Key research challenges to supporting farm transitions to agroecology in advanced economies. A review

Lorène Prost, Guillaume Martin, Rémy Ballot, Marc Benoit, Jacques-Eric Bergez, Christian Bockstaller, Marianne Cerf, Violaine Deytieux, Laure Hossard, Marie-Hélène Jeuffroy, et al.

Agronomy for Sustainable Development (2023) 43:11
https://doi.org/10.1007/s13593-022-00855-8

REVIEW ARTICLE

Check for updates

Key research challenges to supporting farm transitions to agroecology in advanced economies. A review

Lorène Prost[1] · Guillaume Martin[2] · Rémy Ballot[3] · Marc Benoit[4] · Jacques-Eric Bergez[2] · Christian Bockstaller[5] · Marianne Cerf[1] · Violaine Deytieux[6] · Laure Hossard[7] · Marie-Hélène Jeuffroy[3] · Margot Leclère[3] · Marianne Le Bail[1] · Pierre-Yves Le Gal[8,9] · Chantal Loyce[3] · Anne Merot[10] · Jean-Marc Meynard[1] · Catherine Mignolet[11] · Nicolas Munier-Jolain[12] · Sandra Novak[13] · Virginie Parnaudeau[14] · Xavier Poux[15] · Rodolphe Sabatier[16] · Chloé Salembier[1] · Eric Scopel[17] · Sylvaine Simon[18] · Marc Tchamitchian[16] · Quentin Toffolini[3] · Hayo van der Werf[14]

Accepted: 9 December 2022

Abstract

In response to the sustainability issues that agriculture faces in advanced economies, agroecology has gained increasing relevance in scientific, political, and social debates. This has promoted discussion about transitions to agroecology, which represents a significant advancement. Accordingly, it has become a growing field of research. We reviewed the literature on and in support of farm transitions to agroecology in advanced economies in order to identify key research challenges and suggest innovative research paths. Our findings can be summarized as follows: (1) Research that supports exploration and definition of desired futures, whether based on future-oriented modeling or expert-based foresight approaches, should more explicitly include the farm level. It should stimulate the creativity and design ability of farmers and other stakeholders, and also address issues of representation and power among them. (2) Research that creates awareness and assesses farms before, during or after transition requires more holistic and dynamic assessment frameworks. These frameworks need to be more flexible to adapt to the diversity of global and local challenges. Their assessment should explicitly include uncertainty due to the feedback loops and emergent properties of transitions. (3) Research that analyzes and supports farms during transition should focus more on the dynamics of change processes by valuing what happens on the farms. Research should especially give more credence to on-farm experiments conducted by farmers and develop new tools and methods (e.g., for strategic monitoring) to support these transitions. This is the first review of scientific studies of farm transitions to agroecology. Overall, the review indicates that these transitions challenge the system boundaries, temporal horizons, and sustainability dimensions that agricultural researchers usually consider. In this context, farm transitions to agroecology require changes in the current organization and funding of research in order to encourage longer term and more adaptive configurations.

Keywords Transformation · Sustainable agriculture · Farm · Coupled innovations · Assessment · Design · Foresight

Contents

Lorène Prost and Guillaume Martin contributed equally.

✉ Guillaume Martin
guillaume.martin@inrae.fr

Extended author information available on the last page of the article

Published online: 10 January 2023

1 Introduction

In response to the sustainability issues that dominant agricultural models face in advanced economies, a variety of alternative agricultural models has emerged, including organic agriculture (Lotter 2003), agroecology (Altieri 1989), eco-efficient agriculture (Keating et al. 2010), and regenerative agriculture (LaCanne and Lundgren 2018). Among these multiple models, agroecology has gained increasing relevance in scientific, political, and social debates in recent years (Wezel et al. 2009). This was first identified in France following the "Agroecology Project for France" set up by the Ministry of Agriculture in 2012 (MAAF 2016). Since then, the European Commission's Farm to Fork and Biodiversity strategies have recognized the potential benefits of agroecology for a greener, more sustainable, and more resilient European agriculture (European Commission 2020a, b). These political orientations are likely encouraged by the increasing evidence for greater sustainability of agricultural and food systems in agroecology compared to their dominant counterparts (van der Ploeg et al. 2019; Boone et al. 2019; Borsato et al. 2020; Zira et al. 2021).

This development of agroecology has rapidly fostered discussions on transitions to agroecology, which constitute a significant step forward in advanced economies, and a real challenge. Most farms in Western Europe are highly productive, with few yield gaps (Global Yield Gap and Water Productivity Atlas 2021). However, they are also highly specialized (Eurostat 2021a), strongly dependent on synthetic inputs (Eurostat 2021b), closely integrated with agri-food industries and export-oriented (Eurostat 2021c). These features of agriculture in advanced economies contradict the principles of agroecology enacted by the FAO (2018) (i.e., diversity, synergies, efficiency, recycling, resilience, co-creation and sharing of knowledge, responsible governance, circular and solidarity economies, human and social values, culture and food traditions) to transform agricultural and food systems and meet sustainable development goals (FAO 2022).

Transitioning a farm to agroecology entails systematically changing the entire system of farming practices towards the implementation of agroecological principles. It thus requires diversifying the species and genetic resources (Fig. 1), which can increase farm resilience to perturbations (Dardonville et al. 2022). It also involves taking advantage of synergies among these components of agrobiodiversity, between agrobiodiversity and associated biodiversity, and among types of agricultural production (Duru et al. 2015b). Strengthening these synergies can improve ecological functions and increase resource-use efficiency (Lemaire et al. 2014). The latter also involves recycling nutrients and water within farms, among farms, or between farms and industries at the local level to limit environmental pollution. Contributing to circular and solidarity economies requires reconnecting farmers to consumers (Borrello et al. 2020). These changes are expected to meet sustainability challenges at local and global levels.

