Social–ecological experiments to foster agroecological transition

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Abstract
1. A paradigm shift is needed to make agriculture sustainable, and various substitutes for intensive agriculture have been proposed. However, moving from theory to practice, in the context of climate change, natural resource depletion and worldwide economic and social disorder requires a novel approach that goes beyond the confines of ‘normal’ scientific practice, to (a) consider ecological and socioeconomic processes within the agricultural socio-ecosystem and (b) involving stakeholders in the research process.

2. We propose an innovative experimental approach for identifying management practices that optimize multiple objectives, deliver a portfolio of ecosystem services and satisfy the social demands of key stakeholders while improving the socio-economic welfare of farmers. Social–ecological experiments are undertaken in real-field conditions, involving stakeholders explicitly, all along the experimental pathway, to help untangle the drivers of social–ecological dynamics under various practices of land management and farming. As an example, we describe a social–ecological experiment to reduce the intensity of weed control.

3. These ‘social–ecological experiments’ go further, to participatory action research by not only involving stakeholders in the research process but also by manipulating simultaneously socioeconomic and ecological processes under real-field conditions to foster agroecological transition. Such experiments are distinct from adaptive management, participatory agricultural research and scenario-planning approaches as they highlight the interactions between ecological and social processes, manipulate the processes shaping the system and show causal links between patterns and processes.

4. Social–ecological experiments offer great opportunities for increasing stakeholders’ acceptance of environmental policies or sustainable agriculture programmes implemented through adaptive management. These experiments may help to identify management practices that deliver a portfolio of ecosystem services and satisfy key stakeholders.

Keywords
agroecology, biodiversity, ecosystem services, post-normal science, social–ecological systems, stakeholders, sustainability, transformation
One of the main societal challenges for the coming decades is to meet the food requirements of a growing world population without further sacrificing the integrity of local landscapes and the global environment (Díaz et al., 2019; Godfray et al., 2010; Phalan, Balmford, Green, & Scharlemann, 2011) or increasing social inequalities (Pretty & Bharucha, 2014). Sustainable agricultural systems rely on multifunctional landscapes as well as transforming the intensive agriculture system; both will require technological and institutional innovation (Berthet et al., 2019; Tittonell, 2014), which may be made difficult by the pressures arising from climate change, finite resources and economic volatility. Most alternative approaches to current agricultural models (e.g. organic farming, eco-agriculture, agro-ecology or ecological intensification) are based on ecosystem services, assuming that ecological regulation processes can replace some or all chemical inputs (Bommarco, Kleijn, & Potts, 2013; Garnett et al., 2013). Such a new paradigm has stimulated the framing of several conceptual frameworks (Dendoncker et al., 2018; Gaba, Fried, Kazakou, Chauvel, & Navas, 2014; Therond, Duru, Roger-Estrade, & Richard, 2017) and theoretical propositions (Altieri, 1983; Gliessman, 2016; Tittonell, 2014; Wezel et al., 2009). Although these provide key information and guidelines to determine the best pathways towards agroecological transition, they do not offer operational solutions for food security (Loos et al., 2014), limiting their use by decision-makers (Pywell et al., 2015). A key challenge is moving from top-down, global analyses to local and farmer-centred approaches (Altieri, 2004; Loos et al., 2014; MacMillan & Benton, 2014), that is, translating concepts into practical strategies for natural resource management.

