Multi-annual experimental itinerary: an analytical framework to better understand how farmers experiment agroecological practices

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Agronomy for Sustainable Development (2022) 42: 20
https://doi.org/10.1007/s13593-022-00758-8

RESEARCH ARTICLE

Multi-annual experimental itinerary: an analytical framework to better understand how farmers experiment agroecological practices

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Accepted: 19 January 2022 / Published online: 10 March 2022

Abstract

Farmers' experimentation has long been identified, but until now, its dynamics has hardly been studied at all. The subject is however gaining new interest, as by enabling farmers to learn new cropping practices on their farms, their experimentation could be a driver of transition towards agroecology. The aim of this study is to understand the multiannual experimental itineraries that farmers follow when they try new agroecological practices on their farms. Sixteen cereal and vegetable French farmers were surveyed to establish how they had experimented with agroecological practices over the last decade. They were questioned on their experimentation objectives, the origins of the practice tested, their observations in the field, and the degree of attainment of their objectives. We defined the concept of experimental itinerary as the chronological and logical combination of annual experimental situations. Similarities and differences between the experimental itineraries of the 16 farmers were sought. The results are threefold. First, we showed how a farmer progressively builds an experimental itinerary over years after the introduction of a brand new practice. Second, by analyzing the 33 experimental itineraries identified in the sample, we demonstrated that some types of experimental situation occur more frequently at the beginning, some in the middle and some at the end of the experimental itinerary. Third, we identified four patterns of experimental itinerary (low investment, linear, tree, and grove patterns) that correspond to different ways the farmers organize the annual experimental situations over the years. The novelty of the results lies in the in-depth understanding of the inter-relations between successive experimental situations that has never been described before. We finally discuss the results with an operational focus, that is, how the representation of experimental itineraries could support farmers in their experiments and enable them to learn more efficiently.

Keywords Market gardening · Arable crops · Experimentation · Learning · Innovation · Organic agriculture · Pest control · Conservation agriculture

1 Introduction

Agroecology appears as a promising alternative model to address the negative impacts of agricultural intensification on ecosystems, climate, and human health. Transition to agroecology challenges both scientists' and farmers' knowledge acquisition. On the one hand, using biological regulation to manage agroecosystems calls into question the ways in which scientists build agroecological knowledge (Doré et al., 2011) for at least three reasons: (i) The numerous interactions between plants, soil, and living organisms call for a system analysis (Médiène et al. 2011); (ii) uncertainty in the intensity at which the biological regulation may occur question the capacity to build generic agronomic laws; (iii) agroecology gives more attention to the local ecological context in which a farming practice is applied (Uphoff 2002, cited by Altieri 2002).

On the other hand, farmers' knowledge is also challenged by the transition towards agroecology. Since agroecological systems cannot be entirely planned in advance, farmers have to develop skills in observing plants, soil, pests, and their antagonists, to check whether ecological regulations are being put in place on a plot (Doré et al. 2011) and, if not, to seek other practices in an adaptive management way (Duru et al.

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2015). To face the uncertainty and unpredictability inherent to agroecological systems, they constantly reapply pieces of local knowledge elaborated from their practical experience and combine it with more generic agronomic knowledge in a learning-by-doing approach (Gliessman 2007; Altieri and Toledo 2011). Hence, agroecology deeply challenges the extension model built after World War II, based on the technology transfer or “top-down” approach, where generic knowledge developed by scientists is transferred to farmers through extension services (Schut et al. 2014). How farmers can be helped to learn from their experience and adapt the universal agroecological principles to local situations is therefore a challenging question.

Several initiatives have been developed to support agricultural innovation on farms. Their common features are that they usually are embedded in local situations, based on exchanges among farmers and with scientists, and mixing social and biotechnical dimensions. For example, Farmer Field School is a participatory field-based approach, in which several farmers realize practical training on a field over years to increase their knowledge. Future change on farms is supported by a specific device based on collective observation and mutual learning, between farmers and possibly with a technical advisor (Van den Berg and Jiggins 2007). The co-innovation approach is another collective learning process, based on close interactions between farmers and scientists, to redesign and implement a new farm system and assess the impacts of such change at the farm level. Another learning tool consists in on-farm experimentation of cropping practices (Darnhofer et al. 2010; Chantre and Cardona 2014; Navarrete et al. 2021). But the experimentation dynamics driven by the farmer him-/herself have rarely been described in detail. To make a clear distinction with the day-to-day learning-by-doing process, we define the farmers’ experimentation of farming practices as an intentional activity where an intervention (new crop or cropping practice, etc.) is performed for a practical purpose on a limited surface area, and where empirical observations are performed (Fig. 1) to understand the farming practices tested or to check the degree to which an expected change occurs (Kummer et al. 2012; Catalogna 2018; Hansson 2019). Several decades ago, anthropologists reported farmers’ experimental activity in traditional agriculture around the world (Richards 1989). But the interest in farmers’ experimentation is now growing in Western countries as a way to secure farmers when learning how to move towards agroecological transition (Kummer et al. 2012; Duru et al. 2015; Navarrete et al. 2021). A wide range of farmers’ experiments has been described worldwide (Saad 2002; Bentley 2006; Kummer et al. 2012; Leitgeb et al. 2014). Most articles propose narratives about experiments seen as success stories (Bentley 2006), explaining the sociological background and the motives to initiate an experiment, the subject of the experiment, and the outcomes (Bentley 2006; Kummer et al. 2012). Some studies have focused on the role of social interactions in experimentation and learning (Bentley 2006; Maertens and Barrett 2013; Sumane et al. 2018), between farmers or with extension agents. In particular, Bentley (2006) showed that farmers use various sources of knowledge to build their experiments: other farmers’ experiences, advice or training operated by agricultural institutions, agricultural journals, and even scientists. Two key points can be highlighted from this literature analysis. First, farmers’ experiments have mainly been studied by sociologists and anthropologists, and more rarely by agronomists. Agronomists mostly focused on the experiments they themselves have devised and managed with farmers on commercial farms (Anderson 2012). In more recent agronomy studies on farmers’ learning activity (Chantre and Cardona 2014; Toffolini et al. 2018), their experimenting is identified as a learning tool among others, but not analyzed in depth. The second key point is that experiments have so far mainly been studied from a short-term and external scientific viewpoint. Very few studies have analyzed the multi-annual dynamic of experimentation, and depicted the farmers’ points of view on the causal relationships between the successive experiments. And yet, understanding how farmers experiment agroecological practices in the long term is a matter of interest both for cognitive and ecological reasons. First, we assume that the succession of experiments along the years reflects how farmers learn on agroecological practices. Kolb’s learning cycle depicts the repetition of phases of concrete learning experience, reflective observation, abstract conceptualization, and active experimentation (Kolb 1984) that echoes to such succession of experiments. Second, we assume that the multiannual experimentation process enables to take into account the progressive establishment of some ecological regulations on a plot and how agroecological practices need to be adapted in the long term (Altieri and Toledo 2011).

Fig. 1 Farmer observing earthworms during his experiments with wheat cultivation without tillage (photograph by M. Catalogna).

