Intertwining deterministic and openended perspectives in the experimentation of agroecological production systems: A challenge for agronomy researchers

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1. Introduction

For decades, change in agriculture has stemmed primarily from the development of technical innovations such as new cultivars, machinery, and synthetic inputs. During this "modernization" phase, researchers and technical advisors assumed that farmers would adopt new techniques and knowledge that they had developed and disseminated. This top-down linear process was criticized extensively (Klerkx and Leeuwis, 2008; Duru et al., 2015) and was gradually enriched through the involvement of farmers in the innovation process (Salembier et al., 2018). With expanding interest in agroecology, the ways in which knowledge and innovations are generated are now receiving close attention, as recognition increases with respect to the numerous and complex interactions between the components of farming systems, between groups of living organisms, and between short- and long-term dynamics. Our base of scientific knowledge remains insufficient to understand the consequences of these complex interactions and dynamics on agroecological systems and to develop predictive models to help farmers manage their farming systems in an agroecological way. In particular, the intensity and speed at which natural regulations may occur are not fully predictable. For example, will the sowing of a particular pest-trap crop be sufficient to control the pest all along its development and provide a satisfying production? Moreover, agroecological knowledge is context specific, that is, the performance of a particular practice heavily depends on the local

ecological conditions in which it is applied. Grounding farming system approaches on ecosystem services that are supported by ecological processes and biodiversity requires profound redesign rather than simple adaptation. Duru et al. (2015) refer to this alternative path forward as the "strong ecological modernization of agriculture," which focuses more attention to farmers' learning and on-farm innovation processes in order to overcome problems related to uncertain and situated ecological processes (Doré et al., 2011; Prost et al., 2016).

On-farm experimentation, where farmers create a specific situation to be observed in their own farming context, is an important way to generate practical knowledge and favor technical change (Leitgeb et al., 2014). On-farm experimentation is also a way to address the uncertainty and complexity associated with biodiversity-based agriculture (Duru et al., 2015). In science, experimentation has been a foundational way to produce knowledge, especially in agronomy where it has enabled the identification of generic laws regarding field and crop functions, and hence the optimization of techniques and the prediction of their effects (Maat and Glover, 2007). These authors note that "experimentation plays a crucial role in connecting the academic discipline of agronomy with agricultural practice" (p.132). As agronomic topics and methods are questioned by the agroecological transition, re-opening the debate on best practices for impactful experimentation is a timely discussion. In addition to the predefined classical agronomic experiments which were designed to produce generic knowledge under controlled conditions, alternative experimental approaches have emerged, which occur in an open framework to support both researchers' and farmers' learning processes (Cardona et al., 2018). In this chapter, we analyzed several experimentation processes of agroecological systems, through the lens of deterministic and open-ended perspectives. It gave a fresh look at our role as researchers in agronomy involved in experimentation and engaged us *a posteriori* in a self-reflection process, with the help of a sociologist. First, based on a literature analysis, we delve deeper into the exploration of how experimentation is questioned by agroecology and draw two broad conceptions of deterministic and open-ended perspectives in experimentation (Section 2). We then present the empirical material, coming from four French case studies on experimentation falling within both deterministic and open-ended perspectives (Section 3). We describe different ways by which the two perspectives complement each other (Section 4), and we finally discuss the interests and limits of such a combination (Section 5).

2. Reconsidering experimentation on farming systems with agroecology

For a long time, agronomic experimentation[1] only consisted in testing hypotheses based on the current scientific knowledge and established causal links between actions and effects. The experimental layouts consisted in creating controlled environments (in laboratories or fields) to compare experimental treatments (Maat and Glover, 2007), which were then analyzed with a highly formalized protocol. For example, in factorial experiments, which are emblematic of that period, the biophysical environment is split into a limited number of factors, highly controlled to avoid potential interactions with factors considered as minor, and unstudied. Almost all decisions are set prior to the implementation of the experiment to fit to statistical requirements (location of the treatments, experimental protocols). The behavior of the experimental system is assumed to be representative of real farming situations, so that recommendations usable by farmers in a large range of conditions can be defined. Outside of this monolithic definition of acceptable experimentation, new experimental approaches progressively emerged with the need to address systemic issues, particularly in France at the end of the 20th century. These new approaches realized on-farm or on-station involve stakeholders in the experimental decisions and provide opportunities for knowledge-generation through improvement feedback loops rather than predetermined protocols. Two types of experimentation deserve special attention because they offer strong potential for reconciling agronomic experimentation with the challenges of agroecology: system experiments and farmers' experiments. **A system experiment** consists of designing and implementing what is hypothesized to be the optimal set of crop sequence and technical management to reach certain predetermined goals (e.g., agronomic, environmental and economic goals), in order to assess their performance within a given context (Debaeke et al., 2009; Meynard et al., 2012). Such experimented systems are not necessarily fixed throughout time, but can be adapted over years according to biotic, abiotic and social contexts, to the development of new knowledge or techniques, or to day-to-day management (Lechenet et al., 2017). System

