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Social-Ecological Experiments to foster agroecological transition

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Abstract

Sustainable agriculture is essential to provide food security for a growing world population without further sacrificing the integrity of the environment. To make progress towards agricultural sustainability we must consider ecological and socioeconomic processes within the agricultural socio-ecosystem and involve stakeholders in the research process.

We propose an innovative experimental approach for examining how natural regulation of ecosystems may provide an alternative to increasing external inputs in agriculture while improving the socio-economic welfare of farmers. 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 give a faster route to sustainability.

Social-ecological experiments are undertaken in real field conditions, explicitly involving stakeholders, and help untangle the drivers of social-ecological dynamics under various land management and farming practices. Social-ecological experiments are distinct from adaptive management and scenario-planning approaches as they highlight the interactions between ecological and social processes, manipulate the social and ecological processes shaping the system and show causal links between patterns and processes. As an example, we describe a social-ecological experiment for reducing herbicide use.

Social-ecological experiments offer great opportunities for increasing stakeholders’ acceptance of environmental policies implemented through adaptive management. These experiments may help to identify management practices that optimize multiple objectives, deliver a portfolio of ecosystem services and satisfy key stakeholders.

Keywords: agroecology, biodiversity, ecosystem services, post-normal science, socio-ecological systems, sustainability, stakeholders

The multiple challenges of sustainable agriculture: moving from concept to practice

The main societal challenge 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 (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 conventional agriculture system; both will require technological and institutional innovation (Berthet et al., 2018; Tittonell, 2014), which may be made difficult given 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 part of, 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 lock remains: moving from top-down global analyses to local and farmer-centered approaches (Altieri, 2004; Loos et al., 2014; MacMillan & Benton, 2014), i.e. the translation of 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 that span nested spatial and temporal scales (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 scales, while market access and the local organization of the economy influence the landscape organization. Such interactions between humans and the environment feed into the complex dynamics between farming systems and the global environment, with feedbacks and cross-scale interactions. For instance, land use creates 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 intervention improve (fertilization and irrigation) or replace (pesticide use) ecological processes, while land use changes disturb the natural flows of biodiversity and matter. These human actions are moreover diverse, as no two farmers cultivate their fields in exactly the same way (Gaba et al., 2016; Lechenet et al., 2014), resulting 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 agricultural SESs dynamics are highly uncertain and complex. Global change and human use of agricultural SES are creating novel social ecological conditions and associated problems that are difficult to understand and solve. Solving these wicked problems with complex causes and consequences calls for a new research posture, shifting from mono-disciplinary local-scale approaches to adaptive, participatory and transdisciplinary landscape scale strategies (Angelstam et al., 2013, 2018). This new research posture allows accounting for various and diverging viewpoints, through explicit involvement of stakeholder knowledge, and 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) and actively involves decision makers and stakeholders in knowledge co-construction and problem-solving (Funtowicz & Ravetz, 1994). Such posture may also help to unlock the socio-economic barriers and thus foster agroecological transition, while dealing in the same time with climate change, natural resource depletion, and worldwide economic and social disorder. The main objective of this paper is to present a new research approach, that we name "social-ecological experiments". In the context of sustainable farming, these experiments explicitly involve farmers and enable to assess, simultaneously in real conditions, how ecological and social processes affect the SES dynamic in a context of uncertainty. Such experiments are (i) based on hypotheses arising from a combination of ecological predictions and stakeholder objectives, (ii) tackle the diversity of stakeholders and the complexity of the system and (iii) promote social learning and the integration of knowledge by multiple stakeholders, facilitating the transition toward 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-case studies, by providing as well a working example.