Agricultural researchers have a key role to play about agroecological transitions, both in analyzing and supporting them. Agroecology has been the topic of productive conceptual debates (Altieri 1989; Francis et al. 2003; Wezel et al. 2016; Gliessman 2016), and research on agroecological agriculture has covered a broad range of themes (Mason et al. 2021). However, transitions to agroecology have only recently become a growing field of research, with a few articles published each year in the 1990s and 2000s, to ca. 150 each year in the 2020s (Web of Science query from 1992-2021 using the topic [(transiti* AND (agro-ecol* OR agroecol*)]; query performed 21 February 2022). Conceptual frameworks for transitions to agroecology have emerged to help design (Duru et al. 2015a) or scale (Ferguson et al. 2019) transitions, but empirical studies of them remain rare.

To date, most agricultural research on transitions to agroecology has focused on designing and assessing more sustainable cropping systems at the field level (e.g., Le Bellec et al. 2012; Lesur-Dumoulin et al. 2018). This research does not sufficiently encompass the systemic changes that occur at the farm level, and the complexity of interactions and trade-offs that farmers must manage on their farms and between the farms and their environment. Transitioning to agroecology involves multiple changes to several aspects of farmers' daily work (e.g., objectives, values, management practices, work organization, sales management, professional networks) (Coquil et al. 2014; Chantre et al. 2015; Bouttes et al. 2019b). The farm can thus be considered the level that connects the two management levels of transitions: that of biophysical processes and that of socioeconomic processes. This is why it is important to focus on transitions to agroecology as they actually happen on farms.

This article reviews the literature on and in support of farm transitions to agroecology in advanced economies to identify key research challenges. We first explain the theoretical framework we built to investigate farm transitions and then describe the collaborative methods used to develop the review. Next, we identify three state-of-the-art research activities — supporting the exploration and definition of desired futures; creating awareness of and assessing farm states, performances and dynamics before, during and after transitions; and analyzing and supporting farms during transitions — to identify key research challenges and suggest promising research paths.

2 Methods

2.1 Theoretical framework of farm transitions

A farm is a technical and economic unit that operates under a single management and performs economic

Fig. 1 Agroecological landscapes with (left) several fruit tree species combined in a circular orchard (photograph: T. Nicolas) and (right) a mixture of species in a cover crop at the edge of a wood (photograph: L. Paravano).

activities in agriculture within an economic region (Eurostat 2021d). Within this region, which also defines an ecological environment, food production, processing, and consumption are strongly connected, which suggests that the transitions of farms and the entire agricultural sector to agroecology cannot be isolated from those of processing and consumption (Francis et al. 2003; Gliessman 2016; Anderson and Maughan 2021). Thus, the farm level is considered to be nested within socio-ecological and socio-technical system (Geels 2002). As a consequence, if changes at the farm level are key, they can be hindered by the multiple organizations, strategies or representations of other actors upstream and downstream of the farm (e.g., Meynard et al. 2018). This perspective extends the conceptualization of a farm beyond what agronomists usually use, in which the influence of the environment on the farm is limited to climatic and market conditions. It considers an entirely new set of inputs, outputs, and surrounding actors to conceptualize farm transitions to agroecology. It also challenges the knowledge-production approaches (Compagnone et al. 2018) that agronomists may want to use to analyze and support these transitions. Many scientists and non-scientists recommend placing value on farmers' experiential knowledge and learning to address the complex and situated issues of farms within sociotechnical systems (e.g., Leeuwis 2000). This requires transdisciplinary work between farmers and other actors (e.g., advisors, experts, researchers) (e.g., Méndez et al. 2013; Hazard et al. 2018). These elements shape our theoretical framework of farm transitions to agroecology. Transitions in society result from co-evolution processes (Rotmans et al. 2001; Geels and Kemp 2007). Following this logic, coupled innovations in the agricultural sector are described as enablers of transitions, by simultaneously and consistently diversifying cropping systems and the sociotechnical system in which they are embedded by revising factors such as processing techniques (Meynard et al. 2017), markets (Magrini et al. 2016), farm equipment (Salembier et al. 2020), or cultivar breeding (Vanloqueren and Baret 2009). Such an ambitious approach implies that farm transitions follow a step-by-step approach and are open-ended. Objectives are regularly redefined due to changes in farmers' thinking, mismatch between expected and observed results, or innovations in the sociotechnical system.

The literature on transition management suggests several models of transition-management cycles. One of the most common models follows successive stages: (i) structuring the problem and envisioning and establishing the transition arena; (ii) developing coalitions, images and transition agendas; (iii) mobilizing actors and conducting projects and experiments, and (iv) evaluating, monitoring and learning (Kemp and Loorbach 2006). This conceptualization echoes several other conceptual frameworks that have been developed to support change and learning processes in agriculture, such as describe-explain-explore-design (Giller et al. 2008) and step-by-step design (Meynard et al. 2012). These frameworks focus on the gradual nature of transitions over time and their particular rhythms, with a combination of slow and rapid adaptive changes at different spatial scales.

Extending these stepping stones, we conceptualize farm transitions to agroecology as an open-ended succession of stages that starts with an initial unsatisfactory situation with or without a few agroecological principles implemented. This is followed by an uncertain and unpredictable transitory stage characterized by step-by-step changes that ultimately result in a given point at which agroecological principles are widely implemented. Despite reflecting this implementation, this point can either reflect or differ from the multiple desired futures imagined at the beginning of the transitions (Fig. 2). This point is not an end in itself; it is followed by further experimentation, monitoring, learning, and adaptation processes towards continuous improvement of the farm (Darnhofer et al. 2010). These slow and rapid