[1] In this chapter, the term "experimentation" refers to the whole process of experimenting including its social and financial dimensions, whereas "experiment" refers to the practical layout.

experiments are thus a major breakthrough in approach as compared to the classical factorial perspective where framework and modalities are predetermined and a complex system is broken down into smaller units to be experimented. The second type is the **experiments carried out by farmers** to identify efficient cropping practices to implement on their own farms (Johnson, 1972; Saad, 2002). While farmers' experiments have existed from the onset of agriculture, renewed interest has emerged with the perspective of agroecology, as it provides farmers with tools to adapt their systems to uncertainty and to build situated knowledge (Navarrete et al., 2018).

From the perspective of agroecology, optimizing ecological processes in crop management is complicated by the lack of scientific knowledge, the close dependence of such processes on site-specific environment, and the numerous interactions of biological, chemical, and physical factors with cropping practices. All these elements result in a high level of variability on dynamics overall, which impedes any reliable prediction. We therefore consider as irrelevant the application of rigid experimental protocols only. A more relevant approach would be to define general objectives as support for decision making, and to modify decisions along the way based on on-going observations of the system. Additionally, to increase the relevancy and utility of data generated from experiments, we advocate that such day-to-day management of the experimented cropping systems should be considered as a rich contribution to experimenters' learning. And finally, we consider that experimentation could broaden learning through social interaction between scientific and non-scientific actors, professional and non-professional experimenters.

In line with the main theme of the book, we analyze agroecological experimentation through the lens of deterministic and open-ended perspectives. Agronomic experimentation carries in itself a vision of a technical change that can be steered by humans, from an existing biophysical system (often considered as a reference) to a new and improved one which is expected to better reach the specified aims. Experimentation thus consists in three main activities: imagining the new system, implementing it practically, and observing its properties to check to which degree it satisfies the aims. With agroecology, we pay specific attention to the question of predictability of the systems to experiment and the degree to which experimental decisions can be planned in advance. As an initial approach, we consider that the deterministic perspective refers to experiments where most elements (goals, objectives, type of knowledge

to build, hypotheses to test, assessment criteria, data collected, etc.) are fully stabilized from the outset. By contrast, an open-ended perspective requires an iterative approach where both the goals and the means to reach them are intentionally adapted based on system observations and social exchanges. The overall strategic implementation of practices is gradually refined on the basis of ecological and social dynamics even if different from the practices thought out before the experiment. One might imagine that the experiments undertaken by researchers would belong essentially to the deterministic perspective, whereas farmers, who are not expected to scientifically validate their results to the same degree, would adopt a more open-ended perspective for experimentation. In this chapter, we show that experiments on agroecological systems largely transcend this rough categorization. **More precisely, we assume that deterministic and open-ended perspectives coexist in experimentation and that such coexistence is linked to the specificities of agroecological systems.** Therefore, such a proposal carries along with it the need for a paradigm shift in knowledge production for agronomy**.**

3. Methods

We cross-analyzed four case studies (CS) of experimentations located in France (Tab. 1). The four experimentations have been developed with a participatory approach of agroecological transition, valuing singular and local knowledge of farmers coming from practical experience (Berthet et al., 2016). In all the CS, experimentation was the place for a specific dialogue organized between farmers and researchers.