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 provided important insights within the efficiency-substitution-redesign model (Hill & MacRae, 1995) in 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, and 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 the following 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 winter wheat or park grass experiments in Rothamsted, UK (Johnston & Poulton, 2018), Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg, Germany (Dalchow, Bork, & Schubert, 1998), which provide important insights to improve agricultural practices such as tillage or weed control and enhance the understanding of ecosystem functioning. Other field experiments have been set up for testing the whole cropping systems (Debaeke et al., 2009; Hossard et al., 2014), and hence have been limited to comparisons of complete cropping systems rather than controlling the variation of each individual factor. These experiments rely on a simplification view of the agroecosystem 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 socioeconomic context and rarely cover a period long enough for evaluating the sustainability of land management practices (Lechenet, Makowski, Py, & Munier-Jolain, 2016). Finally, they rarely 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 research. PAR has been developed successfully in several networks worldwide (see Méndez, Caswell, Gliessman, & Cohen, 2017). 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 often conflicting social, environmental, and economic sustainability goals related to sustainable agriculture (Cramb, 2000). PAR 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 creating knowledge that can be put into practice. However, the innovative agroecological practices resulting from PAR often remains site specific, making general recommendations for a sustainable management difficult (Cramb, 2000). Furthermore, this approach does not explicitly link social and ecological variables, limiting our understanding of the feedback between human intervention and ecosystem functioning (**Figure 1**) and 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. We argue that combining an experiment and a participative dimension could be a powerful mean for promoting agroecological knowledge and supporting 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 includes adaptive management approaches wherein farmers and researchers implement and monitor specific actions to identify the management practices that optimize multiple objectives, deliver a portfolio of ecosystem services and satisfy the social demands of key stakeholders.