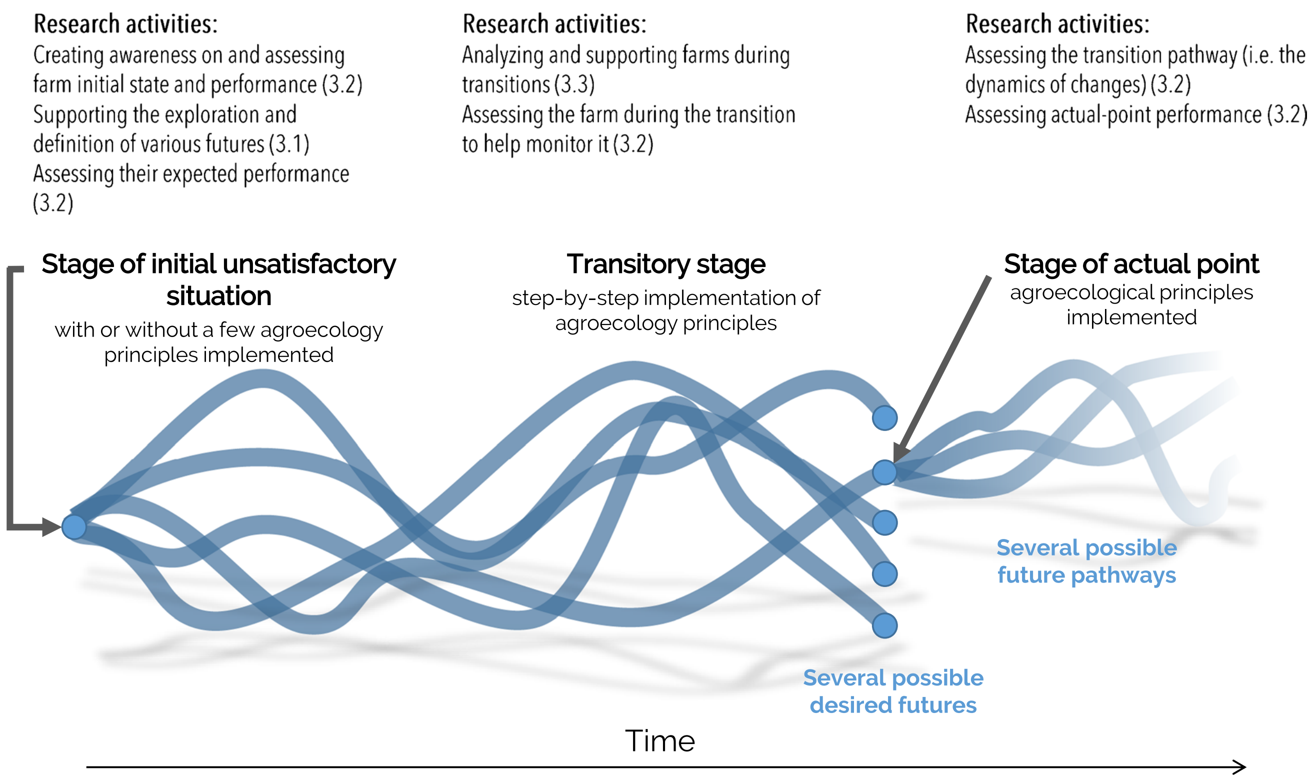

Fig. 2 Conceptualization of farm transitions to agroecology and research activities that focus on and support the transitions. Numbers in parentheses refer to sections of the article.

changes involved in implementing agroecological principles at the subsystem (e.g., cropping system) and farm levels occur along with other slow and rapid changes in the broader sociotechnical system.

Agricultural research contributes to each stage of transition processes. At the beginning, research can assess the initial situations to create awareness of and frame a problem or an objective and induce the need for change. It can also help to explore possible futures and their likely performance. During the transition, research can monitor and support the step-by-step changes required to reach these futures. When agroecological principles are implemented, research can assess the performance reached, as well as the transition pathways taken and their effects. These activities remain relevant after the transition to continue adapting and improving the farm when new problems arise (e.g., new contextual changes) and/or when new objectives are defined. Thus, research on and in support of farm transitions to agroecology combines three types of research activities that cross the transition stages (Fig. 2): (i) supporting the exploration and definition of desired futures; (ii) creating awareness of and assessing farm states, performances and dynamics; and (iii) analyzing and supporting farms during transitions to consider the transition's step-by-step nature.

2.2 Identification of current knowledge, research challenges, and innovative research paths

The literature describes several methods to define a research agenda for agricultural issues. Examples include eliciting questions from a large and diverse group of individuals and then iteratively voting on the questions to identify those most relevant for policy (e.g., Pretty et al. 2010; Sutherland et al. 2011; Ingram et al. 2013). They also include targeted exploratory workshops that use creativity and innovative design methods to help researchers from different scientific disciplines identify questions that break with the status quo (e.g., Brun et al. 2021), as well as discussions generated from a keynote presentation prepared by a few specialists to elicit cross-disciplinary questions (e.g., Giller et al. 2011). Our method was most similar to the last one.

First, the lead authors (LP and GM) identified key conceptual and methodological research topics on farm transitions to agroecology that they had defined (Section 2.1). These research topics reflect recent literature that provides new insights into farm transitions. They then brought together French agricultural researchers from multiple disciplines who had previous research experience on these topics, regardless of institution, age or gender (Supplementary Material 1). The lead authors then organized subgroups of 2–4 researchers for each key research topic. Researchers in these subgroups, who were chosen for their cross-disciplinary backgrounds, shared expertise on the topic but had not necessarily worked together before. The lead authors asked each subgroup to summarize the research on each topic to review ongoing challenges and highlight innovative research paths (i.e., research fronts or emerging questions identified as promising). The subgroups discussed preliminary versions of these summaries with the lead authors and then presented their summaries during a 2-day webinar attended by approximately 200 participants. The presentations and questions that followed were recorded to keep track of participants' comments, questions, and ideas. Following the webinar, the lead authors grouped all of the research challenges identified in the presentations into broader categories that represented the three research activities defined (Section 2.1). To verify the novelty of these challenges, the lead authors performed additional literature reviews to assess the knowledge and conceptual and methodological gaps identified.

