thanks to the reduction in the risk of lodging allowed by changing other techniques (delayed sowing, lower sowing density, cultivar resistant to lodging, delay of the first N fertilization application). After checking the crop performance and the absence of lodging in one or two of their fields conducted without growth regulator, the farmers extended this management to their whole farm. The *step-by-step design* of situated cropping or farming systems thus appears to go hand-in-hand with the implementation of intermediate versions of the systems under design: implementation makes it possible to stimulate new explorations and to validate the current version of the system under design.

4.2.2. Trait 2: iterative design loops fostered by learning

Implementation was the support for iterative design loops, which took similar forms in the 9 cases. The design loop always involved four sequential activities (**Fig. 1**): diagnosis, exploration, implementation and assessment. The assessment is then followed by a new diagnosis, thus starting a new loop.



1st Diagnosis: identification of the causes of the damages observed on organic eggplants: damages due to mites (Tetranychus *urticae*) ➔ what could be done to control these mites?

2nd Diagnosis: How maximising the positive effects of sprinklings while minimising its negative effects?

Exploration:
- Release of mites beneficials (*Phytoseiulus persimilis)*: not efficient enough in previous tests
- Using micro-sprinklings ? Humidifying the leaves could limit the development of mites, while fostering the population of mites predators. But when to do it ? With which amount of water ?

Implementation:
2mm/day, every 2-3 days, at midday;
Combining micro-sprinklings with prior removal of the very damaged plants or leaves.

Assessment (based on observations):
- A decrease in the spread of mite populations;
- A decrease in verticilium on leaves
- But the development of botrytis on eggplant fruits

Figure 1: Learning loop during step-by-step design of a pesticide-free market-gardening system under shelters (case 7). Literature, pilots' knowledge, and exchanges with experts were used to feed each of the four activities (diagnosis, exploration, implementation, assessment)

We illustrate this loop with case 7, consisting of the implementation and assessment of micro-sprinkling on eggplants under shelter to control a pest.

Diagnosis. The diagnosis aims at understanding why the state of the agroecosystem is not satisfactory as regards the target. This diagnosis thus allows identifying the main elements of the system to be improved. As an example, in the cropping system dedicated to an organic vegetable short supply chain (case 7), damages unacceptable by the customers were observed on fruits of eggplants. The diagnosis allowed to identify mites (*Tetranychus urticae*) as the cause of these damages. To perform the diagnosis, the pilots searched and gathered knowledge on mites and their damages from literature and consulted experts.

Exploration. In this step, actors explore various changes that could contribute to solve the problem, and to improve the system's performance. In case 7, to control the mite pest, two paths were considered: (i) release predatory mites beneficials (*Phytoseiulus persimilis),* and (ii) use micro-sprinkling, which was renowned to improve climatic conditions under shelters favoring mite pests' predators. The first technique was known by the pilots, but not effective enough for such a high injury level. The second one was poorly documented, nor well known by the pilots and local experts, and its implementation required a learning process for the pilots. This second solution, considered as more promising and suitable, was chosen for testing.

Implementation. The imagined solution is then confronted with the reality of the agricultural situation. As micro-sprinkling was chosen, the pilots of case 7 then had to decide how much water to apply, when and how often. Based on the few references available, and on the experience of a neighboring farmer and an advisor, they chose to apply 2 mm of water per day at midday every 2 to 3 days with the already installed sprinklers. This practice was a compromise between having a significant effect on air moisture under shelter for mite pest control, and avoiding fungus disease development on plants. To increase the effectiveness of the control, they chose to combine micro-sprinkling with prior removal of the plants or leaves most affected by the pests. The adaptation of the technique to the reality contributes to the creativity required during the design loop. The implementation involves not only knowledge but also know-how, and accounts for a source of learning, contributing to further explorations.

Assessment. The pilots assess the effect of the implemented solution by observing the changes in the system, and decide to keep, reject or adapt it. The analysis and understanding of these effects are again a source of learning. In case 7, the assessment of the sprinkling technique was carried out in the days and weeks following its implementation. The pilots observed a decrease in the spread of mite populations (intended effect), a decrease in verticillium on leaves (unintended, favourable effect), but also a development of botrytis on fruits (unintended, unfavorable effect).

New diagnosis, initiating a new loop. In case 7, observing the development of botrytis triggered a new diagnosis, focusing on the relationship between sprinkling parameters (frequency, moment, water volume) and the fruit disease. A new exploration was then initiated, concerning not only alternative modalities of sprinkling, but also its combination with the choice of botrytis-tolerant eggplant varieties, and with other known ways of controlling this disease.

In all cases, several design loops occurred throughout the change pathway, progressively shaping the new system, until the pilot was satisfied. A loop was sometimes carried out in a very short time frame (case 7) but could also last several years (case 8, effect of farming system on biodiversity). Most often, as in case 7, a loop was initiated by a diagnosis that identified what prevents from reaching the target, or that considered new external constraints to be overcome (case 6: removal of some pesticides). Yet, in some cases, the loop was initiated by a new practice, discovered elsewhere by the pilots, that appeared interesting for them. The exploration was sometimes tacit and so rapid that it was barely noticeable (cases 1, 9), or conversely structured in specific actions, for example within design workshops (cases 4, 5, 6, 7) or on-farm innovation tracking (cases 3, 7). The exploration was generally supported by the pilot's knowledge or readings, and sometimes enriched by proposals from other farmers, advisors or researchers. Depending on the case, the exploration led to choose solutions well-known by the pilots, but also to very audacious ones.

While in most commercial farms all activities were managed by the farmer, in experimental farms (cases 7, 8, 9) implementation and diagnosis were conducted by different people, respectively farmworkers and pilot-scientists. For assessment and exploration, the complementary nature of the pilots' and farmworkers' observations sometimes led to gather them in working groups. This allowed not only to take into account the feasibility constraints (available working force, available inputs, skills of the workers, work calendar), but also to fuel the design loop with knowledge previously built in the action, and formalized in a reflexive analysis.

Learnings were observed throughout the design loops, linked to each of the four activities. Indeed, the pilots' learnings covered the knowledge mobilized during the diagnosis, that enriching the exploration, that derived from the assessment, and the know-how resulting from the implementation. In case 7 (**Fig. 1**), the pilots did not know anything on sprinkling before identifying the mites. They have progressively acquired a rare competence on this technique, its principle, its practical modalities, its effects, and its interactions with other techniques. In case 6, the project manager (coordinating the design process of the 58 farmers at the catchment level) stimulated learnings concerning soil N dynamics over a year, soil mineral N amount left after different crops, and links between soil N content in mid-autumn and N leaching during winter. These learnings were enhanced thanks to field trips dedicated to assess the efficiency of the practices implemented by each farmer to catch nitrate. More generally, the learnings from one loop fed into the next loop.