The first two CS describe multi-annual system experiments implemented at research stations and dedicated to the design of agroecological farming systems in a step-by-step process. The two cases enabled the analysis of why and how an open-ended perspective was embedded in an initially deterministic one, and which specific elements of the experiments were impacted. Step-by-step design system experimentation (Coquil et al., 2014) emerged recently as a new twist of system experimentation, where researchers, technical advisors and farmers share their knowledge to manage and analyze the cropping system, and progressively adapt it to fit uncertainty (e.g., unacceptable development of a pest, lack of efficiency of a technique, etc.), in a learning-by-doing approach (Meynard et al., 2012; Navarrete et al., 2017). In the two CS, the experiments were carried out at INRAE experimental stations. The

first CS, conducted at Gotheron station, dealt with apple orchards using two different approaches: (a) the BioREco, a pioneering system experiment on fruit, assessed 9 planned cropping strategies combining 3 types of crop management (conventional, low-input, organic) and 3 apple cultivars differing in disease susceptibility (Simon et al., 2011; Alaphilippe et al., 2013); and (b) the agroecological Zero pesticide orchard project (in short, the Z project) aimed at redesigning and assessing a pest suppressive fruit production area by strongly reinforcing ecosystem services. The second CS, 4SYSLEG, at the experimental station of Alénya, focused on the evaluation of 4 vegetable cropping systems designed to avoid or greatly reduce synthetic pesticides while meeting the standards of a specific food value chain (organic production or conventional, long supply chain or local direct sale) (Lefèvre et al., 2015; Perrin and Lefèvre, 2019).

These first two system experiments, which had been conducted by researchers even if farmers were involved, were compared to **two additional CS where the experiments were conducted by or with farmers.** The goal was to determine if the strong involvement of non-professional experimenters led to a more open-ended way of experimenting. In the CS on farmers' experimentation in the Drôme *département*, we analyzed the experiments initiated by 17 individual farmers over the past ten years. They dealt with no-till, cover-cropping or conservation agriculture on arable crops, and the enhancement of natural enemies of pests or biocontrol practices on vegetable crops. The short and long-term experimentation processes previously characterized (Catalogna, 2018; Catalogna et al., 2018) were re-analyzed here according to the deterministic or open-ended perspectives. The last CS consists of on-farm multi-annual system experiments closely associating farmers and researchers on 4 arable farms through the SOIL network in the Isère *département*. The experiments had two aims: to test and assess some indicators on the biological status of soils that had previously been developed by the researchers, and to describe how soil health evolved over the years with conservation agriculture practices (Boidron, 2018).

The present analysis was based on a reflexive and retrospective review of how the experimentations on the 4 CS were carried out. We looked at how the experimental layouts and their on-going management were decided, implemented, and adapted in the course of the projects, and what the reasons were for stabilizing some decisions or conversely making them evolve. After detecting situations falling within the scope of open-ended and deterministic perspectives, we established whether each

perspective was devoted to one specific phase in the experimentation process, to one specific type of stakeholder, and to specific elements of the experimental layout. Then we analyzed the coexistence between the two perspectives. How concretely do open-ended and deterministic perspectives articulate to one another? Do they fall within complementarity or competition? Do they sometimes lead to inconsistent decisions in experiments?

4. A large diversity in the way deterministic and open-ended perspectives coexist in experimentation

4.1. From a deterministic experimentation to a combination of the two perspectives

The system experiment on apple orchards in the BioREco project was initially built by researchers in agronomy and entomology with a deterministic perspective (Fig. 1a), even though farmers and extension agents were involved during some aspects of project development and implementation. The researchers formalized objectives, constraints (on soil, climate, field surface, machinery and labor availability), economic context (sales channel targeted), the experimental layout, agroecological practices and a specific set of decision rules for each experimented cropping system. The initial experimental layout was designed to compare the 9 experimental treatments over time, with a scientific approach even if there were no replicates as in factorial experiments. This type of framework, set from the outset, was very useful for managing the experiments and evaluating the systems. However, 8 years after planting, the management of the conventional systems was changed to include new knowledge learned and exchanges with stakeholders (Fig. 1a). For example, the conventional systems accounted for the farmers' most common practices in the area as basis for systems comparisons. Updates to those systems were implemented in 2013 as some new practices, such as mating disruption, had largely been adopted by the local farmers and became standard practice. Hence, from that year onwards, the experiment became more open-ended to tackle farmers' expectations, include recent innovations and improved practices (e.g., organic fertilization practices were adopted in low-input systems to limit environmental impacts). However, despite such flexibility, the experimented cropping systems based on monoclonal high-density orchards still failed to drastically decrease pesticide

Tab. 1: Short description of the four case studies.