Catalogna (2018) proposed a conceptual framework based on Kolb's learning cycle and on-farm innovation and learning dynamics, in which the farmers' experimental activity is described with two complementary concepts: (i) experimental situation, as a short-term component, characterizing an experiment performed on a plot for a cropping season; and (ii) experimental itinerary, as a long-term component, describing the logical combination of annual experimental situations over years. In a previous article, the diversity of annual experimental situations (short-term component) was described on a case study in South of France (Catalogna et al. 2018 and Table 1). The aim of the present article, based on the same case study, is to analyze the farmers' long-term experimental itineraries. We analyzed how successive annual experimental situations inform one another, according to the farmer's point of view, and how they feed his or her long-term learning process. Our focus is on the farmer's individual logic, even if as shown previously his/her experiments are influenced by social networks. The reason is that, as agronomists, we were interested in the biotechnical logic developed by farmers along their experimental itinerary, rather than on the social interactions playing on it. In Section 2, we first present the methods used to collect and analyze data. Then in Section 3, we characterize and discuss the diversity of experimental itineraries in the case study, and discuss about how the representation of experimental itineraries could help farmers learn more efficiently and secure their transition towards agroecology.

2 Materials and methods

2.1 A survey of 16 market gardeners and cereal farmers experimenting with agroecological practices in south-eastern France

The study was carried out in Rhône-Alpes (south-eastern France), a region where farmers have been experimenting with organic and agroecological practices for several decades. Sixteen experimenting farmers were surveyed, covering a diversity of farming systems. We assumed that farmers would perform their experiments differently, depending on technical, social, and economic conditions. This is why the sample comprised vegetable and cereal farmers, carrying out organic and conventional farming practices. Nine and seven farmers, respectively, cropped vegetables and cereals. The two production systems were selected because they present specific constraints possibly impacting the process of experimentation (e.g., vegetable crops involve a bigger variety of crops on smaller plots than arable crops do, and offer the opportunity for frequent crop observations during manual cropping operations, which could impact the way farmers implement the experimental itinerary). We also posited that the mode of farming could impact the experimentation and learning methods. This is why our sample included 10 organic farmers, and 6 conventional farmers with agroecological practices. We wondered if organic farmers, more sensitive to interactions within the cropping system and long-term effects than conventional ones, would experiment differently. The farmers were chosen with the help of the local technical advisers, for their interest to learn on new agroecological systems. A phone interview enabled to identify those really experimenting agroecological practices, before conducting the face-to-face in-depth interview. The market-garden farms selected were small and diversified: vegetable surface areas ranged from 1.5 to 10 ha, mainly in open fields, and with a limited part under plastic shelters (between 0.1 and 1 ha). The market-gardeners surveyed cropped more than 10 vegetables (tomato, zucchini, onions, lettuce, etc.), whereas on cereal farms, surface areas devoted to cereals ranged from 14 to 140 ha (wheat, sorghum, maize, and soya were the main crops). Most farmers had set up their business more than 6 years earlier, except one who officially started just 1 year before the survey date but had already been working on the family farm for several years. This is important because farmers who have set up recently have to tackle too many technical problems to make a strong commitment to experimentation (Saad 2002).

The survey was carried out between February 2016 and November 2017. The conceptual model based on the short-term "experimental situation" and the long-term "experimental itinerary" concepts served as a guide for the farmers' interviews, which were semi-structured, lasted 2 h on average and were recorded. There were two rounds of interviews. In the first round, the farmers were first asked to briefly describe their farms as well as any recent changes, to provide the context for the experiments. They were then asked to talk about any experimental situations that spontaneously came to mind, which were then positioned along a timeline established during the interview (see Fig. 3). The timeline was used again to question them about any other experimental situations in which they had been involved, to complement as far as possible the chronological succession of experimental situations. Moving from the most recent to the most distant one, it was usually possible to go back to the first ones, 10 years earlier. The farmers were questioned on the relationships between two successive experimental situations related to a same agroecological topic (e.g., cover cropping); thus, they were asked how the cropping practice was changed from one experimental situation to the next and why, and how the experiments informed each other. For example, the failure to sow a clover cover crop after the wheat harvest in an experimental situation led a surveyed farmer to experiment with earlier clover sowing, before the following year's wheat harvest. The first survey enabled us to trace one to four experimental itineraries for each of the 16 farmers. The second round of interviews was held with 7 farmers who had very complex experimental itineraries that had not been understood in depth during the first round. Compared to the first study (Catalogna et al. 2018), the data of a seventeenth farmer were not used in this article because only one experimental situation could be identified. Due to the complexity of on-farm experimentation, we restricted the study according to three axes.

Table 1 Ten types of experimental situations identified on the case study (Catalogna et al., 2018). An eleventh type (non-represented) consists in unclassified experiments.

Type	Name	Description and example
Improvement experiments		
1	To improve agronomic performance of a practice	Farmers already used the practice under test and now try to improve agronomic performances, e.g., a cereal farmer fractionated intake of organic fertilizer on wheat crop to increase yield without observing the rest of the agroecosystem.
2	To improve work or economic performance of a practice	Farmers already tested the agroecological processes they are targeting. Now they adjust the practices to make them easier or cheaper to implement, e.g., a cereal farmer targeting to improve soil functioning replaced a vetch cover crop by a buckwheat catch crop, which was easier for him to implement.
3	To transpose a practice	Farmers try to transpose the logic previously experimented to another part of the cropping system, e.g., a farmer tested a vetch cover crop between onion and wheat after testing it between wheat and soya (Fig. 3, farmer named NT).
4	To repeat the previous experiment identically or with minor change	Farmers test a practice previously assessed, and repeat the previous experiment with hardly no change, e.g., after a successful use of ladybugs against aphids on a tomato crop, a farmer released them again to control new aphid attacks.
5	To improve feasibility of a practice thanks to minor change	Farmers test a practice already experimented to improve their mastery in the practice, e.g., after experimenting no-tillage practice, a cereal farmer reversed the seed driller to avoid wheel compaction.
Failing experiments		
6	For lack of being able to implement the technique	Experiment is stopped before its end because the farmer faces technical difficulties to implement the practices as planned, e.g., a cereal farmer had to interrupt the experiment because the clover seeds sown as cover crop did not germinate.
7	For lack of agroecological efficacy	Experiment is stopped before its end because the farmer discovers major agroecological defaults linked to the practice tested, e.g., a vegetable grower experimented the introduction of *Tetranychus* spp. on eggplant crop but he failed to control *Amblyseius swirskii* and had to spray insecticides.
Breakthrough experiments		
8	Where a new agroecological logic is tested for the first time	A new agroecological logic is being tested for the first time, discovered off the farm or imagined in mind, e.g., on a friend’s advice, a vegetable grower transferred ladybugs from an old chard crop to a zucchini crop to control aphids.
Comparison experiments		
9	Two or more modalities of a technique compared	Several modalities of a technique are compared in the same plot to identify the best modality, e.g., one cereal farmer tested no-till maize and compared two modalities: strip till in one plot and direct sowing in the other.
10	A technical modality compared to a reference	A technical modality is compared with a reference to check whether it is worth adopting, e.g., a vegetable farmer tested no-till and mulching with ramial chipped wood, to improve biological life, and he compared it with another plot where vegetable beds were tilled normally, which is his standard practice.

First, we only collected and analyzed situations that were considered as experiments by the farmers themselves, and therefore, kept trial-and-error processes silent. Second, we focused on agronomic practices and ignored other subjects of experimentation such as on equipment, social, or economic aspects. And last, we focused on the individual process of experimentation. These elements will be discussed in the last part.