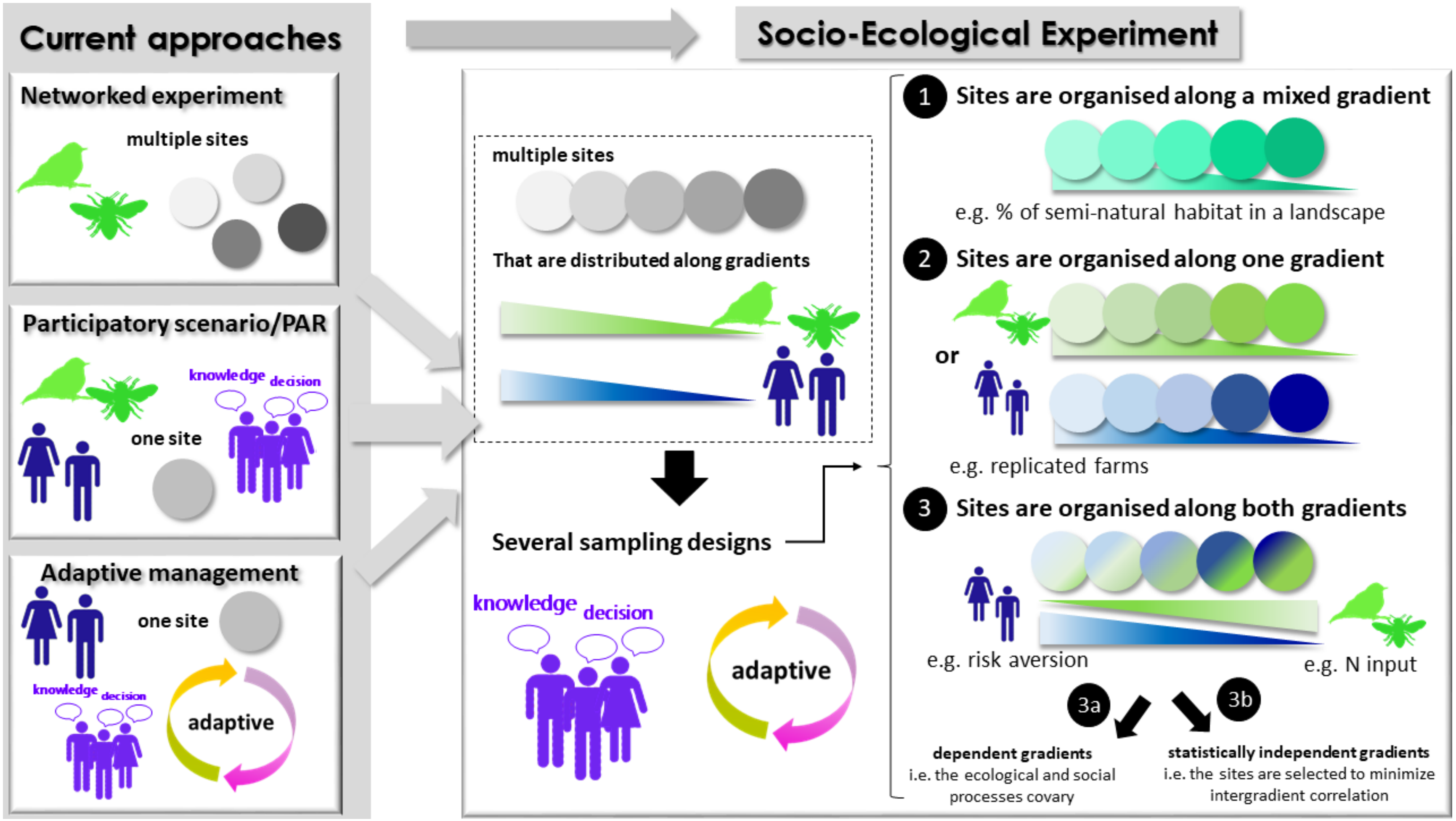

Figure 1: Socio-ecological experiments to investigate socio-ecological systems. The figure shows the components of a SES experiment in comparison with three approaches used for creating knowledge that can be put into practice. Socio-ecological experiments account for social ( ) and ecological ( ) processes in multiple sites in a transdisciplinary and adaptive way. Networked experiments rely on multiple sites (e.g., NutNet; www.nutnet.umn.edu), but do not involve stakeholder and social processes, contrary to adaptive management or participatory processes (i.e. participatory scenario or participatory action research (PAR)). The later however 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. The multiple sites should be spatially organized over gradients. In its simplest form (1), the sites are distributed along one gradient that covers a given range of situations (e.g., a landscape gradient that result from interacting social and ecological processes). More accomplished version (3) involves both ecological and social gradients, which, in the best case scenario (3b), may be statistically independent (i.e. low correlation) by design, therefore allowing higher statistical power in the analysis.

Designing social-ecological experiments

We refer to this new type of research as social-ecological experiments, a research that aims at identifying the best management actions, through an iterative process, considering the inherent uncertainty and complexity of the SES. 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. Their originality lies in making explicit use of gradients of ecological, socio-economic components, or both, to investigate how management actions affect the interaction of ecological and social processes, and ultimately the delivery of a bundle of ecosystem services (**Figure 1**). In this approach, each experimental unit (field, farm or landscape) represents a particular intersection of ecological and social processes. Setting up an experimental design over multiple sites allows overcoming the difficulties and the ethical issues related to the manipulation of social parameters to capture the variability and the unpredictability of human decisions and actions (see details below). Moreover, by covering a wide range of pedoclimatic conditions, landscapes, past management history and farm socio-economic characteristics, it examines a variety of possible adaptive pathways to sustainability and ensures for generalization of the outcomes. Below, we describe the main features for formalizing and applying this multidimensional and transdisciplinary approach (**Figure 2**), and illustrate it with a working example.

Context and background

Agriculture is currently facing wicked problems: environmental and health consequences of pesticide use is one of the most controversial topic involving citizen, farmers, science and policy. In France in 2007, a societal demand toward innovative solutions for reducing pesticides use was strongly expressed, giving birth to the National Ecophyto Plan in 2008. One of the core purpose of Ecophyto was to identify, innovate and then disseminate the best low-pesticide agricultural practices (Lechenet, Dessaint, Py, Makowski, & Munier-Jolain, 2017). Ecophyto has, however, failed to reduce herbicide use, which has actually increased over the past 10 years. Farmers generally wish to maintain their levels of weed control to keep short-term yields and profits, prevent the build-up of the weed seed bank, and maintain appearances (Doohan, Wilson, Canales, & Parker, 2010). Moving to low-pesticide agriculture practices is therefore a difficult problem to come to grip with. Next we present the different steps of the SES experiment approach and illustrate how such approach can help providing knowledge and implement agroecological management actions.