Case study	Step-by-step design system experiments in research station		On-farm experiments	
	From BioREco to Z project (2004–ongoing)	4SYSLEG project (2012–2018)	On-farm experiments by individual farmers (2016–2018)	Joint experiments between researchers and a farmer network in SOIL network (2015-ongoing)
Location	Drôme, INRAE Experimental Station of Gotheron	Pyrénées-Orientales, INRAE Experimental station of Alénya	Drôme	Isère
Socio-economic context	Experiments funded by the French Ecophyto program searching for robust cropping systems using 50% fewer pesticides than historical available references		Farmers interested in developing agroecological practices on their farm	Project funded by Fondation de France
Agroecological issue	Reduce (BioREco) or withdraw (Z project) pesticide use on apple orchard	Reduce or withdraw pesticide use on vegetable sheltered crops	Develop agroecological practices on arable (A) and vegetable (V) crops	Increase soil biological fertility on arable cropping systems
Agroecological practices experimented	BioReco: resistant cultivars, biocontrol, agronomic practices Z: natural and cropped biodiversity, plant spatial arrangement, sanitation	Spatial and temporal crop diversification, natural regulations	A: Conservation agriculture, cover crops V: Biocontrol, reduction of soil tillage	Conservation agriculture, cover crops, crop diversification
Experimental layout	BioREco: 9 cropping systems Z: 1 agroecosystem No replicate Pluriannual data collection	4 cropping systems No replicate Pluriannual data collection	1–19 annual experiments per farmer, between 2003 and 2017 No replicate	4 cropping systems on 4 farms No replicate Pluriannual data collection

use. The following Z Project orchard was consequently completely redesigned. In this multi-actor project, there was no preconception about spatial design or management practices; experimental goals were to control pests through the promotion of ecological processes, without any chemical pesticide. Agronomic and economic performances to target remained open and determined as the project progressed. Conversely, some features of the orchard needed to be formalized before putting the experimental prototype into practice (e.g., orchard shape, cultivar choice). Moreover, researchers felt the need to formalize practical guidelines to steer how to reinforce targeted ecosystem services through practices. They were used not only to manage the experimental layout in a learning-by-doing approach, but also for generic purposes and to share the approach beyond the project partners.

4.2. A planned coexistence between deterministic and open-ended perspectives to tackle uncertainty

In the 4SYSLEG project at INRAE Alénya experimental station, a system experiment was implemented on vegetables. During the 6 years of the project, researchers in agronomy assumed that both strategic planning and tactical adaptation would be alternatively or simultaneously useful, not only to design the four agroecological crop management strategies, but also to implement them in field plots, and to continuously assess and improve them. At the initial stages of project development, a deterministic perspective was adopted to meet the criteria of the Ecophyto call for proposals in 2012 (Fig. 1b), which aimed to specify clear and operational sets of objectives for the crop protection strategies. Thus, quality specifications from marketing chains were translated into a range of priority functions that the cropping systems experimented were expected to fulfil, with the help of invited farmers and extension agents. Experimenters expressed these functions as practical agronomic management at strategic and tactical levels and for each cropping system. On the strategic level, for the low-pesticide cropping system devoted to the direct sale market, it was expected to produce moderate volumes of vegetables but with a wide assortment of vegetables throughout the year. As minor damage to the vegetables is accepted for direct sale, it was decided to continuously enhance natural regulation of pests and diseases, using synthetic pesticides as little as possible and to spend as little time as possible on crop protection. Thus, cropping high levels of spatio-temporal

plant diversity, prohibiting deep tillage and soil solarization were identified as key agroecological strategic practices. To bear initially determined sets of objectives in mind for 6 years in each of the four experimental systems, the experimenters summarized each overall strategy into a short slogan (e.g., "Natural balances work with me" for the low-pesticide direct sale system). It framed their decisions and choices, and in particular tactical decisions to sustain natural regulation mechanisms.