Agroecosystems are socio-ecological systems (SES; Fischer et al., 2017) whose social and ecological dynamics involve multiple interactions between continuously changing human and natural components with feedbacks and cross-scale interactions (Redman & Kinzig, 2003). Ecological and social processes, however, often act at different spatial scales, resulting in scale mismatches (Cumming, Cumming, & Redman, 2006). Field or farm scales, at which farmers make management decisions, are rarely biologically meaningful. On the other hand, market access and the local organization of the economy influence the landscape together with land use, creating complex spatio-temporal mosaics of habitats that affect broader-scale processes such as the nitrogen cycle or water regulation. Human actions, through farming practices and landscape management, are thus significant drivers of ecosystem dynamics. They create new systems in which external inputs and mechanical interventions improve (e.g. by soil enrichment and irrigation) or replace (e.g. by pesticide use) ecological processes, while land use changes disturb the natural flows of biodiversity and matter. These human actions are diverse, as no two farmers cultivate their fields in exactly the same way (Gaba, Gabriel, Chadeœuf, Bonneu, & Bretagnolle, 2016; Lechenet et al., 2014): this results in a wide range of management strategies that may interact differently with ecological processes.

Given the multiple scales, the diversity of stakeholders and the many different interactions between social and ecological processes, the dynamics of agricultural SES are highly uncertain and complex. Global change and human use of agricultural SES are creating novel socio-ecological conditions and associated problems, such as food quality, water quality or health, that are difficult to understand and tackle. Solving these wicked problems, with complex causes and consequences, calls for a new approach in research, shifting from positivist, mono-disciplinary, local-scale approaches to adaptive, participatory and transdisciplinary landscape-scale strategies (Angelstam et al., 2013, 2018). This new way of performing research allows various and diverging viewpoints to be accounted for, through (a) the explicit involvement of decision-makers and stakeholders in knowledge co-construction and problem-solving (Funtowicz & Ravetz, 1994), and (b) effective cooperation between science and society (Spangenberg, Görg, & Settele, 2015). This requires moving from classical normal science posture to a novel approach that remains ‘constantly in the fuzziness of the science in the making’ (Barnaud & Antona, 2014). Such posture may also help to unlock the socio-economic barriers and thus foster agroecological transition.

The main objective of this study is to present a new research approach that expands the concept of social-ecological experiments. In the context of sustainable farming, these experiments explicitly involve farmers and allow the simultaneous assessment, in real conditions, of ecological and social processes affecting the dynamics of the SES in a context of uncertainty. Such experiments (a) are based on hypotheses arising from a combination of ecological predictions and stakeholder goals, (b) tackle the diversity of stakeholders and the complexity of the system and (c) promote social learning and the integration of knowledge by multiple stakeholders, facilitating the transition towards sustainable agriculture. We first examine how this new approach is related to existing ones. Then, we describe the main features for formalizing and applying this multidimensional and transdisciplinary approach to real cases, by providing a working example.

2 | EXISTING APPROACHES TO FOSTER AGROECOLOGICAL TRANSITIONS

Experiments have been widely used in agricultural sciences to establish causal links between patterns and processes, for example, between yield and insect pollination (Bommarco, Marini, & Vaissière, 2012; Perrot, Gaba, Roncoroni, Gautier, & Bretagnolle, 2018). They have provided important insights within the efficiency-substitution-redesign model (Hill & MacRae, 1995) for making best use of resources within existing system configurations, using new technologies and practices to replace existing ones that may be less effective on both productivity and sustainability grounds, or by designing agricultural systems that ensure food production while limiting negative impacts on the environment. However, the way in which they are usually designed and implemented limits
their ability to foster agroecological transition for several reasons. Many experiments have been conducted in enclosures, such as greenhouses or experimental fields, to control the environment and exclude exogenous sources of variation, in particular human variation in farming practices. This is also the case for long-term field experiments such as the Broadbalk or Park Grass experiments in Rothamsted, UK (Johnston & Poulton, 2018), or Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg, Germany (Dalchow, Bork, & Schubert, 1998). Other field experiments have been set up for testing whole cropping systems (Debaeke et al., 2009; Hossard et al., 2014), but have necessarily been limited to comparisons of complete cropping systems rather than controlling the variation of each individual factor. These experiments rely on a simplified view of the agroecosystems and are usually conducted with few replicates (Sebilo, Mayer, Nicolardot, Pinay, & Mariotti, 2013), impeding the generalization of the outcomes. Even the use of networks of such experiments, which may be an option for exploring field-scale or farm-scale systems, still fails to take account of the landscape and socio-economic context and rarely covers a period long enough for evaluating the sustainability of land management practices (Lechenet, Makowski, Py, & Munier-Jolain, 2016). Finally, they seldom incorporate stakeholder knowledge into the research process, barely record human factors (behaviours, practices and decisions), and when farmers are included, they are often considered as research subjects or passive components of the system under investigation (Pretty, 1995).