2.2 Analyzing the diversity of experimental itineraries in the case study

For arable crops, the topics experimented were first cover cropping (which species, dates, density of sowing? which effects on the following crops?), then reduced tillage (how to manage it? how to control weeds?), and intraspecific and interspecific crop diversity management (which optimal mixture of varieties or species? how to manage them?). For market gardening, the topics were first biodiversity management and natural biocontrol enhancement (how to introduce natural antagonists to control pests? which ones? how to establish grass strips?), organic fertilization (when to supply it? how to favor soil micro-organisms?), and crop association against pests (which species? where in the plot?). Each experimental situation identified among the 16 farmers was characterized by its own characteristics and its position along the experimental itinerary. As regards the first point, we used the typology of experimental situations described by Catalogna et al. (2018): 10 types of experimental situation were characterized (Table 1). The first five types relate to the progressive improvement of the practice tested. Types 6 and 7 relate to failing experimental situations, i.e., that were stopped during the cropping season for lack of feasibility or performance. Type 8 is a breakthrough experimental situation in which a brand new agroecological logic was tested for the first time. Types 9 and 10 relate to experimental situations based on the simultaneous comparison between several technical modalities of a practice.

When representing farmers' logic of experimentation, we adopted an agronomists' external point of view and analyzed it through its materially noticeable manifestation in farmers' practices. An experimental itinerary organizes all of a farmer's experimental situations relating to the same agroecological topic. Each experimental situation was positioned along the experimental itinerary, depending on its year of implementation. Each experimental itinerary was split into three parts: the starting, intermediate, and advanced position (Fig. 2). Any causal relationship between two experimental situations was represented with an arrow. A branching out occurred when an experimental situation produced two others, one in direct relation to it (e.g., same crop, same cropping technique), which constituted the main branch, and the other one a derivation (e.g., when a reduced tillage technique tested on a wheat crop was applied to another crop of the rotation, or when the practice consisting of collecting biological antagonists, developed for one auxiliary species, was applied to another one). As a consequence, branching is a representation inspired at the same time by the farmer's narratives (e.g., he says that he reproduced the practice of cover cropping at another place of the crop rotation) and by the agronomy theory (the cover crop effect is known to be dependent on the crop sequence) (Fig. 2).

In short, an experimental itinerary is a set of closely interrelated experimental situations. In theory, it starts when the farmer starts experimenting with an agroecological practice, and stops either when he/she decides to implement the practice on a large scale, or when he/she stops using it (respectively called "adoption" and "abandonment"). In practice, in our case study, the majority of experimental itineraries started with the oldest experimental situation identified during the survey. In only a few cases did the farmer seem to have experimented earlier, but the memories were not accurate enough to take these experimental situations into account. The experimental itineraries ended with the last experimental situation implemented at the date of the survey. In the survey, the real end coincided with the last experimental situation identified in the survey for only 12 out of the 33 experimental itineraries identified. These corresponded to the cases where the farmer definitively adopted or abandoned the practice experimented with.

To describe the experimental itineraries, both a quantitative and a qualitative method were used. Four variables were calculated: *Sit_Nb*, the total number of experimental situations in the experimental itinerary, including those on secondary branches; *Br_Nb*, the number of branches of the experimental itinerary, including the main branch; *It_Dur*, the duration of the experimental itinerary, calculated on the longest branch from the first to the last year, and expressed in years; and *It_Int*, the intensity of experimentation, calculated as follows: *It_Int*=*Sit_Nb*/*It_Dur*. *It_Dur* is survey-dependent, because it is the duration observed up to the survey date, even though the experimental itinerary may have continued afterwards. This is why the last variable, *It_Int*, i.e., the mean number of experimental situations per year, was easier to interpret: the higher the value, the more intensive the experimental itinerary was. A qualitative method based on the authors' expertise was used to search for common patterns among the 33 experimental itineraries, based on the in-depth analysis of farmers' narratives and of the visual representations of the itineraries, with specific attention to the degree of connection between the experimental situations of the itinerary. This qualitative variable takes into account not only the mean number of experimental situations per year *It_Int*, but also the causal relationship between successive experimental situations, which was characterized in Catalogna et al. (2018). Two experimental itineraries with the same *It_Int* value were therefore classified differently if one of them strictly derived each experimental situation from the outcome of the previous one (high degree of connection), whereas the other one implemented two poorly interrelated experimental situations. Finally, we compared the patterns identified and their characterization according to the four quantitative variables.

3 Results and discussion

3.1 An experimental itinerary drawn on causal relationships between successive experimental situations

In the sample, 33 experimental itineraries were identified, 18 on cereal crops, and 15 on vegetable crops. The surveyed farmers simultaneously implemented 1 to 4 itineraries over

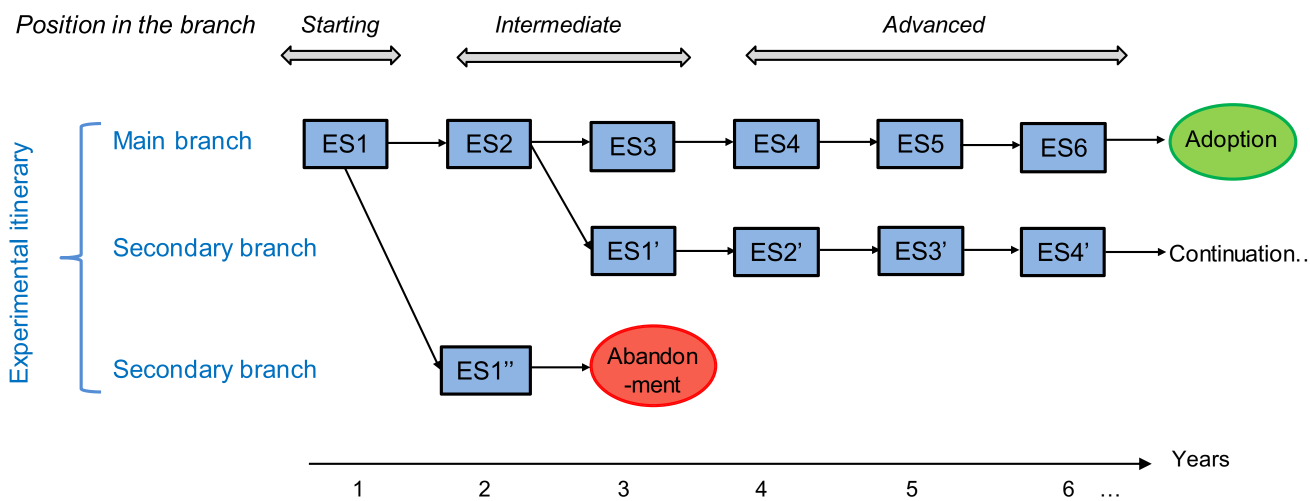

Fig. 2 The conceptual framework of the experimental itinerary. On each branch, the first experimental situation (ES) is referred to as the starting position, the second and third ES as the intermediate position, and the following ones as the advanced position. The terms "Adoption" and "Abandonment" indicate the time when the practice experimented with is either adopted by the farmer or abandoned. In the example, 11 ES were performed (*Sit_Nb*=11), the experimental itinerary lasted 6 years (*It_Dur*=6) and was composed of 3 branches (*Br_Nb*=3), the intensity of experimentation was 1.8 ES per year (*It_Int* =11/6=1.8).

the period studied. Each itinerary lasted between 2 and 15 years (*It_Dur*) and was composed of 2 to 20 experimental situations (*Sit_Nb*) that were organized along 1 to 9 branches (*Br_Nb*).