3 Key research challenges and innovative research paths on and in support of farm transitions to agroecology

3.1 Supporting the exploration and definition of desired futures

3.1.1 Ongoing challenges

Exploring and defining desired futures as targets to aim for is necessary for transition. These targets are desires or visions that sustain the farmers' determination for change. These targets sometimes focus on previously identified solutions (e.g., reintroducing livestock, diversifying crops), but they are sometimes much more open, and their solutions remain unknown (e.g., having more free time to spend with family). They define a horizon (whose distance depends on farmers' ability and willingness to project into the future) that, to be reached, will require farmers to be creative. Exploring and defining these targets can provide the incentive for farmers to reconsider their values and goals or help them define a plan that meets their existing values and goals. By envisioning desired futures, farmers can develop strategies and rationales for action during transitions. Once the transitions have begun, these visions still have several functions, such as paving the transition pathway through frequent backcasting exercises or questioning the choices made and how well they fit with the desired futures. Because transitions are open-ended and depend on changes in the farm environment, these visions should not be considered normative end-points, but rather open-ended heuristics that support farmers' decisions without undermining their adaptability and agility.

Research helps explore and define desired futures in many ways. Future-oriented modeling is one approach for defining and assessing ex ante future farm systems or their subsystems (e.g., cropping systems) (Keating 2020). Among the models available, some use optimization algorithms to identify the most promising options according to certain criteria (Rossing et al. 1997; Bergez et al. 2010; Britz et al. 2021), while others simulate scenarios predefined by farmers (Rodriguez et al. 2014; Le Gal et al. 2022). For instance, Pissonnier et al. (2019) used simulation to assess the influence of radical innovations in farm functioning on three types of performances — pesticide use, work organization, and economics — of apple production systems in which sheep were used to control grass growth in pesticide-free rows between trees. Use of these models by end-users, especially farmers, remains low, since the models are usually complex and have small domains of validity. These models may be easier to use as serious games in which farmers collectively design potential farm system or subsystem configurations and use a farm model to assess them (Hernandez-Aguilera et al. 2020). For instance, in forage rummy (Martin et al. 2011), groups of farmers design alternative configurations of pastoral or crop-livestock farm systems and assess their performance. Playing the game thus helps identify locally relevant future farm systems.

In contrast, expert-based foresight approaches, which have been developed in agricultural sciences (e.g., van der Meulen et al. 2003; Freibauer et al. 2011; Bourgeois and Sette 2017; Mora et al. 2020), often operate at much larger levels than that of farms (Eames and McDowall 2010), ranging from regions or sectors (Bergez et al. 2011) to all of Europe (Poux and Aubert 2018). They have difficulty combining micro and macro levels, which is reflected well by the range of actors who have participated in them (e.g., no farmers). Accordingly, only a few integrated foresight approaches consider the agronomic consistency of the farms they design. For instance, Poux and Aubert (2018) developed a scenario based on integrated crop-livestock systems that included typical crop rotations and related cropping practices. However, this challenges the local relevance of macro-agronomic scenarios that were designed to function in larger-level scenarios (e.g., Europe).

3.1.2 Innovative research paths

We identified three complementary research paths that should be investigated to support the exploration of desirable futures for farms: supporting farmers' creativity, addressing issues of farmers' representation and power, and adapting foresight approaches to more explicitly include the farm level.

(i) Supporting farmers' creativity and design ability Consistent with a vision of agroecology as a bottom-up approach guided by farmers' needs, abilities and strategies, several researchers suggest considering farmers as designers of their own farm systems whom agricultural researchers and advisors should support (e.g., Salembier et al. 2020; Rossing et al. 2021; Prost 2021). This approach values farmers' creativity and ability to tailor solutions to their own contexts, especially when defining desired futures for their farms. The challenge for research is to develop methods, tools, and knowledge that support farmers' own future-oriented design processes by encouraging their creativity (Prost 2021) and showing them that other ways of doing exist and can be effective. "Disruptive" knowledge (Vogl et al. 2016; Toffolini et al. 2017) such as functional trees (e.g., organizing knowledge by relating an objective to multiple farming techniques, some of which are unusual, such as crop mixtures with 7–10 species) can stimulate exploration of scenarios of novel farm systems (Quinio et al. 2022). Inspiring examples, identified by tracking on-farm innovation or system experiments, can also support this exploration since they embody the systemic reasoning required to design scenarios of innovative agroecological systems (Goulet 2013; Salembier et al. 2021). Exploration also helps farmers frame their issues and plans (Chizallet et al. 2020). Several participatory design methods based on participants exchanging knowledge have been developed to organize this exploration, such as structured design spaces (e.g., KCP method, Berthet et al. 2016), use of drawings or sketches (e.g., RIO method, Bos et al. 2009; Elzen and Bos 2019) or simulation modeling (e.g., Rodriguez et al. 2014). However, research on this topic is required to help farmers address design fixations (i.e., processes that result in focusing on a few unvaried solutions) while exploring ideas and realistic actions (Crilly 2019; Quinio et al. 2022).

(ii) Addressing issues of representation and power Farmers' desired futures and plans are contingent on coupled innovations that involve multiple influential actors (e.g., upstream input suppliers, food processing actors, consumers, institutional actors, Klerkx et al. 2017; Meynard et al. 2017; Aare et al. 2021; Boulestreau et al. 2021) who can hinder or support on-farm change processes. Issues of representation and power must be addressed when including these actors in exploring desirable farm futures, because they may have different representations of the problems to address, the objectives to reach or the systems to design. The literature in agroecology addresses these issues of representation and power, but does so mainly through conceptual thinking. It explains how agroecology can give power back to certain actors, especially farmers (i.e., "those who do agriculture" vs "those who know agriculture" (e.g., Coolsaet 2016)), unlike the dominant regime (e.g., Anderson et al. 2021). As described by Barnaud and Van Paassen (2013), few authors address how to consider power asymmetries when setting up a multi-stakeholder process (see also Jeuffroy et al. 2022), although this is a central question when imagining new methods to explore desirable farm futures with diverse agricultural actors. Including them requires carefully selecting which actors to bring together, aligning their representations through participation and facilitation, and knowing how to manage the influence of the diverse actors on the definition of system boundaries and the range of alternative options considered. Power issues could hinder farmers' creativity (either farmers do not dare to explore, or key players do not allow them to). It could also place them in the position of being underlings of influential upstream and downstream actors (e.g., processing actors may prevent the use of a pest-resistant cultivar because it would disrupt their processing). Avoiding this pitfall requires preparing and managing multi-actor settings to explore new solutions (Bos et al. 2009) and identifying, framing and brokering knowledge (Berthet and Hickey 2018). Sociotechnical analysis can be an initial tool to better understand actors' representations, anticipate power issues and identify innovative paths that could bring together several actors to yield systemic change, as done for crop diversification in France (Meynard et al. 2018).