Participatory action research (PAR), conversely, involves farmers through transdisciplinary approaches, characterized by continuous interactions between scientists and stakeholders, thus engaging stakeholders in knowledge co-production through processes of collective inquiry and reflection with relevant stakeholders (Lang et al., 2012). Participatory action research incorporates farmers as protagonists of the approach and has been developed successfully in South America (Méndez, Caswell, Gliessman, & Cohen, 2017) and Spain (Guzmán, López, Román, & Alonso, 2013). Such participatory approaches that make the most of the expertise of farmers, other stakeholders and scientists (Méndez et al., 2017) are increasingly seen as a way to address the multiple and

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**FIGURE 1** Socio-ecological experiments to investigate socio-ecological systems. The figure shows the components of a socio-ecological systems experiment in comparison with three approaches used for creating knowledge. Socio-ecological experiments account for social (1) and ecological (4) processes in multiple sites in a transdisciplinary and adaptive way through collective design and implementation (2). In comparison, networked experiments rely on multiple sites (e.g. NutNet; www.nutnet.umn.edu), but do not involve stakeholder and social processes. Similarly, adaptive management or participatory processes (i.e. participatory scenario or participatory action research [PAR]) usually involve a single site. Socio-ecological experiments gather the strength of these approaches and go further, by including multiple sites, ensuring for sufficient genericity. Several options are available with regard to how the multiple sites are spatially organized. In its simplest form (3), the sites are distributed along a single gradient that combines ecological and social processes, for example, a landscape gradient that result from interacting social and ecological processes. In a more accomplished version (4), both ecological and social gradients are involved separately, which, in the best case scenario (5), may be statistically independent (i.e. low correlation) by design, therefore allowing higher statistical power in the analysis.
often conflicting social, environmental and economic sustainability goals related to sustainable agriculture (Cramb, 2000). PAR may encompass participatory rural appraisal (Menconi, Grohmann, & Mancinelli, 2017), participatory scenario building (Oteros-Rozas et al., 2015), participatory mapping (McCall, 2003) and participatory modelling (Matthews, Gilbert, Roach, Polhill, & Gotts, 2007). Such collaborative work is very useful for co-creating knowledge and learning, which can be put into practice. However, the innovative agroecological practices resulting from PAR do not link social and ecological variables explicitly, which limits our understanding of the feedbacks between human intervention and ecosystem functioning (Figure 1). Furthermore, PAR is not an experimental approach in the strict sense, as true experiments involve the manipulation of some system characteristics to assess their effects on the system. Finally, making general recommendations for a sustainable management from PAR is difficult because the processes and mechanisms involved are not documented (Van De Fliert & Braun, 2002). We argue that an experiment with a participative dimension could be a powerful way to promote agroecological knowledge and improve the agroecological transition. This calls for a new type of research that explicitly relies on experiments as a means of learning about the system functioning, and, furthermore, includes adaptive management approaches whereby farmers and researchers implement and monitor specific actions to learn about the management practices that optimize multiple objectives, deliver a portfolio of ecosystem services and satisfy the social demands of key stakeholders.