As knowledge and innovative solutions for agroecological crop protection were dispersed among many stakeholders, the 4SYSLEG experimenters organized an open-ended approach to fill knowledge gaps with farmers and technical advisers (Fig. 1b). At the onset of the experiment, researchers listed the main damaging pests and diseases feared for each crop or intercrop in order to anticipate practical solutions. They also adopted an adaptive stance for unexpected situations (e.g., new available biocontrol tool, unexpected sanitary or climatic conditions). Thus, even though the main framing of the agroecological crop management strategies was planned in the first stages of the project in a deterministic way, they regularly mobilized farmers and extension agents' expertise during collective workshops to address specific questions, for example, when initially planned objectives could not be met as expected. For example, aligning practices with the slogan "Natural balances work with me" proved difficult for some pest susceptible crops, and a trade-off had to be found between antagonist goals: after a few months, the experimenters removed the requirement to reduce time spent on pest control and, contrary to the tactical choices initially chosen, they applied natural plant defense stimulators and released natural enemies as preventive actions to limit the potential yield losses.

4.3. A coexistence of open-ended and deterministic perspectives on both the short-term and the long-term time scales

Farmers' experiments in Drôme Departement were described along two temporal elements: annual experiments (on a given plot and in a given year) and long-term experimental sequence (Catalogna, 2018; Catalogna et al., 2018). Both combine deterministic and open-ended perspectives.

As regards annual experiments, some can be related to a deterministic perspective. For example, "comparison" experiments consist in

identifying which is the best cropping strategy among several. Several cropping strategies are implemented side by side on the same plot to compare them with one another or with the farmer's current practice. Here, farmers had specified goals to reach, they planned in advance the experimental layout to allow for comparisons and the mandatory information to gather. By contrast, other types of experiments adopt an open-ended way of experimentation, where only part of the experimental layout is decided before the onset. This is the case in "breakthrough" experiments, when the farmers broaden their inquiry on an ecological process and try it out to evaluate possible consequences on their system. For example, one farmer experimented for the first time with leaving chards to flower to breed ladybugs, wondering if they could then move into the next tomato crop and act as natural enemies of tomato pests. To check the proof of concept of this practice, he had no preconceived ideas but was open to any new information or observation that could occur during the experiment. This process rather refers to Lyon's (1996) definition of "learning during action" and Millar's (1994) definition of "adaptive experiments," while "comparison" experiments refer to more formal experiments realized by researchers to test a hypothesis (Maat and Glover, 2007; Leitgeb et al., 2014).

In the long run, most farmers' experimental sequences evolved over time from an open-ended to a more deterministic perspective (Fig. 1c, Farmer 1). They often started with an open-ended "breakthrough" experiment, to discover whether an ecological process could be activated on the farm. When promising, they would run several "improvement" experiments with little change at a time to optimize the desired ecological processes in an iterative learning loop, a process sometimes called "trial-and-error" (Lyon, 1996). Finally, they would implement a formal "comparison" experiment in which the performance of the new cropping strategies was more precisely quantified and compared to current practices, which enabled them to gain more confidence or convince peers of the interest of the practice (Lyon, 1996). But some farmers had an experimental sequence that was quite the opposite: they started in a very deterministic and reductionist approach by framing a cropping system to reach, then they split the technical problems into several singular questions. For example, a farmer experimenting conservation agriculture assumed he had to simultaneously explore three topics: direct seeding, intercropping and introduction of cover crops. Each topic was

experimented on a separate field with an open-ended perspective to learn by doing (Fig. 1c, Farmer 2).

In this case study, the focus was on the individual experimental and learning processes, although farmers often exchange knowledge with peers and other stakeholders. That collective process was particularly observed in the following case study.

4.4. A combination of deterministic and open-ended perspectives relating to a separation of roles between farmers and researchers

The SOIL network, which involved both researchers and farmers, aimed to co-design and experiment with on-farm cropping systems to promote soil life. Four groups of farmers were created to address the issue in different conditions (farms devoted to grain production, to seed production, combining crops and animal husbandry, or with a specific light soil). In each group, researchers in agronomy and soil science facilitated the process to collectively design a new cropping system capable of reaching a number of prioritized objectives. For example, the "grain" group set 4 objectives for the prototype to test: direct seeding for crops and intercrops, improved soil fertility, pesticide reduction, and yield improvements. Key performance indicators associated with a satisfactory threshold and decision rules for the technical management were collectively defined. The cropping system built by the group was tested by a pilot farmer and compared to a control treatment (i.e. his current practices). This phase led to set a framework (Fig. 1d) in a deterministic way to ensure that the experiments would address a key question for each pilot farmer, and that researchers would obtain data pertinent to their research questions. Once the main decisions were framed, the day-to-day crop management was fully delegated to pilot farmers: The researchers sought to test their indicators in real cropping conditions, and held the conviction that the farmers were experts capable of managing crops in the most appropriate way from their farming context. They agreed that cropping decisions could be adapted from the decision rules initially set, as long as the deviation between what was collectively planned and what was realized by the pilot farmer could be documented. The research team took charge of the monitoring of the experiment as planned initially, not only with performance indicators co-defined with farmers but also indicators to advance scientific understanding on soil biological quality.