To illustrate the multi-annual organization of experimental situations, we briefly present the narrative of an experimental itinerary of an organic cereal farmer, named NT, when trying to introduce a cover crop in a cereal crop rotation (Fig. 3). His aim was to provide nitrogen to the following crops, and thus reduce the need for animal manure. He experimented legume cover crops before maize over 9 years, on a different plot each year depending where maize was cropped. He adapted the choice of the cover crop species and the sowing date and progressively refined the practices until he found a satisfying practice in 2017. Then he introduced cover cropping at other points in the crop rotation (between wheat and soya, or onions and wheat) that we represented as secondary experimental branches. The transposition of the cover cropping practice before soya and wheat led him to adapt both species and sowing dates of the cover crop, as soya is a legume spring crop.

NT's crop rotation formerly consisted of spring cereal, soya and wheat, all repeated twice before a 3-year alfalfa crop. Main branch of the experimental itinerary: From 2009, NT started to test a vetch cover crop between wheat and maize, for nitrogen supply. In an attempt to improve the efficiency of cover crop, he progressively sowed it earlier to benefit from higher temperatures at sowing, and finally in wheat, before its harvest. Secondary experimental branches: From 2014, he experimented with different species (alone or in mixtures) and by introducing cover cropping at different points in the crop rotation (between wheat and soya, or onions and wheat).

How experimental situations feed one another? Let us consider one particular experimental situation (in blue in Fig. 3), which consisted in experimenting with a mixture of vetch and rye, sown in wheat. The farmer decided this experiment based on two hypotheses resulting from previous experimental situations: (1) a legume-cereal cover crop should increase the following soya crop's yield; and (2) sowing a cover crop before harvesting the previous crop should increase its productivity by increasing the growth period. But in 2016, the vetch seeds did not germinate because they were not buried deep enough, and NT was forced to plow the field soon after harvesting the soya. As a consequence, (3) he gave up sowing vetch in wheat, (4) and kept on progressing with his initial idea, by using smaller seeds — red clover — that could be sown more easily.

The NT experimental itinerary illustrates how a farmer decides on an experimental situation based on information resulting from previous situations. The outcomes, in turn, influence the following experimental situation, either on a same experimental branch or on another. Hansson (2019) uses the term "action-guiding experiments" to describe farmers' experimentation processes, a "directly action-guiding experiment as the performance of some action X in order to determine whether, or to what extent, a desirable result Y follows, with the intention that this information should be useful on future occasions when the attainment of Y is desired". It enables farmers to elaborate knowledge about what should happen when some interventions are performed. They differ from scientists' "epistemic experiments" aiming at revealing mechanisms on the agroecosystem. And yet, some scientific articles report cases where the farmers' way of experimenting was guided by a somewhat mechanistic understanding of the crop functioning (Millar 1994; Sumberg and Okali 1997). As

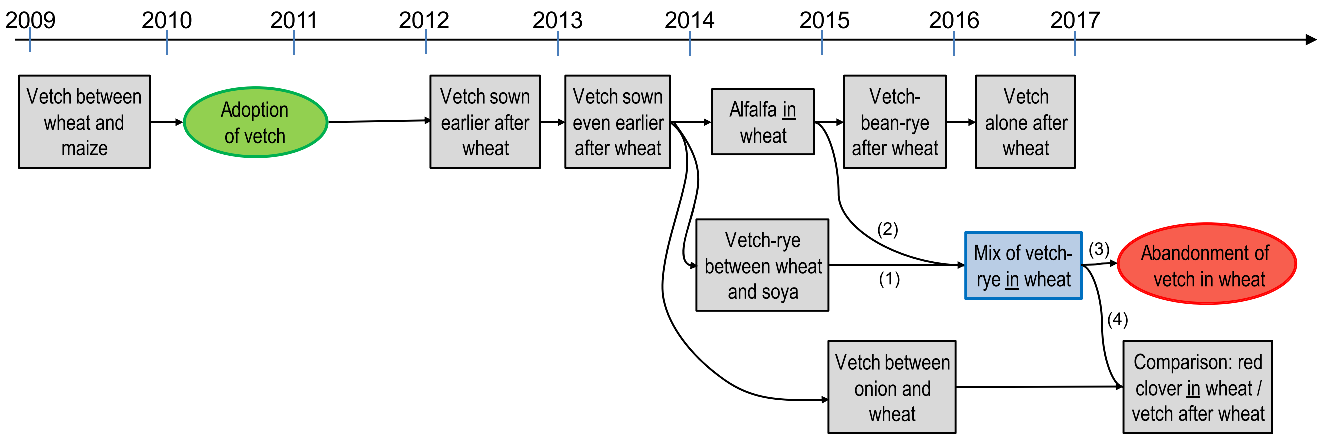

Figure 3 Experimental itinerary of a cereal grower surveyed (NT, the itinerary was named from the farmer's name initials).

shown in the NT's example, successes or failures of the practices in one experimental situation inform the reflection process on technical change, leading either to the continuation of experimentation (for an interesting practice but still insufficiently mastered), or to the adoption of a practice at larger scale (when the farmer is confident in the outcomes and satisfied enough), or else to its abandonment (when outcomes are too bad) (Section 3.4).

The following part seeks a generalization of how experimental situations are sequenced over the years and the reasons for using the whole sample of surveyed farmers.

3.2 Relationships between the types of experimental situation and their position in an experimental itinerary

Among the 16 farmers surveyed, 174 experimental situations have been previously categorized according to 10 types (Catalogna et al. 2018). In a first step, we demonstrate that the distribution of these 10 types of the experimental situations varied according to their position along the experimental itinerary (Fig. 4). At the starting position of the experimental itinerary (first experimental situation), breakthrough (type 8), and transposition (type 3) were the most frequent. As a breakthrough experimental situation consists in trying a practice for the first time on the farm, it is logical that such type was carried out mainly at the beginning of an experimental itinerary, since the farmers started experimenting in order to learn from practices at which they were not skilled. By construction, transposition experimental situations led to the creation of a secondary branch, for example when a practice first tested on a crop (main branch) was applied to another crop of the rotation (secondary branch) (e.g., NT about the vetch cover crop in Fig. 3). At intermediate position (second and third experimental situations) and advanced position (fourth experimental situation and beyond) of the experimental itinerary, breakthrough and transposition experiments completely disappeared whereas the four other Improvement types were the most frequent. They accounted for respectively 79.7 and 86.9% of the total number of experimental situations at intermediate and advanced position, compared to only 48.7% at starting position. These experiments aimed to improve the performances of the practice (yield, cost, economic return) by adapting the way it was carried out (types 1 and 2). Or they aimed to replicate the practice (type 4) or to slightly change it (type 5). For example, NT searched for how to increase the growth of the cover crop by progressively bringing forward the sowing date, and how to make it more practical by sowing the legume cover crop in wheat to avoid wheat stubble plowing. Failing experiments (6 and 7), i.e., experiments that were stopped before the end of the crop because a technical problem occurred during their realization, were mainly present at starting and intermediate positions. Why failing experiments occur more frequently at the beginning and middle of the experimental itinerary rather than at the end? Two complementary hypotheses can be drawn from our results: (i) farmers give up an experimental itinerary after 1–3 years if the tested practice does not yield sufficient results, leading them to build another strategy and start another experimental itinerary; and (ii) farmers progressively gain more knowledge over the years on the practice experimented with and are thus capable to plan satisfying technical modalities to reach their goal after a few years. Comparison experiments (types 9 and 10) were scarce and at about the same frequency along the experimental itinerary (respectively 11.5, 10.9, and 8.7% of the experiments in starting, intermediate, and advanced positions).