3 | DESIGNING SOCIAL–ECOLOGICAL EXPERIMENTS

Social–ecological experiments aim at identifying the best management actions, through an iterative process which takes the inherent uncertainty and complexity of the SES into consideration. Social–ecological experiments are related to adaptive management (Garibaldi et al., 2017), scenario planning (Oteros-Rozas et al., 2015; Peterson, Cumming, & Carpenter, 2003) and PAR (Figure 1). Their originality lies in making explicit use of gradients of ecological, socio-economic or social components, and preferably both, to investigate how management actions affect the interaction of ecological and social processes, and ultimately the delivery of a bundle of ecosystem services. In this approach, each experimental unit (field, farm or landscape) represents a particular intersection of ecological and social processes. Experimental manipulation of social parameters is, however, controversial and raises ethical issues. Setting up an experimental design over multiple sites allows these difficulties to be overcome, and can capture the variability and the unpredictability of human

![Figure 2](image-url)
decisions and actions (see details below). Moreover, by covering a wide range of pedoclimatic conditions, landscapes, past management history and farm socio-economic characteristics, multiple-site design allows examining a variety of possible adaptive pathways to sustainability, which may allow generalization of the outcomes. Below, we describe the main features for formalizing and applying this multidimensional and transdisciplinary approach (Figure 2), and in the next section illustrate it with a working example.

### 3.1 The identification of key social and ecological processes

The first step of the social-ecological experiment consists in the identification of key social and ecological processes that may be relevant to alternative management options at field, farm or landscape scales. The scientific discipline of agroecology consists in the ‘application of ecological science to the study, design and management of sustainable agroecosystems’ (Altieri, 1995); thus, ecological process(es) are at the core of a suitable alternative to intensive agricultural practices (e.g. chemical inputs), and need to be identified using the best available ecological theory. However, the effectiveness of ecological principles to replace partially or entirely intensive agricultural practices will ultimately depend on human decisions. The social processes in the experiments should therefore be chosen from the processes underlying human decision, such as management practices that interact with (or affect the most) the ecological process under study. This means that the social process investigated in the SES experiment may be actually derived from the identification of the ecological ones. The social component of the SES experiment is then organized along a well-designed selection of experimental units, chosen to cover a full range of management practices and intensities, which are generally related to farmers’ decision-making process (e.g. risk aversion, Moschini & Hennessy, 2001). In practice, this requires a prior knowledge of their range and variability in the study area; management gradients can be defined using data from farm surveys (i.e. pesticides use, nitrogen application, tillage) conducted in the study area during previous research projects or from land use cover maps. If there are no such data or prior knowledge, data on social factors under study should be collected. The scale of the experimental units is chosen by the scientists to fit the scale at which both processes act. Each unit on the gradient can be a field, a farm or even a small-scale landscape (e.g. a 1-km² window). The selection of experimental units requires identifying the group of farmers who may be involved in the experiment. Involvement can be built either through one-to-one or group meetings during which the experiment process is discussed. Due to their intrinsic variability, which is a critical feature of the experiment, the number of farmers involved in the experiment should be large enough to test the effects of different treatments effectively. This number depends on the number of factors and modalities investigated, but we suggest that 30 farmers at least are required to reach statistical relevance when testing the effect of two factors (two modalities) alone and in interaction (Sokal & Rohlf, 1995).

### 3.2 Implementation and design

The experimental design is implemented by the farmers themselves, in each experimental unit (field or farm) along the social gradient (Figure 2). It consists, first, in identifying the management practices that interact with (or affect) most strongly the ecological process under study. The management practices may be sowing a mixed crop, reducing pesticides or nitrogen, or modifying the crop sequence. In each unit, different levels of changes in management practices (e.g. intensity of pesticide applications, monocultures vs. mixed crops) are implemented in several plots, while, in the rest of the unit, the farmers use their standard practices as a control. In this way, the ecological processes under study are manipulated by the farmers in each experimental unit. Examining the outcome along the gradient of the social component allows the effect of management to be captured, and account for the interaction between the ecological and social processes. The number and kind of treatments, including the ‘control’ treatments, are discussed between the farmers and scientists (Figure 2). The implementation of the treatments should be driven by the farmers to reflect human variability in decisions, interventions and actions. This allows the farmers’ decision to be accounted for when assessing the effect of management actions.