4.2.3. Trait 3: The progressive shaping of a desirable unknown

As observed in every design process, an initial target was formulated in all case studies. These targets were often very ambitious (**Table 1**). They were not a mere adaptation to a changing context (e.g. price of products or inputs), nor the adoption of the latest technology improvement (new variety, new pesticide active ingredient), as farmers routinely do. These targets, i.e. the desirable unknown, were generally fuzzy at the beginning of the design process: desiring a huge reduction in pesticide use (cases 1, 2, 4, 7), a system self-sufficient regarding external inputs (cases 5, 8, 9), a diversified pesticide-free vegetable system to feed various value chains (case 7), or legume-based cropping systems improving productivity and soil fertility (case 3). These target formulations do not precisely define what the future systems will look like. As mentioned by most pilots, this fuzziness often facilitated the involvement of some farmers, who could hesitate if they were aware of the magnitude of the change that may be required. For example, in case 4 (farmer 1 in **Table 3**), one farmer began a *step-by-step design* process with the wish to reduce pesticide use (shifting from the pesticide-based control of pests to preventive prophylactic practices). Ten years later, not only had he reduced the average Treatment Frequency Index on his crops from 8 to 3, but he had also stopped ploughing, he had increased the number of crop species from 5 to 9, he more often used shallow soil tillage to enhance weed emergence and destruction before sowing the cash crops, he was sowing cover crops on 100% of his area (0% before) and he had introduced strip-till sowing. As mentioned by an advisor involved in the case, "*if the farmer had imagined, at the beginning of the process, that he would implement all these changes, he might not have engaged in such a design process*".

Moreover, along the change pathway, the design target generally became more and more specific, as illustrated in cases 3, 4 and 6 (**Table 3**). In case 4, the initial objective of reducing pesticide use was gradually narrowed down to herbicides for most farmers, as they already succeeded in the reduction of the other pesticides. In some cases, the design target took new directions over time. For example, the farmers of case 4 had similar initial targets, but the targets thereafter diverged (**Table 3**). Moreover, changes in targets were sometimes linked to double-loop learnings that modify values and priority ranking. For example, in case 3 in Burkina Faso, some farmers opted, at the beginning of the design, for intra-annual successions (two short-cycle crops in the same year), in order to harvest food early for the household and to fill the "hunger gap". However, in the first year of testing these techniques, farmers realized that the success of the intra-annual successions was dependent on very early sowing of the first crop, which was very uncertain. The objective of filling the food gap then became secondary to the objective of maximizing production, and farmers turned to species mixtures, which were more productive and less risky. In some cases, the change of targets was fostered by external drivers (personal projects, change in the social-economical context). For example, in case 4, two farms reduced their ambitions in pesticide decrease after a year of very high cereal prices, judging that maximizing margin was incompatible with pesticide reduction. The other 6 farmers maintained their pesticide reduction target, both in relation to their values, and in the belief that years of such high prices would be rare in the future.

In most cases, advisors or scientists played an important role in helping the pilots specifying their targets along the design process, by helping them to make the most of their learnings.

4.2.4. Trait 4: a design process supported by specific tools

In all cases, in order to manage the *step-by-step design* process, the pilots (and advisors or scientists supporting them) used tools, built either by themselves, by their peers, or by other actors from R&D organizations. Most often, these tools were supporting one specific activity of the design loop (**Table 4**).

For the diagnosis, pilots and participants used tools either to support observations in the field (cases 3, 4, 6, 7, 8, 9) or to visually represent the state of knowledge on the systemic relationships between practices and ecosystem services (cases 4, 5, 6). Other tools were used to understand the observed effects of a practice, a combination of practices, or a diversity of practices, on the agroecosystem. For instance, in case 6, a field tour during autumn, within the water catchment area, aimed to compare in several fields the growth of volunteers and cover crops, as an indicator of the amount of mineral N they absorbed. It provided the farmers with ideas for adapting technical options in their own fields. In the mixed crop-livestock case 9, shapes of lactation curves were used for diagnosing animals' health problems, and relationships between health and food.

The exploration activity was enhanced by perusing innovation libraries, proposed by scientists and advisors in different forms: web interactive databases, technical leaflets, or tools simulating the effects of techniques on crops or environment (cases 1, 4, 5). These libraries also gathered farmers' innovations, either available on internet forum, or through oral testimonies of pioneer farmers, or sometimes collected through a farmers' innovation tracking study (cases 2, 3, 6, 7, 9). In case 3, exploration was fostered by the setting up of a "participatory prototyping" experimental platform, proposing on a small area different cropping systems that responded, at least partially, to the target. The power of the platform to motivate farmers, and provide them with ideas to change, was reinforced as they were invited to debate around the systems. They were able to suggest improvements, some of them being implemented on the platform the following year. In some cases (4, 5, 6, 7, 8), the exploration was partly managed in design workshops, gathering all the pilots of one case in order to invent together the technical solutions, sometimes supported by experts in the innovation field.

The implementation was often performed on simple experiments (without replication). They took various forms: a part of a farmer's field, one or several fields, during one or several years (with or without an evolution of the tested practices between years), in comparison or not with the usual practice. In case 2, a typology was built to describe the diversity of aims and management modalities across the farmers' experiments. In all cases, various feasibility indicators, often home-made, were used to identify the conditions for success of the implementation of the new practices (work, skills, equipment, etc.).

Assessment was first performed with simple indicators. They were based either on visual observations (e.g. color of the oilseed rape volunteers indicating their efficiency in soil mineral N uptake, case 6; weed density after hoeing to verify its efficiency in weed control, case 4), or on measurements (soil mineral N content at the beginning of the drainage period, cases 5, 6; dynamics of beneficial populations, case 7), or even on index calculations (e.g. Treatment Frequency Index, cases 1, 4, 7). Assessment was sometimes performed with more complex simulation tools, to assess the mid- and long-term impacts of the change of practices, either *ex ante* (cases 4, 6) or *ex post* (cases 5, 8, 9). These indicators and simulation tools allowed (i) to check that the targeted effect of a new practice was reached (all cases), or (ii) to verify that negative effects (e.g. soil compaction, crop heterogeneities, or development of unexpected pests) were not induced by the new practices (cases 1, 7). Linked with the target evolution (trait 3), new qualitative indicators occurred along the change pathway: e.g. in case 1, reduction of overloads, consideration of farmer's health, pleasure of experimenting. Moreover, in some cases, specific tools were dedicated to the long-term and multi-scale assessment. For instance in case 6, a dashboard was filled year after year, gathering the real practices implemented by each farmer of the catchment area, their effects on N fluxes within the agroecosystem, and their impacts on water quality.

All along the design loop, most indicators, tools, or resources used to monitor the change pathway were specifically built for the case studies, thus being tailored to the situation (according to its human and biophysical features). They were easy-to-implement indicators, proposed and used by the pilot, simple tools built by advisors supporting farmer-designers (e.g. testimonies), more complex tools built by scientists (e.g. simulation tools). In some cases (e.g. 4, 5, 6), tools were intentionally built to support not only the pilots of the case, but also those of future *step-by-step design* processes.

4.2.5. Trait 5: a process intertwining individual and collective dimensions

In all cases, the design process was facilitated and fostered by collective exchanges, even for individual farmer's change pathway (cases 1 to 5). As mentioned by the pilots or by scientists *a posteriori* analyzing farmers' change trajectories (cases 1, 2), these collective exchanges had various configurations and roles.

In terms of configuration, the exchanges involved (i) the pilot(s) managing the whole process, (ii) the person(s) implementing the system (sometimes the pilots, in cases 1 to 6; sometimes different from the pilots, in experimental farms, cases 7, 8, 9), and (iii) people providing new knowledge to the pilot(s) (scientists, advisors or peer farmers). Exchanges were stimulated either by the geographical proximity of the various farms of the case, thus sharing similar soil, climate and constraints (cases 1, 3, 6), or through visits of numerous farmers and stakeholders in experimental farms (cases 7, 9).