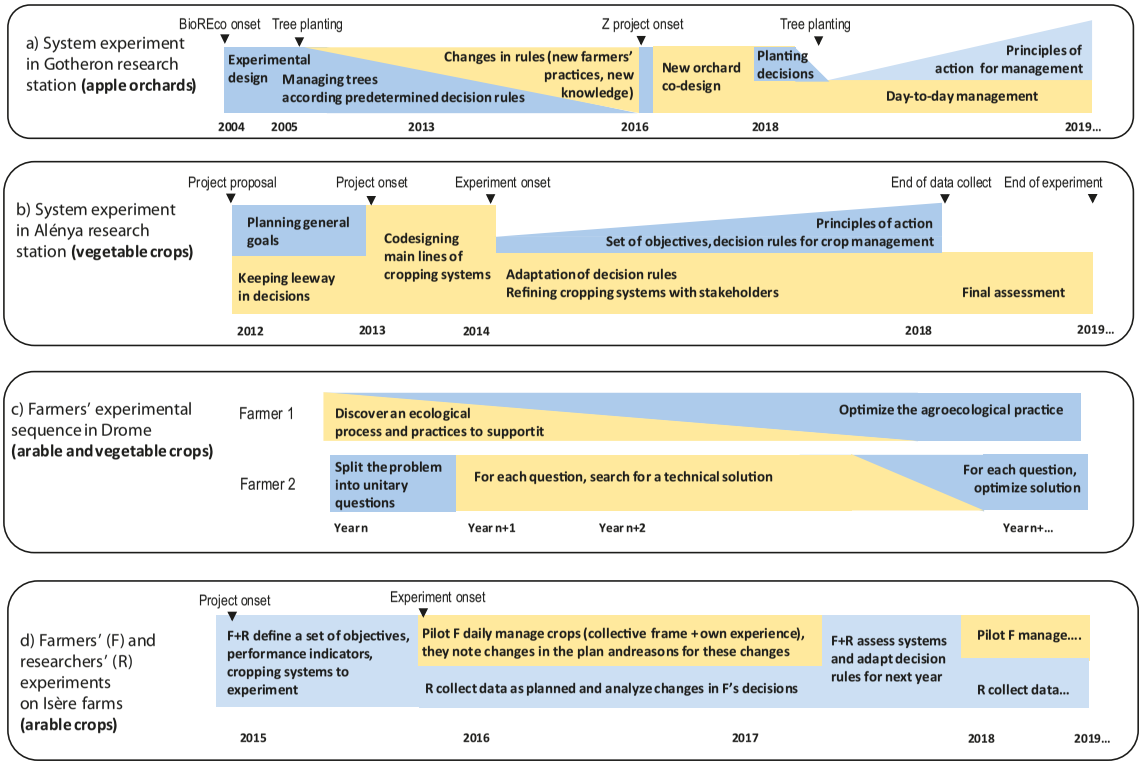

Fig. 1: Coexistence of deterministic (in blue) and open-ended (in yellow) perspectives along the experiments in the four case studies.

Such joint experiments can be related to those described by Lyon (1996) where agronomists follow up farmers' experimentation with their own formal protocols, to produce more generic knowledge. Experiments in this CS, as the three others, associated deterministic and open-ended perspectives, but here with a clear separation between researchers' and farmers' scope of decisions, and a coordination between them during collective workshops.

5. Discussion

The main finding from the cross-case analysis is that the evolving coexistence between open-ended and deterministic perspectives enables managing and learning in agroecological experimentation. After considering the different forms of such coexistence and the reasons for them (5.1), we describe some of their limits (5.2), and argue for working towards a more effective intertwining to support a large-scale agroecological transition (5.3).