### 3.3 The variables (ecological and socio-economic evaluation)

During the experiment, scientists will measure some parameters (the variables). These variables must include the stakeholders’ goals in terms of production (expected yield) and monetary value, identified during face-to-face meeting or workshops. To assess the success in achieving the multiple objectives of sustainable agriculture (soil and water quality, flagship species conservation), the full set of variables should include: (a) biodiversity indicators for key types of organisms such as plants, pollinators and pest enemies; (b) long-term and short-term crop yields, as well as economic returns including fixed and variable costs; (c) ecological functions such as soil properties that contribute to sustaining yields and reducing the long-term variability of yields; (d) the farm infrastructure and the farmers’ practices during the cropping season and, if relevant, during the preceding years; and (e) the benefits to different stakeholders, including yields and other economic and cultural goods, in a multifunctional agriculture perspective. In the process, farmers directly involved in the experiment can assess the extent to which the biodiversity and ecosystem services satisfy their needs and can be asked to indicate the value that they would attribute to each of the ecosystem services. Data collected are then used to perform an ecological and socio-economic evaluation of the effects of each experimental treatment. A variety of analytical approaches, from statistical models to multivariate analysis, can be used to quantify the effect of each experimental treatment alone or in interaction on the different variables related to biodiversity, ecosystem services, yield and the economic performance of the farmers.
3.4 | Discussion and reflection

After data analysis, the results of the experiment are presented and discussed in workshops with the participation of the farmers involved in the experiment and other farmers from the study area (Figure 2). These workshops provide a general overview of the results of the experiment which, up to this point, has been seen as an individual case by each farmer involved. The farmers and scientists may also discuss the pros and cons of the experiment and comment on the results, resulting in a co-production of knowledge. For example, the scientists can unravel the mechanisms underlying changes in key variables (e.g. yield or economic outcome). This enables farmers to gain a better and holistic understanding of the consequences of their practices on the ecosystem functioning. Discussions and debates between farmers and scientists, among farmers involved in the experiment, and between farmers involved and those who were not involved also enhance integration of knowledge by multiple stakeholders and shared understanding of goals. These workshops make it easier to transfer the knowledge gained from the experiment to farmers who were not involved, encouraging them to become involved in future research. Social–ecological experiments are not, therefore, based on a rigid or linear methodology, but a flexible and adaptive approach. This is particularly important for experiments that need to be run over several years (to account for the unpredictability of environmental and market conditions). For long-term experiments, the process may even become iterative with possible modifications to the design, after the workshops, to account for the needs of different participants. Indeed workshops can also promote change in the experimental design to explore solutions that may be more effective to address these needs. Along the process, incorporating participatory evaluation may improve the design of innovative, sustainable solutions by improving social learning and communication between stakeholders (Trimble & Plummer, 2019) and strengthening their sense of ownership and responsibility (Berthet et al., 2019). Our approach in social–ecological experiments may, therefore, be seen as a first step towards adaptive governance (Folke, Hahn, Olsson, & Norberg, 2005).

4 | A WORKING EXAMPLE: A SOCIAL–ECOLOGICAL EXPERIMENT TOWARDS REDUCING WEED CONTROL INTENSITY

4.1 | Context and background

In 2014, half a million tonnes of pesticide (58% being herbicides) were used in Europe (Faostat, 2017). EU Common Agricultural Policy (CAP) has been reformed to limit the environmental externalities of agro-chemicals, but the quantities of pesticides used over the last 15 years have at best remained constant (Kniss, 2017). France is the fourth highest user of pesticides worldwide, and a strong societal demand was expressed during the Grenelle consultation process organized in France in 2007. This led to the Plan Ecophyto 2018 (launched in 2008), targeting a 50% decrease in pesticide use by 2018 (MAAF, 2015). Ecophyto has failed to reduce herbicide use, which has actually increased over the past 10 years (Hossard, Guichard, Pelosi, & Makowski, 2017). Indeed, farmers generally wish to maintain their levels of weed control to maintain short-term yields, profits and appearance, and to prevent the build-up of the weed seed bank (Doohan, Wilson, Canales, & Parker, 2010). Moving to low-pesticide agriculture practices is therefore difficult to achieve. A social–ecological experiment investigating how reducing weed control in winter cereal fields was therefore planned with farmers in the LTSER ‘Zone Atelier Plaine & Val de Sèvre’ over 2 years (Bretagnolle et al., 2018).