(iii) Adapting foresight approaches Foresight approaches include concepts and methods that represent potential futures and organize an open and transparent discussion about the diversity of these futures and visionary planning. One research challenge is to consider the farm level in foresight approaches so that their results can inspire farmers. Since farms are nested in larger systems (socio-ecological and sociotechnical ones), foresight approaches must be revised to represent and combine the contrasting visions of actors involved in the multiple levels of action. In the "territorial agroecological transition in action" (TATA-BOX) research project, researchers developed a participatory method (Bergez et al. 2019) that includes a normative foresight step to design a "territorial agroecological system". This system is a new organization of local agriculture that meets expectations of local actors by considering current local issues and scenarios of exogenous forces, with the iterative use of graphical tools (e.g., conceptual diagrams, rich pictures, cognitive maps). Pelzer et al. (2020) used a participatory approach to design and assess prospective scenarios of crop diversification with legumes at the regional level. This required defining and simulating future cropping systems at the field and regional levels. Although these two examples considered the levels of the rural region and the agricultural sector, they under-represented the farm level, which indicates the need to integrate it more completely.

3.2 Creating awareness of and assessing farm states, performances, and dynamics

3.2.1 Ongoing challenges

Assessments are crucial in transition processes: they help frame the problem, adjust the changes undertaken, and identify the pathways actually taken. Regarding the role of assessment in transition processes, research can help create awareness of and assess farm states, performance and dynamics during the three stages of the transition process, each of which has different challenges.

First, research can support assessments of farm system states, both the initial state as well as desired and projected states, in their overall complexity (e.g., agronomic, economic, organization, values). This is a real challenge that aggregates several dimensions to assess patterns of farm performance from the perspective of scientific frameworks such as sustainability (Marchand et al. 2014; Coteur et al. 2016) or resilience (Dardonville et al. 2021), as well as from farmers' individual perceptions (Jones and Tanner 2017). Assessing the initial state is particularly crucial for framing the problem: it helps identify the problems that farmers actually encounter and also identify new objectives and/or problems involved in implementing transitions to agroecology. Research has developed several types of tools and methods to support this assessment. Diagnostic-type assessments are key for framing initial problems, but few methods exist to perform them (e.g., de Koeijer et al. 1999), and they are often limited to technical aspects, which ignores issues that are potential major obstacles for farmers such as organization and work issues (Delecourt et al. 2019) or cognitive issues (Toffolini et al. 2017). Process-based simulation is a common approach used to assess farm system states (Rossing et al. 1997; Lobell et al. 2006; Le Gal et al. 2011; Ewert et al. 2015), but integrating accurate descriptions of farm systems and farmers' concerns, especially social criteria at the farm level (Dumont et al. 2021), into these simulations remains a challenge. Multicriteria assessment tools based on indicators (e.g., Sadok et al. 2009; Iocola et al. 2020; Soulé et al. 2021) are another option to assess farm system states. However, one of their disadvantages is an imbalance among sustainability dimensions, and that social sustainability is less detailed than other dimensions and is always based on objective indicators (e.g., number of free days per year) rather than on farmers' perceptions (e.g., satisfaction with the free time). Life cycle assessment (LCA), widely used to assess environmental impacts of agricultural systems and products, is another option for assessing farm system states that considers the entire production cycle (e.g., Nemecek et al. 2015). Nonetheless, current LCA methods misrepresent less intensive agroecological systems since they focus on products without considering other ecosystem services provided by agricultural systems and rarely consider aspects that agroecology aims to improve (e.g., soil health, biodiversity, impacts of pesticide use) (van der Werf et al. 2020). The outputs of these tools are difficult to share with farmers, even though it is crucial that farmers take ownership of these assessments. These assessments are key in creating awareness and encouraging farmers of the need to change. They also help farmers to define their own objectives and influence the paths taken. This raises issues about how to design assessments to enroll farmers. Some articles insist on the importance of co-designing assessments with farmers, especially in peer-to-peer exchanges, and other agrifood actors (e.g., Guzmán et al. 2013; Boulestreau et al. 2021; Leclere et al. 2021), but they remain rare. Even rarer is research on how initial assessments shape the subsequent transition process.

Second, assessments are needed to monitor farms during transitions to agroecology. Farmers need indicators to describe effects of the changes they implement and the ability of these changes to achieve their desired results. These indicators would allow farmers to adjust their practices iteratively and more easily during transitions. Many indicators developed by researchers reflect precise and quantified objectives, but most of them require too many measurements, are too specific, or are calculated at time steps unsuited to farmers' practices. Toffolini et al. (2016) studied the indicators that farmers use when changing techniques and found that they relied mainly on simple, visual, and qualitative indicators that were not usually developed in research. In this sense, some promising studies are emerging, such as visual assessments of soil quality based on simple indicators such as color, smell and the presence of earthworms (e.g., Alaoui et al. 2020; Luján Soto et al. 2021). Assessments based on qualitative observation are intended for farmers who want to quickly assess the effects of changes in practices.

Third, assessments are useful to assess the transitions themselves, that is, qualify and identify, after transitions, the main changes in farm states (i.e., farm structure, the farmer's mindset, objectives and management practices) and how the transitions unfolded. To qualify the dynamics of the transitions and their changes, most studies assess states at regular intervals. Several studies (e.g., Lamine 2011; Padel et al. 2020) qualified levels of changes in practices, such as by using the efficiency-substitution-redesign framework (Hill and MacRae 1996). Although these approaches provide heuristic devices for the diversity of pathways involved in farm transitions, they cannot relate all of their dimensions. To this end, mixed approaches seem a promising pathway (e.g., Colnago et al. 2021). For instance, in longitudinal studies conducted in two French dairy regions, Bouttes et al. (2019a, 2019b, 2020) used a mixed approach that combined inductive-content analysis of farmers' discourse and statistical analysis of multiple indicators to analyze step-by-step changes in farming practices. They showed that besides changing farm technical and economic performances, farmers changed their level of satisfaction in the land, herd, farm economics and social aspects, as well as their perceived adaptive capacity.