To summarize, the experimental itinerary can be seen as a combination of different types of experiments that were organized for logical reasons. By analyzing inter-relations between successive experiments, we can indirectly trace the progressive building of information on the effects of a practice, or of an ecological process. Anyway, one should not deduce from these results that the experimental itineraries are necessarily planned in advance in the long term. But it is noteworthy that general ways for experimenting were found among a set of

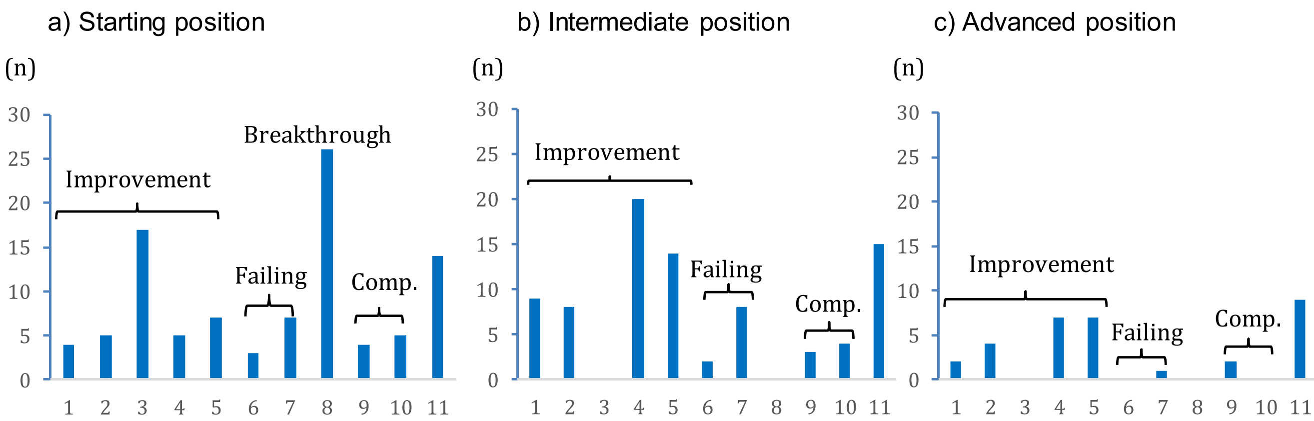

Fig. 4 Histogram of the number of experimental situations per type according to the position along the experimental itinerary. (**a**) Starting position = first experimental situation of the branch; (**b**) intermediate position = second and third experimental situations of the branch; (**c**) advanced position: fourth and following experimental situations of a branch. The numbers on the X-axis refer to Table 1.

experienced farmers, such as progressively refining the practice over years (main branch) or transposing a know-how acquired on a crop to another crop (secondary branch). Despite such common ways looking beyond each one's peculiarities, adaptations were identified. First because unpredicted events may modify the general model, for example, bad weather, development of a new pest, lack of time or machinery to pursue the experimental logic, and evolution of the farm's aims for external reasons. Second, an experimental itinerary is usually not devoted to one specific plot but distributed among several ones because the experiments conducted 1 year are dependent on the yearly allocation of crops on the farm. Previous studies on farmers' experiments did not clearly distinguish the annual and multi-annual dimensions of the process; in particular, we have found no in-depth study of the multiannual dynamic of experimentation.

Another original result is the capacity of farmers to develop and stabilize their knowledge on an agroecological topic without systematic formal repetition of a treatment as in scientific experiments. As mentioned by Catalogna et al. (2018), most of the time, farmers experiment with only the "best bet practice" they can imagine, based on the knowledge available at the time (and updated over their experimental itinerary). Even if the results of experimentation could be surer if different technical modalities were compared, farmers rarely select more than one. We posit that it would be too time-consuming: as farmers give priority to production activity, they experiment only with the practices that could best fit their needs. Nevertheless, comparing several modalities occurs when farmers have free time and/or when it is hard to make a best bet because several modalities are a priori equally interesting. According to Richards (1989) and Hansson (2019), farmers have several ways to compare their results: they can realize side-by-side comparisons between two technical modalities to determine which is the best (as for type 9) or compare one modality with their current practice (type 10). They can also draw historical comparisons over several years or comparisons with a neighbor. In our study, few side-by-side comparisons were implemented (around 10.9% of the total number of experimental situations). This was much lower than the 39% found by Sumberg and Okali (1997) that may have included historical and neighbor comparisons. Another interesting point of comparison relates to the replication question. Replicating an experiment in different places or over 2 or more years is considered by scientists as the best way to build more generic knowledge. As noted by Stolzenbach (1994) and Hansson (2019), it is rare that farmers strictly replicate practices over years; they prefer to take success or failure into consideration to progressively adapt the practices tested. Another reason is that agroecological practices have to be adapted to each local context of the plot under consideration. This observation probably explains why so many experiments identified in our study relate to practice improvement (66.0%) and only 19.4% are strict replications (type 4). Anyway, it seems that for farmers, the succession over years of several experimental situations enables a progressive generalization and stabilization of the knowledge on the practice experimented, as shown by Catalogna (2018). Such a progressive refinement of the practice experimented over years echoes Lyon's (1996) definition of "learning during action" or Millar's (1994) one of "adaptive experiments".