4.1.1 | The identification of key social and ecological processes

Competition between crops and weeds has been identified as an ecological process that may be a suitable alternative to intensive weed control (i.e. herbicide use or mechanical weeding). In arable fields, the density of crop plants is much higher than that of weed plants, and as crop species are strong competitors in high-input environments, crops can control weeds through competition (Gaba, Caneill, Nicolardot, Perronne, & Bretagnolle, 2018). The competitive ability of the crop, however, varies with the crop variety (Andrew, Storkey, & Sparks, 2015), crop density (Kristensen, Olsen, & Weiner, 2008) and agricultural practices such as the level of fertilizer, all of which are related to decision-making by farmers. Consequently, the effectiveness of crop competition to replace partial weed control interacts with these socio-technical factors as they result from human decision-making. The importance of competition can thus be manipulated by varying the level of fertilizer (i.e. and thus the resources available for the plants) and/or weed control intensity (i.e. and thus the abundance of weed plants). We selected farmers to reflect a full gradient of management intensity, as a proxy of human decision-making, using our farm survey database (Bretagnolle et al., 2019). The social process investigated was therefore the intensity of weed control, and the experimental unit was the field. We used one-to-one meetings to engage farmers, and about half of the farmers solicited eventually accepted to participate in the experiment.

4.1.2 | Implementation and design

The experimental design and practical implementation were drawn up in collaboration with these farmers. They selected fields and implemented the design in their own way. In each field, a plot of c. 200 m² was selected in which the presence of herbicide use, nitrogen fertilization and crop plants was manipulated, separately and in combination. The crop presence treatment was used to quantify the effect of crop competition on weed biomass (further details are given in Gaba et al., 2018 and Catarino, Gaba, & Bretagnolle, 2019). When reducing fertilizer or weed control intensity, the farmers
decided by themselves to either skip an application or reduce the quantity applied in each application.

4.1.3 Variables and data analysis

We surveyed the weeds, and harvested weeds and crop plants to estimate weed biomass, crop yield and quality. Information about farming practices (pesticide and fertilizer use, ploughing, weed control) was collected by interviews with each farmer, while data on prices and costs were collected from cooperatives. We analysed the data using statistical models (Catarino et al., 2019; Gaba et al., 2018) that allow comparing yields and gross margins between experimental treatments. The results showed that reducing dependence on weed management may not reduce production, and is economically profitable at the field level on the short term (Catarino et al., 2019: Figure 3a).

4.1.4 Restitution and outcomes

Preliminary results from the first year of the experiment were presented and discussed in workshops with the farmers involved in the experiment as well as other farmers from the study area. After the workshops, we updated the design of the experiment to better meet the participants’ goals and needs, and new farmers were recruited. In total the experiment was performed in 56 fields, and 14 and 23 farmers were involved during the first and second year of the experiment. The main change in the design consisted in exploring the effect of half doses in addition to no application and the farmers’ dose and in setting the experiment exclusively in the core field (Figure 3b). Final results were presented 1 year after the end of the experiment during a workshop gathering around 50 farmers. Results were intensively discussed between farmers as well as between farmers and researchers. Farmers involved in the experiment commented on what they observed in their fields. This revealed that