In terms of roles, the collective exchanges mostly fed the exploration activity, allowing the participants to enlarge the range of solutions considered. In cases 4, 5 and 6, exchanges during structured design workshops allowed a large exploration, mobilizing all farmers to imagine the changes to be made by each one. In cases 7 and 9, visits of stakeholders contributed to foster creativity, due both to the ideas they suggested and to the reflexivity induced by their (sometimes) disturbing questions, and the ensuing discussions. Meetings gathering several farmers of the same case study, within their fields under change (cases 3, 6), led to shared comments based on observations, thus feeding the further design of each of them. Nevertheless, bringing people together does not guarantee an exploratory and creative process. Indeed, belonging to a stable and historical advisory group sometimes locked the system, due to a lack of new ideas (case 1). On the opposite, when groups were specifically built for the *step-by-step* process, they explored a wider variety of solutions, especially if invited participants were open-minded and were chosen for their common motives to change their systems (cases 4, 5). Setting up groups of farmers who are open to change, and guiding the design by combining individual support coaching and group facilitation, is therefore an essential skill for advisors, as emphasized by the cases 1, 3, and 4. In case 2, the 10 market gardening growers (farmer-pilots) engaged in *step-by-step design* regularly met within an informal network. They had various backgrounds and knowledge on pest control, and they worked closely with an advisor and entomologists from research institutes. Farmers progressively gained knowledge in entomology, through the interactions and experiments, particularly the less experienced farmers. This enabled them to control pests with biological methods. By comparing each other's experiments, they learned to better interpret their individual observations, and to disentangle the complex interactions between practices and soil, climate, crop, pests and beneficials. Gathering several farmers sharing the same target (but not necessarily the same solutions) had several other positive effects (cases 3, 4, 5, 6): sharing the diagnosis of problems, identifying the conditions required to reach targeted effects, supporting one another especially after a failure, building a collective identity in a professional world that may be skeptical to the targeted changes.

5. Discussion

After summarizing the overall *step-by-step design* approach (section 5.1), we discuss it from three different perspectives, in the view to propose ways to foster its scaling out in agriculture: the originality of *step-by-step design* compared to other design approaches (section 5.2), the human dimension of the design process (section 5.3) and the specificities of *step-by-step design* in an experimental farm (section 5.4).

5.1. Overview of the step-by-step design approach

Based on 9 case studies, we show that *step-by-step design* is a situated design process, structured by an iterative loop « diagnosis – exploration – implementation – assessment », which organizes, in the medium and long terms, both the progressive technical change towards a desirable unknown, and the learnings required for this change. The various traits of the *step-by-step design* approach and their intertwining are summarized in **Fig. 2**.

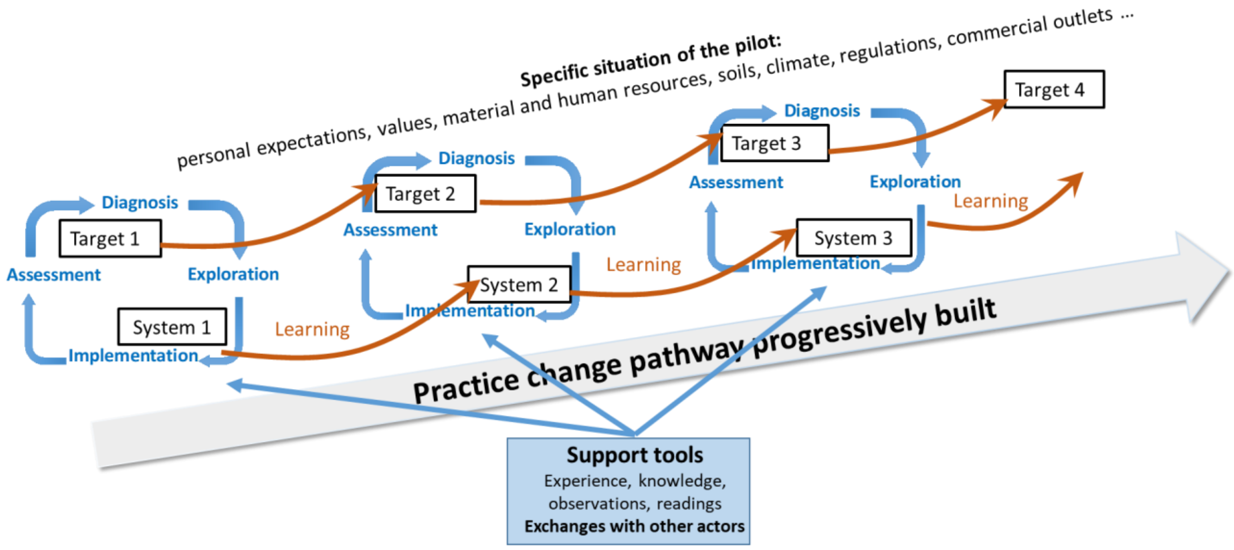


Figure 2: Synthetic representation of the relationships between the traits of the step-by-step design approach. It is a situated design approach, structured by iterative loops of diagnosis-exploration-implementation-assessment, which organises, in the medium and long term, a synergy between the dynamic change of targets, practices and learning, in interaction with different tools and networks of partners.

In-depth studies of some of these traits have already been conducted by different researchers, including some of the authors of this article. Thus, Coquil et al. (2018) and Hazard et al. (2022) shed light on different drivers of the target evolution and on modalities to support this evolution. Catalogna et al. (2018; 2022) analyzed the change pathways of farmers' practices, highlighting the role played by experiments they conduct in their fields. Chantre et al. (2015), Ingram et al. (2018), and Ensor and de

Bruin (2022) highlighted the link between practice change and learning in long-term change pathways. Bredart and Stassart (2017) demonstrated how farmers learn through a dialogue with their practices in the course of action. Salembier et al. (2020) showed the importance of implementation in the progressive design of cropping systems and devoted equipment, to be specifically adapted to their use situations. Toffolini et al. (2017) and Aguerre and Bianco (2023) underlined the complementarities between scientific knowledge (generic) and situated lay knowledge resulting from learning, which are mobilized by farmers in pathways of practice change. Prost et al. (2018) explored the tension between an ambitious desirable unknown and the implementation of practices in real fields. These last authors, as well as Slimi et al. (2022), Chizallet et al. (2021) and Quinio et al. (2022) emphasized the role of tools and groups to overcome this tension. Périnelle et al. (2021) shed light on the role of a collective experiment to initiate design among and by farmers. Lastly, Giller et al. (2011) and Falconnier et al. (2017) put forward the articulation between diagnosis, exploration, and learning.

Complementarily with these studies, a major originality of our article is to bring an overview of the design process, through the five traits and the four activities of the design loop. Thanks to this systemic overview, our analysis of past cases becomes a resource for action, and more specifically for the transition of cropping and farming systems. Relying on an analysis of the way innovative farmers changed, informed by the concepts of design science, we offer keys and general guidelines for action. These could help both other farmers to become more self-sufficient in improving their own systems, and advisors to support farmers in their progressive change towards agroecological systems. The five traits that we highlighted allow to identify the actions to perform in order to foster deep and progressive changes: formulate a design target as a desirable unknown and support farmers in making it evolve while they learn, explore alternative techniques and carry out an in situ diagnosis of their effects regarding the target, develop tools tailored to the situation that help to support such a monitored and adaptive process, organize appropriate collective exchanges to help individual trajectories progress. In this sense, *step-by-step design* is an answer to the need, claimed by Schut et al. (2020), of methods that can facilitate the development of evidence-based scaling strategies. *Step-by-step design* appears as a disruptive way of enhancing transition, compared to the current dominant process of technology adoption (“take-it or leave-it”, described by Dogliotti et al., 2014).