The implementation

The **first step** of the socio-ecological experiment process consists in the identification of key social and ecological processes related to plausible alternative management options (here, reducing the use of herbicides) based on scientific and farmers knowledge. In our case study, crop competition, i.e. an ecological process, may be a suitable alternative to herbicide use. 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, & Sparkes, 2015), crop density (Kristensen, Olsen, & Weiner, 2008) and agricultural practices such as fertilizer amounts, all of them being related to farmers' decision. Consequently, the efficiency of crop competition to partially replace herbicides interacts with these social factors as they result from human decision-making. Here the social component is obtained through a well-designed selection of experimental units, that are 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 variability in the study area. In our example (**Figure 2**), the sites are selected to cover a management intensity gradient as a proxy of human decision-making, using data from farm surveys (i.e. pesticides use, nitrogen application, tillage, …) conducted in the study area during previous research projects (Bretagnolle et al., 2018; Gaba et al., 2018). If there are no such data or prior knowledge, data on social factors under study should be collected before the start of the experiment. The selection of experimental units identifies the group of farmers who should be involved in the experiment. Involvement can occur using either one-to-one or group meetings during which the experiment process is discussed. Due to their intrinsic variability, a critical feature of the experiment, the number of farmers involved in the experiment should be high enough (at least 30) to test the effects of different treatments thoroughly.

The design

The experimental design is implemented by the farmers themselves, in each experimental unit (field or farm) along the social gradient (**Figure 2**). The design first consists in identifying the management practices that should most interact with (or affect) the ecological process under study. The management practices may be to sow mixed crop, reduce pesticides or nitrogen, or modify the crop sequence. In each field, different levels of changes in management practices (e.g. intensity of pesticides pressures, monocultures vs. mixed crop, …) are implemented in several plots, while, in the rest of the field, 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 socio-economic component allows capturing the effect of management, accounting 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. In our example, the importance of competition can be manipulated by varying the level of fertilizer (i.e. related to the resource available for the plants) and/or of herbicides (i.e. related to the abundance of weed plants) along the gradient of farming intensity (defined by the intensity of agrochemical use). When reducing fertilizer of herbicide use, the farmers decide themselves to either skip an application or reduce the quantity applied in each application. This allows accounting for the farmer's decision when assessing the effect of management actions.