FIGURE 3 Illustrations of the social–ecological experiment case study. (a) Effect size ratio in yield (left column) and gross margin (right column) for each experimental treatment for conventional farming. Effect size ratio quantifies the proportional difference between crop yield or gross margin in control and treatment. A negative value indicates that yield or gross margin is higher in control than in treatment, whereas a positive value indicates that yield or gross margin is higher in treatment than in control. NO and N indicate no nitrogen and current (i.e. farmers’ current practice) respectively. W0 and W indicate no and current (i.e. farmers’ current practice) weed control respectively (more details in Catarino et al., 2019). (b) Experimental designs that have been applied during the first and second year of the experiment. Following discussion with farmers at the end of the first year, changes were performed in the experimental design. In the first year, five experimental plots were set up in the field: two in the field margin and three in the field core. The five plots were divided into two subplots and one of the subplots did not received any nitrogen supply. Weed control was stopped in one of the two plots in the field margin. In the second year, the experimental area was placed in the field core and was divided into four subplots corresponding to the four treatments. (c) Pictures of plots with no crop in three different farmers’ fields (credits: CNRS CEBC). Note how weed coverage differs.
participants had different perceptions about certain aspects of the experiment. Several questions arose, among which is the robustness of the outcomes over the duration of a crop succession. This question led to a new SES experiment in the LTSER Zone Atelier Plaine & Val de Sèvre site.

4.1.5 | Ethical approval and consent

All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. All information related to farmers’ individual management practices was collected under the basic principles of lawfulness and according to the Commission Nationale de l’Informatique et des Libertés (CNIL—https://www.cnil.fr/en/home), the French data protection authority (DPA). We obtained prior informed consent by farmers in compliance with the ‘Loi informatique et libertés’ act no. 78–17 of 6 January 1978 on information technology, data fields and civil liberties. Farmers were informed on the research and the ability to refuse or withdraw consent at any time of the research process. We complied with the ethical and methodological standards required of the Article 8 of the CNIL, under the specific case II.1.

4.1.6 | Critical assessment

The approach in this SES experiment, whose aim was to reduce reliance on weed control (mainly herbicide use), was a promising starting point for the agroecological transition. An important outcome of the experiment was the identification of cognitive and organizational barriers to agroecological transition. By undertaking the experiment in their own fields, the farmers could easily compare the effect of the experimental treatment on their production. The experimental design, especially the no crop treatment, also promoted learning as the farmers became aware of the massive decline in weeds in the seed bank (Figure 3c).

The experiment also posed a number of challenges. The first was to ensure that the simple experimental protocol was correctly applied by the farmers. For example, at the beginning of the experiment, some farmers inverted treatment applications between experimental areas. This was solved by continuous and careful communication between farmers and researchers, and therefore had almost no effect on the experimental outcome. Second this transdisciplinary approach requires sufficient human resources for data collection (e.g. plant biomass, soil properties and socio-economic data from surveys) and to facilitate regular communication between farmers and scientists. Third, part of social–ecological experiment entails social learning. Incorporating the assessment of changes in perception by the farmers all through the experimental process may contribute to determining what the changes (i.e. in the experimental manipulation and their consequences) mean for farmers and whether or not these changes affect their way of perceiving the system. This assessment can be coupled with investigating the determinants of farmers’ agricultural practices and choices (e.g. weed control in our case study). These approaches may help to obtain information about the attractiveness of alternative management strategies, and how farmers may take up these changes. Finally, this experiment was site specific. To ensure the generality of the results, similar experiments should be conducted in other pedoclimatic and socio-ecological regions. This calls for research infrastructures that bring together a number of sites and perform interdisciplinary and transdisciplinary research.

5 | CONCLUSIONS

Social–ecological experiments like those described here represent a novel methodology distinguished by:

- its particular metrics and experimental units, both reflect a combination of social and ecological processes,
- its aim of fostering agroecological transition and
- its transdisciplinary approach.