Step-by-step design converges with the co-innovation approach (Dogliotti et al., 2014; Rossing et al., 2021), as they both propose systemic solutions articulating various scales (plot, farm, crop management plan, cropping system, livestock system, farming system). They both also acknowledge the importance of learning loops, as part of an adaptive management dynamics (Biggs et al., 2010; Allen et al., 2011). However, one interest of the *step-by-step* approach compared with co-innovation is inherited from the design sciences. This theoretical framework allows to shed light on the strong and dynamic links between the motivation to change, formalized in an evolutionary target, and the way of changing, relying on a dialogue between the exploration of new techniques and the learnings derived from their implementation. As shown by Le Masson et al. (2010; 2017), a main feature of a design process is the interplay between the exploration of solutions and the management of knowledge. We brought out this interplay by highlighting the nature of the knowledge produced during design, the moments and methods of this knowledge production, and the way this knowledge fuels design (traits 2, 3, 4). Above all, we shed light on the intertwined dynamics between system change and knowledge production. In this sense, the "design of cropping or farming systems" should not be understood as the design of a set of practices that is stable over time, but as the design in real time of a change pathway. Conversely to the co-innovation approach, that requires to map missions and plan actions to reach forecasted outcomes (Rossing et al., 2021), *step-by-step design* does not follow a planned logic.

Indeed, the techniques chosen and assessed along this process are unkown and unpredictable at the beginning, and the successive versions of the farming systems under improvement cannot be predicted. It can start on one farm activity (e.g. in case 9, the feeding of cows) and very quickly move to other ones (e.g. the management of the herd, or the inclusion of pulses in cropping systems). The change of scale (in the case 9, from the herd to the farm) offers additional generative capacities, as pointed out by Rossing et al. (2021).

Another difference between both approaches is linked with the involved actors. We show that the design dynamics derives from an articulation between self-centered individual work (the pilots design for themselves) and collective work, embodied in an exchange of knowledge, experiences and innovations. If the literature is abundant to show and describe the importance of the collective dimension in the processes of transition (Klerkx et al., 2010; Kilelu et al., 2013; Rossing et al., 2021; Bakker et al., 2022), it pays little attention to the synergies between individual and collective dimensions. Unlike the *step-by-step design* approach, which focuses on the individual level, adjusting each design process to each farm, co-innovation studies emphasize the governance and management of collective change-oriented projects (Rossing et al., 2021). Indeed, it highlights the multi-actor dimension of the project and involves a large diversity of types of actors. As a consequence, in the *step-by-step design* approach, scaling out relies on the successive implementation of the approach in new farms, while, in the co-innovation approach, scaling out is at least partially ensured by the preparation and monitoring of the collective project. Besides these similarities and discrepancies, it should be essential to further conduct a deeper compared analysis of the two approaches to better value their synergies for open innovation.

5.2. An original design approach

Most scientific literature on the design of new cropping and farming systems describes two main approaches: prototyping in workshops and model-based design (see section 1). Meynard et al. (2012) called « *de novo* design » these two approaches since they focus on disruption and novelty, without any concern for the way to move from the current system to the innovative one. However, farmers rarely change their entire system at once. To limit risk-taking and give themselves time to learn, they modify their practices gradually, ensuring at each stage that the choices made are satisfactory for them (Chantre et al., 2015). The originality of the *step-by-step design* approach therefore lies in the fact that it manages both design and transition (**Table 5**). Changes are progressively designed, and the interactions between techniques (what "makes a system") are designed in action, whereas they are designed *in abstracto* in the *de novo* design approaches. Unlike *de novo* design, which generally aims at a variety of solutions, *step-by-step design* leads to the development of one solution, tailored to the specific expectations of a farmer (or an experimental farm manager), and to the specificities of a production situation. It is always a situated design (see trait 1), which allows the pilots to invent a new farming system, at the same time as they learn how to manage it, understand how it works, convince themselves of its interest, and progressively reorganize their work and means of production (Meynard et al, 2012). As observed in some case studies, *step-by-step design* allows to empower farmers who are initially reluctant to deep changes: as their practices progressively evolve, they can smoothly reach ambitious and disruptive changes (Chantre et al., 2015; Bredart and Stassart, 2017), thus addressing numerous issues of agroecological transition.

Step-by-step design is slower than *de novo* design but, as the case studies show, it can also lead to disruptive innovations. The changes adopted at a given time step may lead, at subsequent time steps and according to a systemic logic, to other changes in practices or assessment criteria, or even targets, often not anticipated by the design pilot (traits 2 and 3). In the cases that served as a basis for this article, the *step-by-step design* approach resulted in original farming systems, whose characteristics were unpredictable at the beginning of the design, evaluated on criteria that the pilots could not fully anticipate, and based on fields of knowledge sometimes completely new to them. For example, the development of integrated pest management strategies (cases 1, 2, 4, 7) or self-sufficient livestock farming systems (cases 8, 9) led to deep changes, not only in the techniques, but also in the ways of thinking, the work and the skills of the pilots and of the other involved people (Coquil et al., 2014). In our case studies, the identity itself of the systems has changed during the design process. *Step-by-step design* thus combines all the features of "innovative design", as defined by Le Masson et al. (2010). Conversely, if the exploration activity is limited, and if fixation effects (Agogué et al., 2014) are not overcome, *step-by-step design,* as *de novo* design, may result in marginal, and not transformational, changes. We must therefore be careful not to equate *de novo* design with "innovative design", and *step-by-step design* with "rule-based design", defined as a design process in which procedures are standardized, evaluation criteria and knowledge used are initially specified, and resulting in incremental innovations (Le Masson et al., 2010).

At the root of these narrow explorations are fixation effects, both in *de novo* and in *step-by-step* design processes. They are linked to the designers' difficulty in freeing themselves from their usual practices and reasoning (Agogué et al. 2014; Jeuffroy et al., 2022). In *step-by-step design*, implementation adds another source of fixation, especially in commercial farms: the economic risk of a change that might prove to be inappropriate. Experimentation on small areas, or on a few animals, is one way to limit this (Catalogna et al. 2018; 2022). However, this is not always possible, due to difficulties in estimating labor changes on small areas, or in isolating part of the herd to manage it differently. In our different cases, to help farmers overcome their fixation effects in *step-by-step design*, several means were used, original compared to those listed by Jeuffroy et al. (2022) for the design workshops: participation in a group of farmers undergoing change (cases 1, 3, 4, 5, 6), discussion with an advisor or a group of peers of innovative systems designed by other farmers (case 3), sometimes unearthed by innovation tracking (Salembier et al., 2021; cases 3, 7), or consulting a library of innovations (all cases), also called portfolio of promises (Elsen et al., 2017) or basket of options (Ronner et al., 2021).

5.3. Human being at the heart of the design process

The analysis of the traits of the *step-by-step design* approach shows that the pilot (whether a farmer or an on-station experimenter) is at the center of the activities: each pilot is both designer, operator and learner. As Rabardel (1995) points out, in any designed object, there is an artefactual part and a human part. This human part can be seen, on the one hand, in the formulation of a desirable unknown, and, on the other hand, in the activities of the pilots (i.e. implementation of the design loop, management of the agroecosystem). In this sense, Bredard and Stassard (2017) refer to practice change as a co-evolution between goals and means. The evolution of the desirable unknown is fueled (trait 3) by both the evolution of the situation and the evolution of the designer's values, themselves fostered by double-loop learnings (Argyris, 1976). The pilots' activities are also changing, due to the new techniques they design and implement, but also due to the increase in their observation, learning and evaluation capacities (criteria for judging the situation in relation to the target) (Coquil et al., 2018; traits 2 and 4). The human part of *step-by-step design* is also found in what Schön (1983) calls « a *reflective conversation with the situation ».* As this author points out, the designer cannot imagine, before acting, all the dimensions of an object under emergence: confronting this object with action, with its implementation in the real word, specifically makes it possible to discover some properties, and thus to manage its complexity. Therefore, it is essential that the pilots and their teams are not only designer and learner, but also operator in real time of the object under design. Moreover, what is at stake in the design loops is not only producing new knowledge, but also building an experience (Slimi et al., 2022): experience of new practices, experience of implementing loops, experience of creativity in action, experience of observation. At the same time as the designers are refining their innovative systems, they are accumulating design experience, which can be used later for other designs (Eastwood et al., 2021).