3.3 Four patterns of experimental itineraries

Four patterns were identified among the 33 experimental itineraries. They differ according to the four variables (Fig. 5a) and were positioned according to two dimensions in Fig. 5b: the number of experimental branches (*Br_Nb*) and the degree of connection between all the experimental situations of the itinerary (qualitative variable). They are presented here in order of increasing intensity (*It_Int*). The low investment pattern refers to the case where experimentation is quite limited: low total number of experimental situations (*Sit_Nb*), low frequency of experimental situations *It_Int*), and few experimental branches (*Br_Nb*). It corresponds to the case where the farmers stop their experimental itineraries after 1–2 years (low values of *It_Dur*), or perform experiments occasionally over a long period (low values of *It_Int*). This explains why a low investment in experimentation is not systematically associated with a short duration (*It_Dur* varying from 2 to 13 years among farmers). The linear pattern refers to cases where only one experimental branch is carried out (*Br_Nb*=1), the total number of experimental situations is limited (Mean *Sit_Nb* of 4.4), and the experimental itinerary lasts from 2 to 8 years (*It_Dur*). The experimental situations follow one another on the same topic and same branch. The practice experimented with progressively evolves and, once mastered, may be transposed to another crop. The tree and grove patterns refer to cases with the highest numbers of experimental situations (mean *It_Int* respectively of 10.7 and 9.5) and the highest numbers of branches (mean *Br_Nb* respectively of 4.6 and 5). Both differ in the way the branches are organized (Fig. 5b). In the tree pattern, experimentation starts with a main branch (trunk) that later separates into secondary branches: even if the main topic still requires experimentation, new sub-topics emerge and are experimented with in turn. This is the case of the farmer NT, where legume cover cropping was experimented with at 3 positions of a cereal crop rotation: between wheat and maize, wheat and soya, and onion and wheat. In the grove pattern, several experimental branches start from the beginning of the experimental process. All are related to the same agroecological topic, but are organized in parallel branches to simultaneously study several challenging problems. For example, the market-gardener RE wanted to promote biological pest control by conservation and habitat management of antagonists. In the same year, he experimented with several practices: he planted French marigold (*Tagetes patula*) between tomato rows against root-knot nematodes (*Meloïdogyne* spp.), garden nasturtium (*Tropaeolum majus*) among chards to trap aphids away from chards, and *calendula* (*calendula spp.*) to host indigenous predatory insects to control pests in winter. Each of these experimental branches enabled him to test a specific agroecological process (respectively toxic compound production, pest trapping, and natural biocontrol agent pulling). Some agroecological means were quickly adopted whereas others were abandoned, and the different experimental branches interacted poorly. Compared to the tree pattern, the grove pattern had a higher intensity of experimentation (mean *It_Int* of 2.1 and 1.5, respectively). Tree and grove patterns represent the subtlest experimentation processes. The differences between the two may relate to differences in farmers' representation of the agroecological system under study, and in particular to the degree of anticipation: in the tree pattern, one practice is experimented with in a specific situation (e.g., wheat crop for NT), and when learning occurs after a few years, the farmer gets the idea that he or she may use it in other conditions (leading to transposition to other crops and branching). In that sense, adaptation occurs on the way, as solutions arise. By contrast, in the grove pattern it seems that once the farmer has perceived the advantages of a new agroecological approach (biocontrol on vegetables for RE), he or she rapidly experiments with different components or possibilities for using it, which suggests a higher capacity of anticipation.

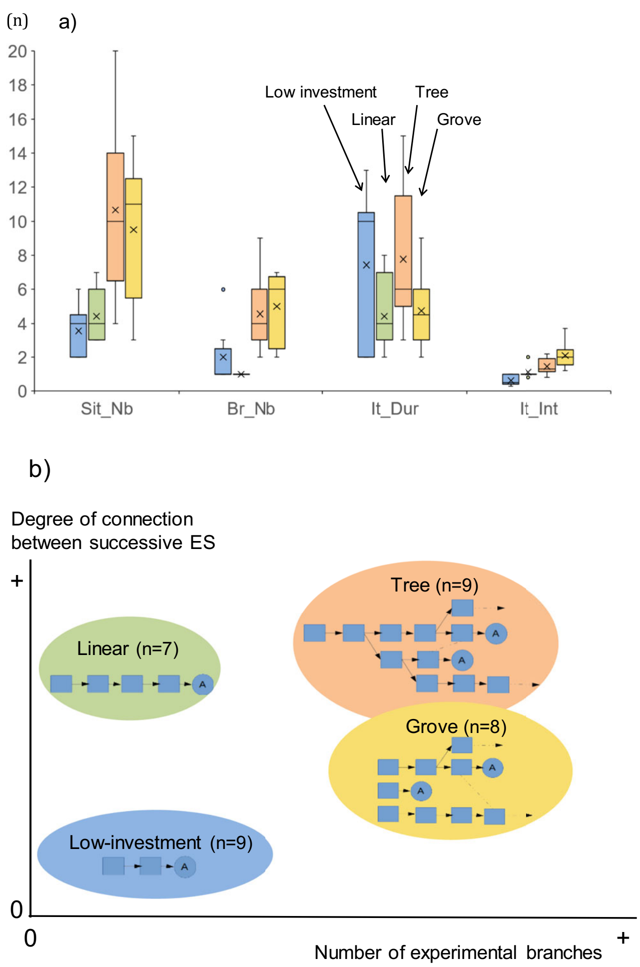

Fig. 5 Four patterns of experimental itineraries identified in the sample: (**a**) Box-plots of descriptive variables; (**b**) qualitative representation. *Sit_Nb*: total number of experimental situations (ES) including those on secondary branches; *Br_Nb*: number of branches of the experimental itinerary, including the main branch; *It_Dur*: duration of the experimental itinerary, calculated on the longest branch from the first to the last year; *It_Int*: intensity of experimentation with *It_Int*=*Sit_Nb*/*It_Dur*. Y-axis represents numbers. The upper and lower horizontal lines of the box represent the 25th and 75th percentiles respectively, the horizontal midline represents the median, the upper and lower horizontal whiskers lines are the upper and lower limits and the cross is the mean.

3.4 How does on-farm experimentation favor the adoption of agroecological practices?

During the survey, the farmers closely associated their experimentation process and the technical change occurring on their farm in the long term. Experimentation, by definition, concerns a limited part of the farm area (usually a plot or plot strip) and can be stopped when it becomes too risky (at the end of the cropping season or even earlier, for example for NT when the cover crop seeds did not germinate). One wonders how such a localized and transitory process could favor the adoption of agroecological practices at the larger scale of the farm and in a lasting way. This is why we now focus on the end of the experimental itineraries, e.g., the point at which farmers either adopt the agroecological practice on a larger scale, or abandon it. Adoption of new practices is a fuzzy concept. In this study, we consider that a practice is adopted when the practice goes out of our definition of experimentation, i.e., when the farmer stops implementing it on a limited part of the farm and for a limited duration to assess its effects. The practice is therefore implemented on a larger part of the farm and for several years, without putting it deeply into question.

Of the 107 experimental branches identified (main and secondary), 17 ended up being abandoned and 49 being adopted. This high proportion (around 46%) of success could be explained by the fact the farmers selected were experienced and managed to be successful in their experimentation process. In the sample, a strong relationship was found between the adoption or abandonment of the agroecological practice experimented and the type of the last experimental situation (Fig. 6).

Just before adoption, experimental situations mainly belonged to the improvement experiments (types 1–5), which accounted for 75.6% of the total number of experimental situations before adoption. This suggests that the last step of an experimental itinerary, just before the adoption of innovation at the larger scale of the farm, is to confirm previous results and adapt only slightly the practical modalities of a practice already known to optimize efficiency. The result is consistent with the previous results from Fig. 4 showing that, along the experimental itinerary, farmers tended to lower the intensity of change from starting position to advanced position, and progressively stabilized the practice. One surprising point is that 21.9% of the experimental situations before adoption were breakthrough experiments, suggesting that adoption could also occur very quickly despite the great novelty. In fact, it was noticed that among the nine experimental situations in question, seven consisted in using a new biological antagonist against pests on vegetable crops for the first time. While the antagonist species was unknown until then, the agroecological lever of biocontrol was already well-known to the farmers. These results confirm the “best bet practice” hypothesis. Farmers mostly experiment with practices that have a high probability of performing. This is particularly true for biocontrol with auxiliaries as it quite easy for farmers who are sufficiently skilled to succeed.