This is a departure from conventional top-down scientific methodologies, as it provides an alternative mechanism for bottom-up creation of scientific knowledge and for sharing this knowledge with a wider audience. It is important to appreciate that social–ecological experiments are a form of co-adaptive management and participatory action research, being original in the use of gradients of the social and/or ecological processes selected. The approach recognizes the links between the biophysical and social systems, the diversity of knowledge and values and the complexity of the systems. This makes them part of the post-normal science movement (Funtowicz & Ravetz, 1994); similar approaches have been suggested before (Janssen, Holahan, Lee, & Ostrom, 2010) and advocated (Rommel, Villamayor-Tomas, Müller, & Werthmann, 2015). The SES experiment has two main advantages: experiments can be improved continuously through real-time adaptive management (Walters, 1986), and their results are available to decision-makers (in this case, farmers) by their direct involvement (Lang et al., 2012). Evidence-based results from such experiments can provide a useful contribution to effectively implementing local context-dependent policies and, at the same time, encouraging more stakeholders to become involved in experiments assessing sustainable management strategies. The involvement of stakeholders and continuous discussions with them also encourage adaptive management of the experimental design. Because stakeholders are directly involved in the experiment in its very first stages, the design of the experiment should minimize risks for the participants; then, as the experiment evolves, higher-risk strategies may be tested using the earlier results.

Social–ecological experiments have, however, some limitations that need to be addressed in the future. For instance, it is difficult to rule out extrinsic variables driving the observed patterns, such as past management strategies. The keystone of this approach is to consider the variety of possible adaptive pathways to sustainability, taking account of the diversity of human behaviour and multiple
uncertainties, and relying on the stakeholders to adapt and respond to the challenges they are facing. Furthermore, as in other approaches, replicates of the experiments should cover a range of landscapes and socioeconomic conditions to ensure for generality. They also need to be long term. The research community therefore needs to overcome some barriers related to funding, stakeholder’s willingness to participate and the capacity to engage an interdisciplinary research. Long-Term Social–Ecological Research (LTSER) platforms can provide dedicated infrastructures to develop a network of social–ecological experiments. Indeed they have been set up to investigate socio-ecosystems (Angelstam et al., 2018) and produce the knowledge required to support sustainable regional development (Berthet et al., 2019; Bretagnolle et al., 2019). Furthermore, in such platforms, stakeholders (farmers/fishermen, practitioners, managers and policymakers) work with scientists from various disciplines (e.g. social sciences, ecology) to improve the knowledge of social–ecological interactions within their social–ecological system. This transdisciplinary collaboration in the design and execution of the experiments facilitates the involvement of the local community in research projects (Berthet et al., 2019).

To conclude, by dealing with interacting social and ecological processes in real conditions, these experiments are ideal for (a) acquiring and quantifying valuable information on complex social–ecological interfaces, (b) supporting collaborative knowledge production which facilitates both learning and sharing, as the stakeholders are directly involved in the experiments, and, sometimes at later stages, (c) increasing acceptance of policy changes based on the results. Politicians and decision-makers need practical, scientifically sound, evidence-based information from the real world for managing land sustainably. Extending larger-scale and real-world studies and experiments to understand and manage both the social and ecological components of agroecosystems is clearly the next step for achieving sustainable agriculture. Further research should therefore explore how to move from long-term monitoring research sites to a network of long-term social–ecological experiments accounting for the characteristics of each SES. To foster sustainability in transformation processes, we also encourage further studies to set up sociological experiments throughout the food production chain that involve different categories of stakeholders (farmers, residents, cooperatives, food producers, consumers) in the experimental process.

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CONFLICT OF INTEREST
The authors declare no competing interests.

AUTHORS’ CONTRIBUTIONS
S.G. and V.B. conceived the ideas. The preparation of the manuscript was a joint undertaking and both of the authors gave final approval for publication.

DATA AVAILABILITY STATEMENT
Data related to the case study are available on Zenodo https://doi.org/10.5281/zenodo.3626126 (Gaba, Catarino, Perrot, & Bretagnolle, 2020).

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Additional supporting information may be found online in the Supporting Information section.

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