3.2.2 Innovative research paths

The innovative research paths we identified focus on the properties that assessment frameworks require to be suitable for farms transitioning to agroecology. The frameworks should be more holistic, more flexible, more dynamic, and explicitly address uncertainty.

(i) More holistic assessment frameworks for farm functioning and farm sustainability Based on the principles of agroecology, the scope of farm assessments has expanded greatly to become holistic. This expansion is a way to acknowledge the complexity of the agroecological phenomena at stake, but this is also a way to include what farmers value in their work, for their farms and for society. Assessment should consider the multiple interactions, which are enhanced on agroecological farms, among farm subsystems that deliver services (e.g., cover crop termination via grazing) as much as they deliver raw products (e.g., meat). The functional units that make sense to farmers may also differ, such as when additional activities (e.g., processing, selling) strongly interact with farming practices (e.g., local customers for dairy products demand a continuous supply of products, whereas long value chains accept interruptions during the year). More generally, agroecology generates new relationships between farms and their sociotechnical systems to meet the global challenges of sustainability. This means that assessments of farming practices should include those that define the farm within its sociotechnical system (e.g., Martin et al. 2020) and the ability of changes to address global challenges (e.g., Aguilera et al. 2020). This is the aim of several approaches. Metabolic approaches (i.e., studies of exchanges of matter and energy between a system and its environment (e.g., Guzmán et al. 2018)) have emerged to address overall production efficiency. The issues involved in producing high-quality food (e.g., van der Ploeg et al. 2019) have been considered using new indicators such as nutritional value, safety, and organoleptic properties (e.g., Peri 2006). Circular and solidarity economy approaches (e.g., Velasco-Muñoz et al. 2021) aim to expand economic sustainability beyond issues of profitability. To improve the social dimension of sustainability assessments (Janker and Mann 2020), several studies consider subjective well-being measures as useful indicators to describe sustainable and resilient farm systems (e.g., Jones and Tanner 2017). Thus, subjective assessments are a promising way to consider the social dimension of sustainability, via satisfaction (Perrin et al. 2020), aesthetics (Boeraeve et al. 2020), and work conditions (Duval et al. 2021). In the same spirit, analyzing peer exchanges about their transitions to agroecology provides privileged access to the way farmers assess their situations (Slimi et al. 2021). These peer-to-peer exchanges create awareness of the need to transition, provide useful support for the transition, and help researchers understand what farmers consider relevant. The remaining challenge is to combine these different approaches to develop a more holistic assessment of agricultural system performance that would also be meaningful and relevant for farmers.

(ii) More flexible assessment frameworks to adapt to global and local challenges Agroecology involves addressing diversity in a broad sense, which makes the assessments more complex (Catarino et al. 2021). For instance, implementing an agroecological system on a farm depends on the farmer's willingness and the larger enabling environment of the farm (e.g., Ryschawy et al. 2019), since practices implemented at a given level can influence other levels. The assessments are more complex because they must address the increasing expression of specific local characteristics (e.g., soil-climate contexts) and farmers' individual characteristics (e.g., personal values) that accompany agroecology (Coquil et al. 2018; Bezner Kerr et al. 2022). This requires flexible frameworks in which a subset of indicators can be selected based on the farm's context (e.g., MESMIS, López-Ridaura et al. 2002). Farmers use many specific indicators that differ from those developed in agricultural research to assess the status of new farm systems (Toffolini et al. 2016). Flexible assessment frameworks are expected to facilitate farmers' and other actors' participation (e.g., TAPE, Mottet et al. 2020) and even adoption for individual use, which has been low to date. This includes frameworks that define assessment criteria that can be adapted to each situation, as well as visualization tools that can be adapted to each context (e.g., literacy, experience in interpreting graphs). These challenges are critical to facilitate ownership of the assessment results, create awareness, and induce the need for change in farmers and other actors in the agrifood systems.

(iii) More dynamic assessment frameworks To date, farm system assessment has been based mainly on snapshot measurements of sustainability indicators. This makes it more difficult to confirm the presumed potential of agroecological farming to increase farm resilience (Leippert et al. 2020; Soulé et al. 2021). Global changes, especially climate change, threaten the future of farms due to predictable and highly impacting trends, as well as unpredictable extreme events. We thus need to better consider farm system dynamics to assess the diverse dynamics of changes and their influence on farm performance patterns, as well as unexpected results. This focus is essential to understand how to consistently prioritize changes during transitions. Two main types of approaches exist to assess these dynamics: means-based (or causal), at a single point in time, and effect-based, over time (van der Werf and Petit 2002; Dardonville et al. 2021). From a means-based perspective, a survey at a single point in time is used to collect data on pre-defined properties considered favorable for farm system dynamics from a researcher's or other actor's perspective (e.g., diversity, connectivity) (Diserens et al. 2018). Its main disadvantage is that it ignores threshold effects and interactions among properties. For instance, diversity is always considered a factor of resilience, regardless of its level (Cabell and Oelofse 2012; Dardonville et al. 2020), even though diversity beyond a given threshold might complicate management too much for most farmers. The effect-based perspective uses longitudinal surveys of farm samples to obtain a range of quantitative and qualitative data and to relate the multiple changes that occur on the farm. Its advantage is that it integrates the logic that underlies farmers' decisions and assigns meaning to quantitative data (e.g., Chantre et al. 2015). However, this approach is costly, which limits the size of farm samples (Bouttes et al. 2019a, 2020). Accordingly, developing evidence from local case studies should be based on cross-case analysis. A third approach is to focus on slow variables (e.g., soil organic matter) that are key determinants of the long-term performance and resilience of farms (van Apeldoorn et al. 2011) and provide information about their legacy effects (Pullens et al. 2021). However, this requires identifying the slow variables relevant to agriculture, which available assessment frameworks do not adequately represent.