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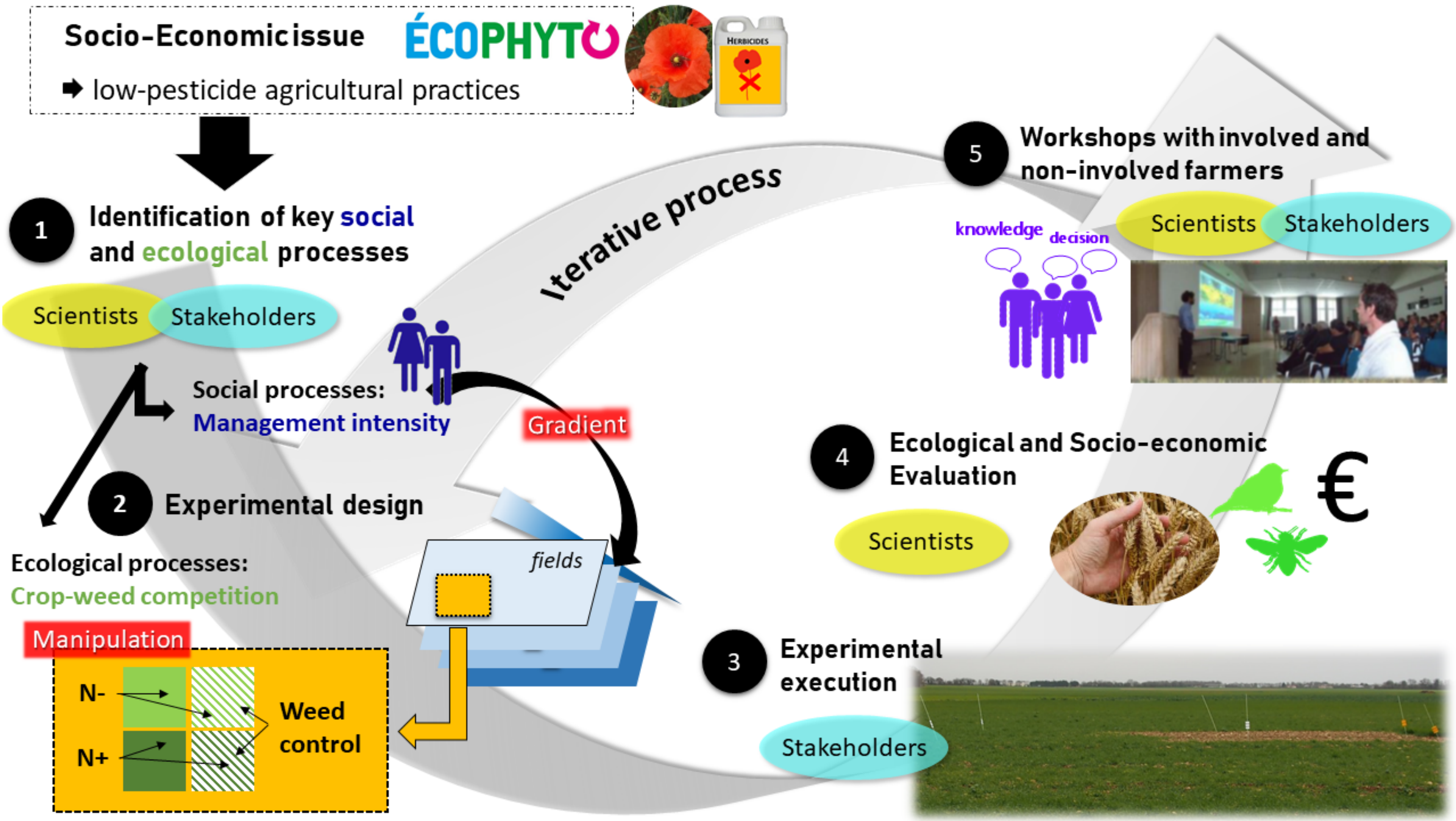

Figure 2: The five stages of a social-ecological experiment for the case study in Box 2. Stakeholders involvement is shown by a blue dot ; whereas scientists involvement is indicated by an orange dot . This social-ecological experiment for weed control in winter cereal fields was run with farmers in the LTSER "Zone Atelier Plaine & Val de Sèvre" over two years. The social process investigated was the weed control intensity. We used one-to-one meetings to engage 14 farmers who had been selected to reflect a full gradient of management intensity using our farm survey database. 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, herbicide use, nitrogen fertilization and crop presence were manipulated, separately and in combination. Crop presence was used to quantify the effect of crop competition on weed biomass. We surveyed the weeds and harvested weeds and crop plants to estimate weed biomass and crop yield. Information about yields and farming practices (pesticide and fertilizer use, ploughing, weed control) was collected by interviews with each farmer. We analysed the data, and the yields and profits were discussed in workshops with the 14 farmers as well as other farmers from the study area. After the workshops, we updated the design of the experiment as requested by the participants and nine new farmers were recruited for a total of 23 farmers the second year.