Because of this major place of human being in *step-by-step design*, there is a challenge to support the pilots of the process, but it would not be reasonable to try to propose a standardized design procedure. Indeed, important questions such as "where to start a change" or "how to choose between several options from the exploration" cannot find a unique answer. The answers to these questions depend on the subjectivity of the designers, who choose the change option they feel most able to implement, or the one that seems most beneficial to them, based on their personal satisfaction criteria, as observed in the analysis of farmer-designed innovations (Salembier et al., 2021). These criteria often combine indicators and tools derived from technical rationalities, with professional standards, or even more subjective, but sometimes determining, impressions (Perrin et al., 2020; Hazard et al., 2022). Therefore, in order to help farmers or experimenters to implement *step-by-step design*, this article proposes the main traits of a generic approach, which has to be tailored to the singularity of each design situation.

In several case studies (1, 3, 4, 5, 6), advisors played a major role in this adaptation. Our results thus enrich the literature on the role of advisors in supporting farmers in their agroecological transitions (Coquil et al., 2018) and in their design dynamics (Kivimaa et al., 2019). Supporting farmers in implementing the *step-by-step design* approach requires several activities and skills. First, that means helping them to overcome fixation effects, and supplying them with technical innovations (trait 2) or standardized assessment criteria (trait 4). That means also supporting farmers in building this human part of the design process. Therefore, helping farmers to explain but also to question their projects, helping them to make choices consistent with their values, and even helping them to think the unthinkable, are becoming decisive activities that are transforming the advisors' job (Cerf et al., 2012; 2017). "*Access to the unthinkable*, point out Coquil et al. (2018), *refers to the subjectivity of discovery and to access to a new realm of possibilities through a discovery"*. Workshops, knowledge bases and social network contents that can contribute to this support are still to be invented (Klerkx, 2020; Prost et al., 2017b).

5.4 Specificities of step-by-step design in an experimental farm

In our analysis, we chose to consider all cases together, whether the design process was conducted on commercial or experimental farms. Despite differences in the contexts and the pilots' jobs, we identified numerous common features. However, several peculiarities of the use of *step-by-step design* approach by research experimenters have to be highlighted.

In the experimental farms, the *step-by-step design* approach takes place in system experiments, which aim at testing, in the field, the ability of innovative agricultural systems to reach challenging objectives, and at helping to improve them (Debaeke et al., 2009; Caniglia et al., 2017; Lechenet et al., 2017). *Step-by-step design* appears a preferred way to carry out these improvements. Experimental farms allow to partially free the pilot from some of the constraints of commercial farms, in order to test further possibilities (Eltun et al., 2002; Debaeke et al., 2009). They allow researchers to (i) test highly innovative techniques, which involve a high risk of economic loss; (ii) organize comparisons between alternative solutions; (iii) strengthen the observations and measurements on the effects of innovative practices; (iv) add factorial experiments to the system experiment in order to analyze the effect of some techniques in more detail. In an experimental farm, an original outcome of this design approach is the identification of new research questions, arising from the knowledge gaps that emerge during the design loops. Examples are given, for our case studies, by Coquil et al. (2014), Perrin et al. (2019), Durant et al. (2020b) and Lefevre et al. (2020).

In the *step-by-step design* taking place within an experimental farm, all actors are in a situation of change. While the pilots organize the design loop and enrich their agronomic knowledge, their assistants implement solutions, develop know-how, learn to observe the system differently, build innovative equipment and invent assessment indicators (Fiorelli et al., 2014). They do not only implement the technical solutions designed by the researchers, as in a usual experimental farm. The design highly depends on the coordination of the learning of the experimental farm actors, a skill that should be developed by the pilot (Fiorelli et al., 2014; Ingram et al., 2018). This facilitates the acquisition, by all, of new relevant reference points and know-how, and the collective understanding of the cropping or farming system and its evolution. Ultimately, the experimental farm becomes a resource for hybridizing expert and scientific knowledge while designing new systems (Ingram et al., 2018). The collective learning in the team of experimenters produces new knowledge to be formalized and circulated beyond the experimental farm.

The work carried out on cases 7, 8 and 9 highlights the scientific contribution of *step-by-step design* in a system experiment: scientific articles describe the agronomic logic and assessment of highly original cropping and farming systems (Gouttenoire et al., 2010; Durant et al., 2020a; Lefèvre et al., 2020), as well as the transformation of activities (Fiorelli et al., 2014). Indeed, Toffolini et al. (2020) show that the design process, involving the confrontation of the objects under design to the field, can be the source of original knowledge, the nature of which being not foreseeable at the start of the project.

6. Conclusion

Based on a cross analysis of 9 case studies, we have highlighted the features of a *step-by-step design* approach for cropping and farming systems. This situated approach, closely linked to action, stimulates individual and collective learning, and hybridizes both scientific and empirical knowledge. We have shown that this approach is well adapted to support the agroecological transition: by its temporality, by its capacity to overcome knowledge gaps through learning, by its contribution to farmers' empowerment, and by its capacity to tailor solutions to local specificities. It enhances the invention of diverse systems, and allows the progressive implementation of profound systemic changes. Training farmers and advisors in this approach would help them to adapt to a changing world (e.g. climate, regulations) in the long term. Scaling agricultural innovations for agroecological transition should benefit from spreading out this design approach. However, it remains to be tested and enriched on new case studies in other situations, and further work could explore such a design approach in the case of more complex objects, for example at the level of agri-food systems or territories. This article provides guidelines to encourage increased R&D investment in such approach, contributing to enhance open innovation for the agroecological transition.

Moreover, our analysis leads to various research questions that should be addressed in priority, not only to enrich our understanding of the *step-by-step design* process, but also to contribute to its scaling out. What are the drivers to engage in *step-by-step design*, how can they be fostered? How can the exploration of unknown technical choices be stimulated? How can agronomic consistency between practices be maintained all along the change pathway, and the risks associated with unfamiliar practices be assessed? How should farmers and advisors be trained in *step-by-step design*, and how should collective exchanges be enhanced to support this approach? How to stimulate learning about practices whose effects can only be observed in the long term, while taking into account the interannual variability of the climate? How to value new technologies and web-based social networks to facilitate and stimulate *step-by-step design*? How research and development could be funded and organized to support such long-term dynamics, and incentives could be identified at different levels (e.g. territory, regional, national, European)? How *step-by-step design* could be combined with *de novo* design, with a view to promoting the efficiency and speed of change dynamics, in the face of climate, health and environmental emergencies?

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Author contributions

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Table 1: Description of the case studies including the area, the type of farming system (OA= organic agriculture; CA= conventional agriculture), the main agroecological design target, the number of designed cropping or farming systems, the period of the design process, the pilot(s) and other actors involved in the design process, the type of research (RA: restrospective analysis; AR: action-research), and published references.