(iv) Assessment frameworks that explicitly address uncertainty One challenge when assessing agroecological farms is their high uncertainty. This uncertainty is due to the nature of the dynamics involved (e.g., ecological, human interactions), which are fundamentally uncertain and include multiple feedback loops and emergent properties. These dynamics are not fully understood, and it is not possible to know everything about them on each farm.

By testing and monitoring these systems, experimentation is one approach used to assess uncertainty and decrease it in their results, as long as system experiments are performed (Dejoux et al. 2003; Simon et al. 2017; Ciaccia et al. 2020). A complementary approach is to model the farm or its subsystems. Traditional process–based models (e.g., FASSET, Berntsen et al. 2003; FLORSYS, Colbach et al. 2021) can simulate the unknown. However, the novel interplay between farm entities and farming practices induced by agroecology might challenge the domain of validity of most of these models, thus requiring careful interpretation of outputs. Hybrid modeling approaches are promising ways to integrate scientific and expert knowledge into parsimonious models. They are not necessarily process-based and can consider effects of practices for which data are not yet available (e.g., IPSIM, Robin et al. 2013; PERSYST, Ballot et al. 2018). Another promising path is to assume that a farm's behavior is not purely deterministic. In this way, uncertainty is no longer considered as marginal noise around predictable dynamics but rather as a core element of the dynamics. When adopting this perspective, properties such as resilience (Tittonell 2020), vulnerability (Bouttes et al. 2019a), viability (Sabatier et al. 2015) or robustness (ten Napel et al. 2011) become as important as productivity when assessing system performance. Thus, studies of agroecological systems increasingly focus on the ability of different system configurations to address uncertainty (e.g., Paut et al. 2020; Benoit et al. 2020). Beyond system configurations, recent algorithmic developments provide tools to explore management options themselves. This is the case for recent developments in viability theory that can search for resilient management options in an agroecosystem. For instance, Sabatier et al. (2017) used viability theory to quantify engineering resilience (i.e., return time after a perturbation) and ecological resilience (i.e., magnitude of a perturbation that a system can tolerate) of a mixed-species livestock farm system.

3.3 Analyzing and supporting farms during transitions

3.3.1 Ongoing challenges

The term "transition" implies the presence of "processes". Recent studies of farm transitions include longitudinal studies that describe the long-term and experiential nature of transition pathways (e.g., Sutherland et al. 2012; Chantre and Cardona 2014; Falconnier 2016; Coquil et al. 2017; Aare et al. 2021; Hazard et al. 2021). These studies highlighted the diversity of dimensions that explain these pathways (Merot et al. 2019), the learning processes involved (Mawois et al. 2019; Marinus et al. 2021), and the role of experiments in the learning process (Ingram 2010; Catalogna et al. 2018; Périnelle et al. 2021). These change processes can be considered as "step-by-step design" processes (Meynard et al. 2012). This term highlights that farmers in transition are constantly assessing, generating new solutions and testing these solutions in their context, which makes them designers of their farms. Similarly, using concepts from natural resource management, other studies analyze transitions as adaptive-management processes during which farmers address uncertainties through constant reassessment and learning (e.g., Prost et al. 2018; Bouttes et al. 2019b). Beyond their different conceptual foundations, these studies analyze farmers' change processes "in the making" to bridge the gap between thinking and doing in design processes (Lacombe et al. 2018). This raises several analytical questions about these processes, especially their drivers, steps and dynamics. For instance, Merot et al. (2019) combined several indicators of change to describe conversion processes to organic farming, which enabled them to qualify the intensity and speed of change during these transitions. This perspective also challenges the knowledge and tools that support the monitoring of these long-term, adaptive, and interactive processes. Approaches must be developed to make use of ecological and biological dynamics of the farm and its environment, and to support farmers' learning processes. For instance, to encourage changes in farm systems, Périnelle et al. (2021) and Leclere et al. (2018) brought together farmers with diverse farming experiences and combined tracking of on-farm innovation with farmers' assessments in participatory prototyping experiments designed from farmers' own innovations.

3.3.2 Innovative research paths

We identified four directions for innovative research. The first two address the need to improve understanding of actual change processes on farms: the activities that farmers engage in and their specific dynamics. The last two include revising the methods and tools used to analyze and support monitoring of farms during transitions: the role that experiments may play and the need for strategic tools.

(i) Improving understanding of what happens on farms during transitions Identifying the activities that these transitions involve for those who implement them in a change process has renewed interest in farmers' skills, creativity and knowledge, with multiple promising perspectives. Several studies investigate ways to value the innovative pathways farmers have taken that inspire others. These studies investigate ways to support farmers by encouraging their own exploration, such as by tracking farmer innovations (Salembier et al. 2021) or long-term iterative monitoring (Dogliotti et al. 2014; Falconnier et al. 2017; Prost et al. 2018). The idea is to increase farmers' ability to design their own pathways of change by valuing their "creativity of action" (i.e., addressing conditions and adapting objectives flexibly and incrementally to situational contexts) (Milestad et al. 2012; Coquil et al. 2017). Other studies are based on the idea that farm transitions to agroecology are a knowledge-intensive process (e.g., Holt-Giménez and Altieri 2013; Coolsaet 2016; Teixeira et al. 2018; Bendfeldt et al. 2021) that should value farmers' knowledge along with scientific knowledge. They are reactivating the research approach that studies how practitioners' knowledge can fuel innovation (Rossing et al. 2021) and how science can make it explicit, make use of it or articulate with it (e.g., Ingram 2008; Girard 2015; Toffolini et al. 2017; Girard and Magda 2020). Many questions are already known (but not answered): how to make farmers' knowledge explicit, how to make it relevant for others even if produced under different agricultural conditions, and how to formalize it. Other questions are emerging, such as the connection with the digitization of agriculture and how digital technology can generate, formalize, capitalize, and circulate this distributed knowledge (e.g., Carolan 2020).