The situations where the farmer did not implement the practice experimented on his farm and abandoned the experimental itinerary were quite rare (17 out of 174 experimental situations in the sample). As shown in Fig. 6, this was mainly triggered by an unsuccessful experiment (53.3%), which is logical. Before adopting an innovation, farmers seek empirical regularities on the effect of the practice. One wonders if, in cases of non-adoption, the farmers considered the results too uncertain to adopt the practice at a large scale and/or if they lacked mechanistic knowledge on the agroecological process to help them draw some new hypothesis and carry on the experimentation itinerary (Hansson 2019). The other main type of experimental situation leading to the abandonment was the transposition experiment (type 3), where a practice already confirmed in one specific situation was transposed to another one. It suggests that the interest in developing a practice already experimented on another crop has proved to be bad.

Before adoption or abandonment, the comparison experiments were rare (they represented respectively 7.3 and 6.7% of the number of experimental situations for each category). From an agronomic point of view, one could consider that comparison experiments are useful at the end of the experimentation process, to definitively act if the new practice deserves to be adopted. As noted above, the reality of comparisons in farmers’ experiments is probably under-estimated with the two types of “comparison experiments”, because farmers also use informal comparisons with the performances observed on their farm over years or at neighbors’. Another reason probably comes from the distinction between what Hansson (2019) called “epistemic” and “directly action-guiding” experiments, the first ones relating to “how and why things happen” whereas the second relate to “what will happen (possibly with an unknown mechanism) if certain actions are taken”. Most farmers probably find themselves relating better to the latter form of experimentation, where strict comparisons are not necessary. It seems that experiments from types 1 to 5 are more efficient to help farmers take a decision to adopt or renounce to a new agroecological practice.

The definition of practice adoption we chose has its own limits, for at least two reasons. First, a practice experimented during several years does not necessary move from a plot scale to the whole farm: it could be only accurate on one part of the farm (e.g., a type of soil), on only after or before one specific crop, or in some specific situations (e.g., high pest pressure). The area concerned by the practice is thus not easily identifiable. Second, even after experimentation stops, the farmer keeps on learning through trial-and-error process and may adapt the practice. We therefore agree with Chantre and Cardona (2014), who consider that “the transition toward sustainable practices should be considered more as a process of constant adjustments and successive adaptations of farming practices than as the adoption of a technical package at one

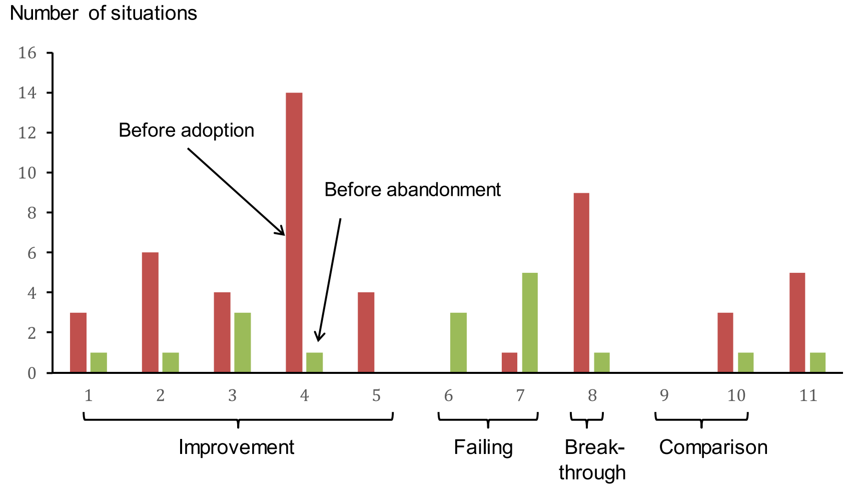

Fig. 6 Histogram of the number of experimental situations per type before adoption and abandonment of the experimented practice. The total number of experimental situations differs from the number of experimental itineraries because adoption or abandonment is defined for each experimental branch, and it may also not have happened yet at the date of the survey.

point in time and forever". Nevertheless, further studies should therefore be developed on the question of adoption of the practice experimented.

3.5 The experimental itinerary: from an analytical framework to a tool supporting farmers' learning process?

3.5.1 A key concept to understand and characterize the farmer's experimentation process

In this study, we showed for the first time that the concept of experimental itinerary proposed by Catalogna (2018) is useful to characterize the long-term experimentation dynamic, which was up to now understudied by scholars. From our analysis of the experimenting dynamics of 16 vegetable and cereal farmers, organic or conventional, we found common ways by which experimental situations are organized over time, both in the short term (10 types of experimental situations) and in the long term (four patterns of experimentation). We initially assumed that experimentation could differ depending on it was on cereal or vegetable, organic or conventional systems. In our sample, even if some differences were observed between farmers, we could not relate them clearly with the sample characteristics. More generally, one wonder if such concept of experimental itinerary can be useful for other types of farmers, especially for livestock farmers, with a specific question: should the experimental itinerary be characterized at the herd, batch or individual level?

Agroecological systems are complex to design and manage, and therefore to learn (Altieri 2002). An original outcome of our study is that most farmers do not experiment with whole agroecological systems, but rather explore parts of them separately. Several ways to decompose and simplify the problems were identified: either farmers split the agroecological systems into sub-systems that they then test successively or simultaneously (e.g., grove or tree patterns), or they progressively optimize the technical modalities over years (e.g., linear pattern), or else they successively tackle different dimensions of the assessment problem (e.g., combination of Improvement experimental situations, focusing on the effects on pests, soil or yield, on the feasibility, and cost.). Such patterns of experimentation can be analyzed through the lens of deterministic and open-ended perspectives characterized by Navarrete et al. (2021): the deterministic perspective corresponds to the scientists' classical way to experiment where the experimental design is definitively planned in advance. On the contrary, the open-ended perspective is defined as "an iterative approach where both the goals and the means to reach them are intentionally adapted based on system observations and social exchanges". A combination between both perspectives was observed in our study. For example, for some farmers, the itinerary started in a very deterministic way by framing a cropping system to reach and splitting the technical problems into several unitary questions (grove pattern), each one leading to specific experiments. Other farmers adopted a more progressive experimentation process (linear and tree pattern) where one experiment was derived from the outcomes of one or several previous ones. In a context of developing agroecological farming systems, the open-ended perspective seems meaningful to adapt to uncertainty about ecological processes.

3.5.2 The experimental itinerary as a representation of long-term technical change on the farm

Our analytical framework was initially built to depict the experimentation dynamic, but at the end, it also enables to capture the on-farm technical changes over years. Indeed, even if it is not necessarily fully explicit in the farmer's mind, each annual experimental situation represents a potential change in farming practices. On the long term, the experimental itinerary traces the successive technical changes experimented, part of them being later adopted on the farm at larger scale. In our study, when an experimental itinerary ended, most of the time, it was because the practice was implemented at a larger scale in a more routine way, i.e., without close attention to observation and result checking. But our representation could suggest that experimentation comes to a sudden stop, whereas there is probably more a transitory period between experimentation and technical change, especially for agroecological systems. Because of uncertainty and unpredictable events, farmers constantly re-adjust their decision rules, which require a continuous learning process (Darnhofer et al. 2010). As farmers gradually gain greater confidence in the practice, they may implement it progressively on a larger number of plots and with fewer and fewer modifications, slowly resulting in a "fixed" practice. In line with that perspective, Kummer et al. (2012) consider that experimentation could therefore be a tool to build (or rebuild) farm resilience, especially in a context of technical, social, and economic change.