Case studies (area)	**Type of farming system** (Organic, OA ; Conventional, CA)	**Main agroecological design target (desirable unknown)**	**Number of designed cropping or farming systems**	**Period under study**	**Pilot, and other actors involved in the design process**	**Retrospective analysis (RA) or participatory research (PR)**	**Published references**
1-Farmers'pathway towards low-input arable crops (Indre: Center France)	Arable crops in CA	Input use reduction	Cropping systems in 20 farms	1985-2011	Farmers, supported by various advisors	RA	Chantre et al. (2015) Chantre and Cardona (2014)
2- Farmers' experiments towards agroecology (Drôme: South-East France)	Market gardening and arable crops in CA and OA	Reduction in input use and/or in soil tillage	Cropping systems in 17 farms	2008-2018	Farmers, with *ad-hoc* support from advisors	RA	Catalogna et al. (2018) Catalogna et al. (2022) Navarrete et al. (2021)
3-Legume-based cropping systems in southern Burkina-Faso	Arable crops in low input CA	Enhancement of soil fertility in maize-cotton rotations by growing legumes	Cropping systems in 34 farms	2017-2019	Farmers, supported by advisors and scientists	PR	Périnelle et al. (2021, 2022)
4-From pesticide-intensive systems to IPM* (Picardie: Northern France)	Arable crops in CA	Reduction in pesticide use	Farming systems in 8 farms	2002-2012	Farmers, supported by advisors and scientists	PR	Mischler et al. (2009) Toffolini et al. (2017)
5- Farms targeting autonomy regarding mineral N in Champagne (North-Eastern France)	Arable crops in CA	Low dependency on mineral synthetic nitrogen	Cropping systems in 7 farms	2013-2018	Farmers, supported by advisors and scientists	PR	Guillier et al. (2020)
6- Low nitrate pollution in a water catchment area (Center-Eastern France)	Arable crops in CA	Low nitrate leaching	Cropping systems in 58 farms	2010-2018	Farmers, in interaction with local stakeholders, advisors and scientists	PR	Ravier et al. (2015) Prost et al. (2018)
7- Diversified vegetable systems under shelters (4SysLeg, Southern France)	Greenhouse market gardening in CA and OA	Reduction or removal of pesticides for short and long value chains	4 cropping systems, in an experimental farm	2013-2018	Scientists, in interaction with farm workers of the experimental farm, advisors and farmers	PR	Lefèvre et al. (2020) Perrin et al. (2019) Navarrete et al. (2021)

8- A self-sufficient and biodiversity-based farming system in marshes (South-Western France)	Mixed crop-livestock in CA (before 2017, then in OA)	Enhancement of self-sufficiency; synergy between farming and biodiversity conservation	1 farming system, in an experimental farm	2009-2017	Scientists, in interaction with farm workers of the experimental farm, advisors and farmers	PR	Durant et al. (2020a, 2020b)
9-Self-sufficient organic dairy systems (Mirecourt : Eastern France)	Mixed crop-dairy production in OA	Enhancement of self-sufficiency in farming systems	2 farming systems, in an experimental farm	2004 - 2015	Scientists, in interaction with farm workers of the experimental farm	PR	Gouttenoire et al. (2010) Coquil et al. (2014)

*IPM = Integrated Pest Management

Table 2: A design process fuelled by action: examples for all case studies. The table gives examples of implemented practices and their consequences for the on-going cropping or farming system design. For each case study, column 2 mentions the main agroecological design target; column 3 gives an example of partial target (intermediary stage to reach the main target); the 3 following columns highlight the knowledge used by the pilot to define technical options, the resulting practices that were implemented, and their *in situ* assessment corresponding to this partial target. The last column summarizes the consequences for the pilots as regards the systems under design.

Case study	Main design target (Cf Table 1)	Example of a more specific and partial target (intermediary stage to reach the main target)	Knowledge used by the designer to define a practice to be tested	Practice implemented to reach the partial target	In situ assessment of the tested practices	Consequence for the cropping or farming system under design
1 and 4	Reduction in input (case 1) or pesticide (case 4) use	Limit the use of growth regulators (against lodging) on wheat crops	Delaying sowing date and first N application reduce the lodging risk	Delayed sowing date and N fertilizer application. No growth regulator (after many hesitations !)	No lodging despite the absence of growth regulator	Adoption of the low-input wheat management to the whole farm
2	Reduction in input use and/or soil tillage	Increase N self-sufficiency in an arable-cropping system based on wheat and maize	Including a legume as cover crop allows to enrich the agrosystem with N while reducing the purchase of fertilizer	A vetch cover crop grown between wheat and maize	Interesting but insufficient organic matter produced (the following maize lacked N)	Early establishment of vetch, before or immediately after wheat harvest, to achieve sufficient growth
3	Enhancement of soil fertility in maize-cotton rotations by growing legumes	Reduce weed growth in legume crops and enhance water infiltration	Legumes grown as intercrop are more competitive against weeds; ridging eliminates weeds and increases water infiltration	Growing legumes (soybean, peanut) intercropped with sorghum and ridging the sorghum	Sorghum ridging is difficult without damages on the legume crop	Sowing the legume crop as soon as possible, to harvest it before sorghum ridging
5	Low dependency on mineral synthetic nitrogen	Apply a low amount of synthetic-N fertilizer within the cropping system	Including legume crops in the sequence allows to decrease fertilizer rates	Including a spring pea crop on the crop sequence	Unstable and low pea yields in average	For some farmers, replace pea with sunflower, with low fertilizer rate
6	Low nitrate leaching	Have a low mineral N content in the soil during autumn and winter	A catch crop with high N uptake capacity, grown in autumn, allows to decrease soil N in autumn, and thus N leaching in winter	Sowing a cover crop or enhancing growth of volunteers of the preceding crop, after harvest	Observation of autumn growth of cover crops and volunteers in the fields of each farmer through collective field trips	Progressive adaptation of the management of cover crops and volunteers (sowing dates, species sown) to maximize N uptake during autumn

7	Reduction or removal of pesticides for short and long value chains	Introduce a diversity of vegetables for local direct sale	Implementing intercropping limits pest damages and allow reduced pesticide use	Growing a mixture of 3 crop species with similar crop cycles and harvested at the same time	Finding 3 species with similar growing periods and rotational constraints is difficult	Different options are implemented: 3 species of similar duration, or combining 2 long-cycle species with a sequence of 2 short-cycle species
8	Enhancement of self-sufficiency; synergy between farming and biodiversity conservation	Move towards feed self-sufficiency for the farm's herd	Improving the nutritional quality of forage from meadows reduces the use of feed concentrates	Increasing legume proportion and stop using N fertilizers on grazed grasslands	New practices are not enough to cover the high needs of fattening oxen	Change in animal products: from oxen to fattened steers
9	Enhancement of self-sufficiency in farming systems	Improve reproduction performances of dairy cows in a 100% grazing system	Reproduction performances are linked with meeting the energy needs of cows	Advancing the reproduction period to a period when forage has a higher quality; lengthening the lactation period of not in-calf cows until 600 days (instead of 300 days usually)	Reproduction performances were improved and milk production was high for long milking durations	Adoption of the advanced reproduction period and the longer duration of milk production

Table 3: Examples of target evolution during the *step-by-step design* process. The examples given here only represent a piece of the pathways of some cases (3, 4 and 6).