5.1. Various forms of coexistence according the types of decision and over time

The challenge is to make two types of decisions interact in agroecological experiments: (i) goals to reach, means and assessment methods; and (ii) day-to-day crop management and monitoring.

With respect to goals and means for the experiments, in some CS, current available knowledge was used to draw hypotheses prior to the implementation of the experiment (as in factorial experiments) and to determine theoretical cropping systems that would be most likely to reach the desired goals (e.g., in BioREco). But in most CS that we evaluated, the experiments were not strictly framed from the beginning (4SYSLEG project, Z project), and were progressively refined during the project. The reasons were that, for a very disruptive innovation, the targets to reach could not be planned entirely; this was a major reason for allowing the open-ended and deterministic perspectives to coexist.

Three patterns of coexistence were identified in the long-term dynamics: a strict succession of the two perspectives, a progressive replacement of one perspective by the other, or the development over time of the two perspectives in parallel. The three patterns could even be present in

a same project. The Gotheron CS offers an interesting example of the succession pattern, in which the same researchers adopted two opposite perspectives over 15 years: a closely framed experiment (BioREco) was later reopened to keep up with changes in commercial orchards. It was followed by the Z project, where they adopted a very open approach until trees were planted, which restrained leeway on the following crop management decisions. For some farmers in the Drôme CS, the two perspectives coexisted at the same time, with one increasing while the other one decreased (Farmer 1). And in SOIL CS, both perspectives were maintained in parallel all along the project, because each was embodied by one specific actor: researchers sought to adopt their logic of a "farm laboratory" and set minimum requirements for the experiments. But they allowed the farmers to decide on the most realistic crop management possible in an open perspective. Nevertheless, it would be a stereotype to consider that farmers would systematically experiment in a more open-ended way than researchers: Farmer 2's deterministic experiments and the scientific open-ended Z project combat this very notion.

As regards crop management decisions, for all CS, all management decisions that can reasonably be determined with a degree of confidence are implemented, but flexibility is maintained for other decisions, to adapt to climate, soil and plant conditions and to farmers' preferences in some cases. Our results highlight how experimenters embrace the issue of uncertainty on agroecological systems, either it comes from current gaps in the state of the art on agroecological regulations, from dynamics of living organisms or from farm constraints. Experimenters at research stations framed the decision process with decision rules or practical guidelines (4SYSLEG, BioREco) or monitored why changes occurred (SOIL project). Such a combination of a predetermined framework alongside flexibility can be related to adaptive management (Foxon et al., 2009). In this paradigm, "managers acknowledge the limits to predictability […] and recognize that knowledge about social and ecological systems is both uncertain and pluralistic."

5.2. Limits to coexistence

We now discuss whether the coexistence of deterministic and open-ended perspectives could impede experimentation projects, interactions with stakeholders, and processes of knowledge building and dissemination.

In the two CS on research stations, complying with funders specifications partly forced the experimenters into a deterministic position. The public funders wanted to know, before awarding funding, the exact level of pesticide reduction and the technical means that would be engaged to achieve that goal. It was necessary to convince them of the interest of the open-ended perspective for a part of the experimental decisions.

The combination of open-ended and deterministic perspectives seemed to facilitate interactions with non-professional experimenters. At the beginning of the Z project, the design of the experimental cropping systems with agricultural stakeholders enabled brainstorming on a wide range of new ideas to build an orchard based on natural regulations and biodiversity. This participatory process within a research station was called "semi-confined experimentation" by Cardona et al. (2018), to highlight the idea that such open processes permit and value the contribution of agricultural stakeholders in the design of agroecological systems while maintaining a scientific basis of experimentation. The experiments in the SOIL project could also be related to semi-confined experimentation, with the particularity that there was here a clear separation of roles and responsibilities between researchers and farmers in the process.

Professional experimenters in 4SYSLEG and BioREco/Z projects considered it would be impossible (or at least very difficult) to learn from a constantly evolving situation. They needed a deterministic phase to frame the system depending on scientific hypotheses. Later, when some decisions were re-explored, it was critical for them to be completely aware of what phase they were in, and of the fixed specifications with which they had comply and those that could be changed. Besides, Catalogna (2018) observed situations where farmers failed to establish adequate stability over time in experimentation, and thus were consequently lost in their experimentation process and unable to learn from it.