The variables

During the experiment, scientists should measure some parameters, the variables. These variables should reflect the stakeholders' goals in terms of production (expected yield) and monetary value. These goals should be identified during face-to-face meeting or workshops. To assess the success in achieving the multiple objectives of sustainable agriculture (e.g., soil and water quality, flagship species conservation), the full set of variables should include: (i) biodiversity indicators for key types of organisms such as plants, pollinators and pest enemies; (ii) long-term and short-term crop yields, as well as economic return; (iii) ecological functions such as soil properties that contribute to sustaining yields and reducing the long-term variability of yields; (iv) the farm infrastructure and the farmers' practices during the cropping season and, if relevant, during the preceding years; and (v) the benefits to different stakeholders, including yields and other economic and cultural goods, in a multifunctional agriculture perspective. In our working example (**Figure 2**), the weeds and harvested crop plants are surveyed to estimate weed biomass and crop biomass, as proxies to estimate the importance of competition. Information about farming practices (pesticide and fertilizer use, ploughing, weed control) is collected by interviews with each farmer. 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.

The outcomes

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 can also discuss the pros and cons of the experiment and comment on the results. 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, a rigid, linear methodology, but a flexible and adaptive concept. This is particularly important for those 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 becomes iterative with modifications to the design, after the workshops, to account for each participant's needs. Our social-ecological experiment concept may, therefore be seen as a first step toward adaptive governance (Folke, Hahn, Olsson, & Norberg, 2005).

Research infrastructures for social-ecological experiments

We finally argue that dedicated research infrastructures are required for such large-scale, spatially explicit social-ecological experiments. Long Term Socio-Ecological Research (LTSER) platforms 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., 2018; Bretagnolle et al., 2019). In such platforms, stakeholders (farmers, practitioners, managers and policy-makers) work with scientists from various disciplines to improve the knowledge of socio-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., 2018). Since the results from a socio-ecosystem experiment apply directly to the socio-ecosystem studied, a network of participatory experiments could cover a range of landscapes, as well as a range of socioeconomic conditions and provide a research infrastructure for social-ecological experiments. Networked experiments of this kind were recently proposed for the restoration of degraded forest land (Gellie et al., 2018).

Conclusion

Social-ecological experiments as described here represent a novel methodology distinguished by its particular metrics and experimental units, both reflecting a combination of social and ecological processes, its aim of delivering a bundle of ecosystem services over the long term, and its transdisciplinary approach. This is a departure from conventional top-down scientific methodologies, since it alternatively provides a mechanism for bottom-up creation of scientific knowledge and for sharing this knowledge with a wider society. It is important to appreciate that socio-ecological experiments are complementary to participatory action research. They recognise 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), as similar approaches have already been suggested (Janssen, Holahan, Lee, & Ostrom, 2010) and advocated (Rommel, Villamayor-Tomas, Müller, & Werthmann, 2015). This approach 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, encourage more stakeholders to become involved in experiments assessing sustainable management strategies. Continuous discussions with, and the involvement of, stakeholders also encourages the 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 minimise risks for the participants; then, as the experiment evolves, higher risk strategies may be tested based on the earlier results. Social-ecological experiments have, however, some limitations that should be accounted for in the future. For instance, it is difficult to rule out extrinsic variables driving the observed patterns, such as past management strategies. In addition, human decision processes and behaviour are in our framework considered as hidden parameters. However, 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. We therefore believe that the benefits outweigh the limitations.

By dealing with the combination of social and ecological processes in real conditions, these experiments are ideal for (i) acquiring and quantifying valuable information on the complex social-ecological interface, (ii) supporting collaborative knowledge production which facilitates both learning and sharing experience as the stakeholders are directly involved in the experiments, and (iii) 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 different SES. To foster food production transformation, 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.

Authors' contributions

SG and VB conceived the ideas. The preparation of the manuscript was a joint undertaking and both of the authors gave final approval for publication.

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Data accessibility

Data have not been archived because this article does not contain data.

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