Case study	**Initial formulation of the target**	**Further formulations of the target**
3 (4 farmers)	2017: enhance soil fertility in maize-cotton rotations by growing legumes	2018: grow two short-cycle crops in the same year, in order to harvest food early for the household, to fill the "hunger gap" 2019: maximize production with intercropping, more productive and less risky
4 (farmer 1)	2003: decrease pesticide use	2005: reduce fungicide and insecticide use first 2009: as the previous target was reached, limit herbicide use, and increase the herd's feed autonomy
4 (farmer 2)	2003: decrease pesticide use	2005: reduce fungicide and insecticide use first 2009: as the previous target was reached, decrease herbicide use and the energy used on the farm
4 (farmer 3)	2003: decrease pesticide use	2005: reduce fungicide and insecticide use first 2012: as the previous target was reached, improve biological regulation processes; prepare the conversion of the farm towards organic production
6	2010: regain water quality at the water catchment (less than 50 $mg.L^{-1}$ NO_3 in water)	2011: target an average of 60 kg mineral N/ha in the soil at the beginning of winter in the whole catchment area 2018: preceding target + reduce the use of pesticides (after detection of a high level of a pesticide in the drink tap water)

Table 4 : Examples of tools used in the various case studies, to support and enhance the *step-by-step design* process: according to the activity of the design loop, type of tools used, description of the tool used, objective of the tool use, cases in which the tool was used. This table does not aim at an exhaustive presentation of the tools used in the various cases.

Activity of the design loop	Type of tools	Precise description of the tool used	Objective of the tool use	Cases of use
Diagnosis	Field observation tool	List of variables to be observed during the crop cycle to be able to identify the reasons for not reaching the target	Qualify the balance between pest dynamics and natural enemies according to the stage of the crop, its sensitivity, and the range of corrective techniques	7, 8, 1
Diagnosis	Visual representation tool to help share the diagnosis	Systemic representation of the relationships between techniques, their efficiency conditions and provided ecosystem services	Take into account the interactions between practices and other systemic effects in the diagnosis	4, 5, 6
Diagnosis	Tool to optimize the reproduction period	Comparison between observed lactation curves and standard shapes	Highlight the periods of feed shortage, in order to avoid their occurrence simultaneously with the reproduction periods	9
Diagnosis (and exploration)	Field observation and participatory prototyping trials	Collective tour, at key steps of the crop cycle, of a variety of fields or experimented systems, aiming at a shared target, but differing in the techniques implemented	Collectively observe and share practices (unknown by the farmers) and their results	3, 4, 5, 6, 9
Exploration	Basket of options (Innovation libraries)	Web-based knowledge sharing tools. Practices and combination of technical options used by pioneer farmers (innovation tracking)	Support the choice among existing technical options, and provide a source of inspiration for new ones	3, 4, 5, 7
Exploration	Simulation tool	OdERA, a tool simulating the effects of cropping systems on weed population dynamics	Assess the effects of various technical options to help farmers combining those allowing to decrease weed pressure	4
Exploration	Simulation tool	Syst'N, a tool simulating N losses at the crop sequence scale	Compare N losses for various cropping systems, implemented or imagined	5, 6
Exploration	Testimonies from innovative farmers, internet forums	Presentations and discussions with farmers who have solved problems faced by pilots	Allow an exchange of experiences between the pilot and farmers with similar questions	1, 2, 3, 5, 9
Exploration	Design workshop	During a design workshop, a group of actors explores and builds *in abstracto* new solutions to a complex design problem	Search for combinations of techniques that can provide answers to the problems identified in the diagnosis	4, 5, 6, 7
Implementation	Indicators to monitor the implementation	Indicators, often not very formalized, specific from pilots, and linked with their experience, to monitor the implementation	Identify the conditions of implementation (work, skills, material, ...) and possible problems related to the implementation (e.g. soil compaction, heterogeneity of effects of new practices)	All cases
Assessment	Indicator for N management	Measurement of the soil mineral N at the beginning of the drainage process; observation of the color of rapeseed volunteers during autumn, observation of the cover crop growth	Judge the efficiency of the establishment of a cover crop (does it empty the soil of mineral N before winter?)	5, 6

Assessment	Indicator for pesticide use	Monitor the evolution of the Treatment Frequency Index and the control of pests	A posteriori analyze the observed effects of the change of practices on the progressive achievement of the target (pesticide use decrease and satisfactory crop health status)	1, 4, 7
Assessment	Indicators for characterizing the self-sufficiency of a farm	Monitor a set of simple variables informing different aspects of self-sufficiency (e.g. the proportion of UAA dedicated to animal feed, number of years the pilot had to buy straw, amount of straw or mineral N purchased)	Characterize and monitor the level of self-sufficiency of a farm in transition, to identify sources of improvement	3, 5, 8, 9
Assessment	Multi-criteria assessment tool	Aggregation of criteria for the ecological, social and economic dimensions of sustainability	Assess ex ante or ex post the mid and long-term impacts of practice change	4, 5
Diagnosis + implementation + exploration + assessment	Dashboard: visual structured representation of various indicators, bio-physical processes and observation tools	The dashboard is a causal chain representing the agronomic reasoning that was proposed to reach a good water status in the catchment; a set of observable or easily measured indicators used for assessment purposes at each link in the causal chain; a protocol to sample and collect data for monitoring purposes; and a set of thresholds for each indicator designed to ensure that the changes were efficient (Prost et al., 2018)	Share the implementation strategies. A posteriori identify and understand the gaps between the targeted and the observed results in the fields; identify anomalies (results reached without implementing the planned practices; results not reached whereas planned practices were implemented)	6

Table 5: Comparative summary of main characteristics of the two families of approaches for the design of farming systems

	De novo design	*Step-by-step* design
General principle	Design of a disruptive system compared to the existing ones	Progressive change of an existing system: the designer manages both the design and the transition
Methods	Explorations using cropping system or livestock system models; Participatory design workshops	Design in action, based on continuous improvement loops: diagnosis of the current system, exploration of solutions, implementation, assessment
Sources of knowledge	Scientific and technical knowledge (favored in model-based design) + all knowledge of workshop participants	Scientific and technical knowledge, knowledge of the pilots and their partners, knowledge from learnings
Result of the design process	One or more systems that can be tailored, or partially generic (adapted to a region, or to a soil or farm type...)	A tailored system, adjusted to the precise expectations of a farmer and to the resources and context of a given farm
Benefits	Exploration of highly innovative solutions; inspiration for *step-by-step design*	Progressive learning of new systems; adaptation to specific farm constraints
Risks	Low realism (lack of consideration of practical constraints). Conservatism (fixation effects linked to the knowledge basis)	Conservatism (related to risk aversion or to designer fixations restricting exploration)

Supplementary Material: detailed description of the 9 case studies

Case 1: Farmers pathways toward low-input arable crops (Indre, Center France).

A retrospective analysis was conducted to describe the trajectories of practice change of 20 farmers, over the course of their professional career (roughly 1985-2011), in the view to reduce the use of chemical inputs. Based on interviews conducted with each farmer, the analysis provided evidence on: (i) the design, by the farmers, of new cropping systems, based on a low use of nitrogen fertilizer and pesticides; (ii) the diversity of the pathways followed by the 20 farmers changing their practices in the same studied area, (iii) the dynamics of knowledge during these trajectories, and (iv) the diversity of the ways farmers learned about implemented technical change (Chantre et al., 2014, 2015). Four types of trajectories were described as a combination of phases of agronomic coherence between practices, and of specific learnings.

Case 2 : Farmers' experiments toward agroecological systems in arable crops and market gardening (Drôme, South-East France).