Another difficulty relates to the dissemination of results due to open-ended processes. Researchers experimenting step-by-step designed systems had difficulties in relating the experimental protocol and the outcomes to an external audience, in both the scientific and the agricultural spheres, because of the open-ended phases. Stakeholders visiting experimental stations expected so-called "hard science based on rigorous protocols" and were surprised by experiments on evolving systems. One reason is that they are often unaware of the fact that such experiments rely on rigorous decision processes as well. This difficulty led researchers

to explore in greater depth the question of decision traceability: Which experimenting decisions were taken initially? Which ones had to be changed to progressively improve the system and why? Some tools were designed to trace such decisions: a computerized table sheet in the 4SYS-LEG project, detailed reports and decision fishbones in the Z project (Penvern *et al*., 2018). On-farm, the analytical framework proposed by Catalogna (2018) could help farmers to trace *ex post* the successive experiments on a timeline and the reasons for their sequencing. But extensive research is still required to build methods to fully synthesize decisions on open-ended experiments.

5.3. From a dual vision towards intertwining various experiments embedding open-ended and deterministic perspectives

We consider that the position of a particular experiment according to deterministic and open-ended perspectives results not only from diversity in the visions of transition to agroecology, but also from the type of question under study (e.g., more or less systemic) and the position according to knowledge (e.g., stabilizing knowledge on a specific question or exploring new ones). A major outcome of our study is a deeper characterization of each experimenting phase. An open-ended vision of agroecology supports the idea that uncertainty and unpredictability are inherent to agroecological systems; it emphasizes improvement loops, multi-actor exchanges, learning from ecological processes and stakeholders' points of view (Altieri, 2002; Francis, 2003; Cristofari et al., 2018). For experimentation, it corresponds to explorative periods where new learning occurs in relation to real-time ecosystem reactions and stakeholder exchanges. Nevertheless, an open-ended vision of the agroecological transition does not completely discredit deterministic experimentation. Experimenting in a deterministic way matches a vision of agroecology where the system to manage is considered as complex but predictable, and where the available knowledge is sufficient to predict the probable effects in advance, therefore where the biophysical system can be steered by humans. For experimentation, a deterministic phase corresponds to a willingness to control a certain number of parameters in order to make a proof, settle controversies and hence stabilize certain knowledge. This was particularly visible when experimentation was

steered by researchers, who regularly closed some avenues of exploration and deepened others.

Far from viewing the different ways of experimenting in opposition to one another, we argue for enabling a tight and explicit intertwining between them. In the previous case studies, the combination of both perspectives rather came along the way – by default – as problems emerged or socio-technical context evolved. It is now necessary to conceptualize the intertwining between both, based on agronomy and agroecology theories and convince other scientific or non-scientific actors of its interest. The challenge is to make more explicit the scientific reasoning of what sort of experiments to implement depending whether the aim is to stabilize existing knowledge or explore new avenues, to learn new knowledge, disseminate the acquired one, or confront different knowledge. The challenge for agronomy researchers is also operational, to help all experimenters, whoever they are, to better clarify why, how and when they combine the two perspectives, and to invent tools to favor such exploration, in particular to trace decision making, to collect relevant data and to assess the performance of the systems. A significant issue for the future of agroecological experimentation consists in our capacity to gather and analyze multi-local and multi-actor data to support a large-scale agroecological transition. It is mandatory to build tools with advisory services to support knowledge exchanges among groups of farmers and favor learning. It is also mandatory to build alternative statistical methods, capable to take advantage of the rich but heterogeneous qualitative assessment from stakeholders.

6. Conclusion

This chapter proposed a cross-case analysis of four experimentation projects differing in several respects: the experimental sites (on farm or research station); the actors and their degree of involvement; the objects under study; and the intensity with which ecological processes were mobilized. We demonstrated that the combinations between deterministic and open-ended experimentations varied, between the actors involved, the periods of the projects, and the decisions made. The coexistence of the two perspectives appeared as an operational way to address the issue of uncertainty on the ecological process and could renew experimental methods. Despite prominent technical aspects in agronomy, the present analysis also highlights social change involved in the agroecological

transition where knowledge and experiences are shared between scientific and non-scientific experts. Agronomy could be enriched by acknowledging a range of intertwining experimental approaches, both from a scientific perspective and from an action perspective, to accompany farmers in the agroecological transition.

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