3.5.3 The experimental itinerary as a possible representation of farmers' learning process?

Although it is recognized that farmers' experiments are situated (Toffolini et al. 2018), we showed that they are not at all a collection of one-shot trials but rather anchored in the farmers' own research process. Each experimental situation offers new pieces of knowledge that the farmers remobilize for the following experimental situations. This process recalls Kolb's learning cycle (Kolb 1984) where the observation gained in one context (in our case, a former experimental situation) is analyzed and re-used to make hypothesis for the future action (in our case, the following experimental situation). This process enables to build, through experimentation, "knowledge useful for action" (Toffolini et al. 2018; Hansson, 2019). Catalogna (2018) considers that during that learning process, the degree of uncertainty (e.g., on the effects of an agroecological practice) progressively decreases along the experimental itinerary, which secures the farmer in the implementation of a technical change. In line with this vision, the development of a new experimental branch could indicate that the confidence in a practice previously tested has grown sufficiently so that it can later be applied on new parts of the system. That could explain why experimentation (as an implementation on limited time and space scales) lead to technical change (as a long-lasting and farm scale process) only progressively.

3.5.4 A heuristic representation to support farmers' ongoing process of experimentation

Although many farmers in the sample succeeded in learning through their own experimentation, some expressed difficulties in understanding why their experiments were successful or not. We assume that our analytical framework could help them to capitalize on the probable reasons for failure and/or to make parts of this tacit knowledge explicit. Therefore, it could prevent them from "being overwhelmed by the complexity of the experimentation process", a feeling expressed by some of the farmers surveyed. From that perspective, several tools could be derived from the representation of experimental itineraries. First of all, monitoring and recording the dynamics of experimentation over several years, as already promoted by extension services, could be more efficient for farmers if they keep track of each experimental situation and of the interrelations between successive ones and if they adapt data collection to the precise aims of each experiment. For example, relating the previous experiment to one of the 10 types of experiments could help them to summarize what they have already explored on a specific topic, what questions remain open and what they should experiment with in the following year. Are they trying a brand new practice? Are they optimizing the technical modalities of a practice already tested? Do they want to know if the practice is more efficient than their current practice? In other words, the experimental itinerary could be seen as a way to organize the known and unknown elements of agroecological systems. Second, recording the experimental itinerary could foster exchanges in groups of farmers, which are known to be very important in the transition towards agroecology (Darnhofer et al. 2010; Maertens and Barrett 2013). As for individual experimentation, characterizing where a farmer is on his/her own multi-annual experimental itinerary could help the group to exchange experiences more efficiently by explaining the farmer's aims, knowledge, past success, or failure of the practices experimented on his/her own situation. Farmer group facilitators seem to be a key element to start this work and could compensate for the fact that few farmers spend time recording their experiments on their own. Farmer group facilitators could both (i) support individual farmers' experimentation process and (ii) bring together the experiments that have been implemented in the farmer group, as in Farmer Field Schools (Van den Berg and Jiggins 2007). This would require meeting each farmer once a year to record their new experimental situations and help them to be reflexive on their experimental itineraries. Tracking farmers' experimental itineraries could then be brought to group meeting to share local knowledge and foster exchange (Maertens and Barrett 2013). Moreover, as agroecology is a science of local conditions, one difficulty is to avoid biases and confusing effects. The comparison among farmers of the performances of a practice could compensate for the frequent lack of repetition in farmers' experiments, and for difficulties to derive knowledge usable in other conditions (Hansson 2019). Toffolini et al. (2018) described agroecology through four interconnected ways of acting, one of them being a "critical and reflexive engagement in action towards learning". To favor it, the authors insisted on the necessity to build tools to support the sharing of experiences (among farmers, but also with advisors and scientists). We therefore consider that the representation of an experimental itinerary could be one of these tools.

Different formats could be imagined but still need to be investigated and experimented:

- A focus on a particular experimental itinerary. Why were some branches abandoned? What was decisive in the experimental itinerary to try out on a larger scale? What sort of observations (on plant, soil, biological agents, etc.) supported the outcomes? A collective reflexive discussion could help to improve the farmers' experimental skills whether it concerns the design of experimental situations, the decisions to take during an experimental itinerary or the capacity of observation.
- A synthesis on a frequent topic of experimentation. What do most farmers start with? What are the common failures? What would be the best practices nowadays? Comparing different experimental itineraries could inform discussion on whether or not it is worth for newly interested farmers to rapidly engaging in such practices, and under what conditions.
- A planning of shared experiments: Farmers who are experimenting on similar subjects could identify some of the best bet practices to experiment with next, and share information on different modalities with one another to deepen the assessment of the practice in different soils or climate conditions.

4 Conclusion

We proposed the new concept of a multiannual experimental itinerary and its decomposition in successive experimental situations as a representation of farmers' experimentation. We described the wide diversity of this experimentation through 10 types of experimental situations and 4 patterns of experimental itineraries. As future perspectives, we posit that such a representation could be a useful support for individual farmers but also groups of farmers, by helping them track their decisions and inform the research process. At a collective level, it could be put forward in European Innovation Partnerships on agriculture (EIP-AGRI) where "Operational Groups" composed of innovative actors share experiences to boost interactive innovation. We also wonder if the representation of an experimental itinerary initially built to describe farmers' activity could also be used for and by scientists, in particular when experimenting with agroecological farming systems in step-by-step processes. In these conditions, as scientists regularly plan and adapt the experimentation decision rules to improve different parts of their system, could our representation help them to record their decisions over the years as a sort of decision tree, and to root the new knowledge thus acquired? In other words, it would be a way to give importance to the scientists' learning process as well, and not only to the final results of a multi-annual experiment, which is today the only knowledge published in agronomic journals. More generally, providing tools to support farmers' and scientists' learning process through the various elements we suggest in this article would improve the connection between empirical and scientific knowledge, and thereby support the bottom-up approaches needed in agroecology. All these elements require further investigations.

Acknowledgements The authors thank all the farmers surveyed for their involvement that enabled us to study their experiments in detail. They also thank Liz Carey Libbrecht for the language editing of the English.

Authors' contributions Conceptualization and methodology, M.C., M.D.D., and M.N.; Resources and access to farmers, M.D.D., M.C.: Investigation, M.C.; Writing — original draft, M.C. and M.N.; Writing — review and editing, M.N

Funding This work was supported by the Drôme Department and the project COTRAE (Programme "Pour et Sur le Développement Régional Rhône-Alpes") funded by INRAE, Auvergne-Rhône-Alpes Region, IRSTEA, and EC FEADER (EIP AGRI).

Data Availability The datasets analyzed during the current study are available from the corresponding author on reasonable request. This excludes the raw documents from interviews, which contain personal information on the participants.

Declarations

Conflict of Interests The authors declare that they have no conflict of interests.

Ethics approval All research procedures involving human participants were in accordance with research ethical standards at the date of the study.

Consent to participate Verbal informed consent was obtained from all individual participants included in the study. Moreover, the study has no clinical trial.

Consent for publication Verbal informed consent was obtained from all individual participants for publication of the results.

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