A retrospective analysis was performed to characterize how farmers (10 market gardeners and 7 arable farmers) implemented on-farm experiments of agroecological practices and progressively changed their cropping systems. Semi-structured interviews were conducted on the annual experiments implemented by the farmers during the last ten years (targeting the introduction of biocontrol agents on vegetable cropping systems, or a reduction of soil tillage, or the development of cover crops and intercropping on arable cropping systems). Ten types of annual experiments, initiated by each farmer, usually without any researcher or advisor (Catalogna et al., 2018) and their causal relationship along the long-term experimental itinerary were described (Catalogna et al., 2022). The analysis showed how farmers progressively designed new cropping systems, depending on what they observed, and on the new knowledge they built.

Case 3: Legume-based cropping systems to enhance soil fertility in smallholder agriculture (Southern Burkina Faso).

In the coton production zone of Burkina Faso, current cropping systems are based on maize, cotton and sorghum. Farmers, wishing to enhance the fertility of the soils, degraded by short rotations and low fertilizer applications, were interested in growing legumes (soybean, peanut, cowpea, mucuna, pigeon pea…) in their cropping systems. At the start of the project (2017), researchers implemented, in 2 villages, prototyping trials, with a diversity of cropping systems, involving legumes in rotations or intercropped. These new systems were derived from local innovative farmers (Périnelle et al., 2021). Visits of the trials with the farmers from the 2 villages were organized, in order to (i) collectively assess the prototypes, in the view to improve them the following year, and (ii) stimulate the interest of the farmers for one of the tested systems. Most farmers (39 out of 73 having participated to the prototype evaluation) tested, in their own farm, one of the experimented systems (Perinelle et al., 2022), modifying it more or less, to adapt it to their preferences and constraints. They assessed it and, in most cases (34 out of 39), implemented it again during the following season, with new adaptations. The farmers thus initiated a step-by-step design process, which started during the visits of the prototyping trials, and continued in their own fields.

Case 4: From pesticide-intensive to Integrated Pest Management systems, in eight arable farms (Picardie, Northern France).

The project involved 8 farmers in arable crops, technical advisors, and scientists from Northern France, between 2002 and 2012, with the aim of decreasing pesticide use at the farm level. In a first step, the advisor proposed to the farmers to implement a science-based low-input wheat management plan: delaying sowing, reducing plant density, decreasing early nitrogen application, and choosing a disease-resistant variety allowed to decrease the number of pesticide applications, together with decreasing the risks of lodging and diseases (Loyce et al., 2012). The good economic performance of this first input reduction convinced the farmers to go further in pesticide reduction, and to implement a systemic rationale to design subsequent changes. During the following years, they tested different innovative practices, and adapted them to their specific constraints. Six years later (2008), they had diversified their crop sequences by introducing new crops, changed their cultivars for disease resistant ones, strongly reduced the use of inputs on their main crops, thus halving the Pesticide Frequency Index at the whole farm scale, without degradation in labour time and economic returns (Mischler et al., 2009). At this stage, herbicide reduction was low, and the rest of the design process focused on reducing herbicide use.

Case 5: Cropping systems autonomous regarding mineral nitrogen in arable crops (Champagne crayeuse, North-East France):

In the chalky soils of north-eastern France, characterized by a low mineralisation rate and a slow reheating in spring, farmers use large amounts of mineral nitrogen, thus inducing high economic and energetic costs, and contributing to water and air pollution. The project aimed at designing and assessing, in farm conditions, cropping systems targetting low N-fertilizer use, and high biomass production, either food or non-food (Guillier et al., 2020). Seven pioneer farmers, each one supported by one advisor, designed and implemented in their own farms, cropping systems with low dependency to mineral N fertilizer. The project facilitator and the advisors supported farmers in the assessment of the results obtained on their farm, which led to a change in practices (waste recycling, reduction of fertilizer rates, introduction of crops with low inorganic N requirements, catch crop for low nitrate losses), or in the farmers' targets.

Case 6: Reduction of nitrate pollution from cropping systems in a water catchment area (Yonne, Center-East France).

In a drinking water catchment area, farmers, advisors and researchers have worked together, since 2010, to change agricultural practices in the view to regain good water quality. During the first two years, the facilitator of the area and the scientists made an agronomic diagnosis, and worked with all the actors of the catchment area to define design targets (Ravier et al., 2015), and to identify changes in cropping systems that could help achieve these targets. They proposed first to sow every year, as soon as possible, cover crops with high N uptake capacity, and second, to foster and keep as long as possible volunteers of rape and pea, crops that leave a lot of nitrogen in the soil after harvest. A dashboard, gathering all the observations to be carried out to check the effectiveness of the cover crops with regard to the control of mineral nitrogen left in the fields in the automn, and then of nitrate leaching, was built with the actors of the catchment area, to monitor the change process over years. Based on yearly implementation and assessment of new practices (e.g. cover crop species, date and modalities of sowing, density of volunteers), a continuous adjustment was implemented over the years. The dashboard supported the farmers' dynamics of change, since the collection of data feeding it was an opportunity to organize field visits and exchanges between the farmers, thus feeding the cropping system design process (Prost et al., 2018).

Case 7: Reduction of pesticide use in diversified vegetable systems under shelters (Pyrénées-Orientales, Southern France).

From 2013 to 2018, in a research station dedicated to agroecological systems in vegetable production under shelters, four innovative cropping systems were designed, experimented and improved : organic or low-pesticide cropping systems, fulfilling specific food expectations for long value chains (super and hypermarkets) or local direct sale (Lefèvre et al., 2020). Agronomists from the station conducted a collective, pluriannual and iterative process involving the workers of the research station, local advisors, farmers and scientists, in the view to implement, assess and make each system evolve according to the on-going experimental results. Finally, robust agroecological crop health management strategies, combining different levers of actions at strategic, tactical and operational levels, were progressively designed. Concurrently, specifications from each food value chain were precised, thus allowing to explicit relevant assessment criteria, used to propose changes in the practices.

Case 8: A self-sufficient and biodiversity-based farming system in marshes (South-western France).

Since 2009, a system-experiment has been set up on a mixed crop-livestock research farm, located in the coastal marshes of the South-West of France (Durant et al., 2020a). The aim was to increase the self-sufficiency of the farming system from inputs (e.g. cow's feed, nitrogen fertilizer), and to synergize agricultural production (cattle breeding and arable crops) and biodiversity conservation (plants, birds, amphibians, insects), a strong environmental issue in wetlands. The objective was to design a biodiversity-based farming system, adapted to specific constraints in marshes (including hydromorphic soils with 60% clay). Involving researchers and workers of the research farm, as well as some farmers and local technical advisors, the approach consisted in a gradual changing over years in i) the agricultural practices concerning cattle grazing on permanent grasslands, the herd diet, the calving periods, the reduction of pesticides and N-fertilizers use, and ii) the agroecological infrastructures, such as grassy strips, hedgerows, ponds, upt to the conversion of the farm to organic farming in 2017.

Case 9: Self-sufficient organic mixed crop dairy systems (Vosges, Eastern France).

The objective of the case study was to design in an INRA experimental station, self-sufficient farming systems valorizing natural land properties. Between 2004 and 2015, two organic and self-sufficient dairy systems were designed, experimented, assessed and progressively improved, one mixing crops, grassland and dairy cows, and the other 100% grassland for dairy cows feeding. Since 2005, the two systems have been continuously evolving to improve their performance and their self-sufficiency: e.g. including multispecies cereal-pulses mixtures in the field and in the dairy cows' diets, matching the reproduction schedule on the feeding one. Moreover, this approach resulted in creating knowledge for (i) feeding the transition of other farming systems toward more self-sufficient forms, and (ii) the adaptation of systems to environmental fluctuations (Coquil et al., 2014).