Some recent studies that address the nature of farm transitions highlight the huge diversity of factors that define farms, which sometimes differ greatly from the traditional model of family farms (e.g., collective farming, farms managed by hourly workers, "company" farms that delegate farm management; see Nguyen and Purseigle 2012; Agarwal and Dorin 2019). This should help to consider how transitions are performed on all types of farms. Increasing the number of collective farms could be an opportunity to manage the complexity of more diversified agroecological farms, or farms that develop practices beyond raw production, such as processing, direct selling or short-supply-chain selling. At the same time, they challenge the construction and management of commons (i.e., land that is shared, managed and maintained collectively) and the development of individual and collective farming practices.

(ii) Analyzing and modeling dynamics of processes involved in changes on the farm Future research should analyze transitions in the making to better understand the reality of farm change processes. As mentioned, this involves considering the multiple dimensions included in these transitions (e.g., biophysical, ecological, technical, cognitive, social). It also requires considering their specific temporal dimensions to define short-term (e.g., actions, events, crises) and long-term (e.g., soils, landscapes, ecological processes, social arrangements) horizons and goals. Understanding and quantifying the dynamic properties of farm systems is a particularly open research path. We have mentioned recent developments for quantifying farm robustness, flexibility, vulnerability, and resilience. Future developments in viability-based modeling could be used to explore transition dynamics when the objective is not clearly defined. Other studies focus on conflicts among temporal dimensions that must be managed when trying to adopt agroecological, and thus more complex, farm systems. For instance, Paut et al. (2021) studied differences in temporal dynamics between crop types within systems that combined perennials and annuals. They demonstrated complex trade-offs between immediate provision of the production service and other ecosystem services in the future depending on the management strategies selected. Although some studies have already provided insights (e.g., Chantre et al. 2015; Merot et al. 2020), organizing the diversity of farm transition pathways to identify types or styles of transition dynamics remains a huge challenge.

(iii) Giving a new role to experiments to analyze farms during transitions Agricultural sciences mainly use observation, modeling and experimentation to analyze phenomena. Beyond the challenges involved in the first two approaches, experimenting with farm transitions also faces major challenges. Long-term system experiments, defined in opposition to factorial experiments, were an initial attempt to experiment with farm changes in the making (Silva and Tchamitchian 2018). Multi-actor platforms of experiments (EIP-Agri 2017; Fieldsend et al. 2021) and now living labs (Gamache et al. 2020; Toffolini et al. 2021) have maintained the idea of learning-by-doing, but they have widened the range of actors concerned by connecting multiple actors in local experiments. These forms of experiments, with their wide range of actual practices, generate multiple methodological questions about how to monitor them, how to analyze the large amount of data they generate at overlapping temporal horizons and organizational levels, and how to make the results of single non-reproducible experiments more general (Simon et al. 2017; Deytieux et al. 2018; Rivero et al. 2021).

Another innovative perspective for experiments is to value on-farm experiments (Lacoste et al. 2022; Catalogna et al. 2022), that is, to make use of farmers' trial and error when they transition to agroecology. This perspective raises research questions about how to produce science with sometimes heterogeneous agronomic data, how to formalize and share what is happening on each farm, how the perspective raises questions about current innovation ecosystems, how to acknowledge and share each farmer's creativity, and how single experiments can support transitions of other farmers. Several recent studies have shown the benefits of collectively sharing results of on-farm experiments to support changes in practices to those that are more sustainable, mostly from an agronomic perspective, such as intercropping (Aare et al. 2021), introducing rarely used or underused species (Leclere et al. 2018) or developing legume-based cropping systems (Périnelle et al. 2021). These approaches need to be expanded to the systemic issues raised by transitions to agroecology (e.g., interactions between farm enterprises, upstream-downstream coordination).

(iv) Developing strategic tools to support farms during transitions Research also faces many challenges when focusing on ways to support transitions in the making. Much research has focused on farmers' decision-support tools, with differing degrees of success in their adoption (e.g., McCown 2001; Cerf et al. 2012; Rose et al. 2016); however, one can wonder whether supporting farmers' decisions still matters. Since farmers who are transitioning are involved in the step-by-step process of adaptive design, there may be less need for decision-support tools (DSS) and greater need for design-support tools (Prost 2021) that would support assessment, creativity, observation and action (e.g., a new method for managing wheat based on monitoring its N nutrition status (Ravier et al. 2018)). An interesting approach would be to develop tools to support farmers in strategic monitoring (vs tactical and operational monitoring) of the farm systems they are developing. As mentioned (Section 3.2.1), farmers need indicators to describe the effects of the changes they implement on patterns of farm performance. Information about long-term effects could be included in these strategic tools. We identified several pioneering studies that focused on developing tools for strategic monitoring (e.g., Hémidy et al. 1993; Hochman et al. 2009). Does supporting farm transitions to agroecology revive the need for such tools (e.g., Pissonnier et al. 2017; Le Gal et al. 2022), or does agroecology come with specific questions that these tools should address? For instance, can these tools capture the ecological processes that should be considered when trying to develop agroecological systems? This question remains open.

4 Conclusions and perspectives

We reviewed the growing literature on farm transitions to agroecology in advanced economies. To support this review, we developed an original conceptualization of farm transitions to agroecology. We identified three types of research activities on and in support of transitions: supporting the exploration and definition of desired futures; creating awareness of and assessing farm states, performances and dynamics throughout transitions; and analyzing and supporting farms during transitions.

For each of these research activities, we identified state-of-the-art research and highlighted key research challenges and promising research paths (Fig. 3). Our work highlights that support of the exploration and definition of desired farm futures suffers from low adoption of the methods and tools developed by researchers and lack of integration of the farm level in expert-based foresight approaches. There is therefore a need to explicitly integrate the farm level in these approaches and develop new methods and tools that stimulate farmers' and other actors' creativity while addressing issues of representation and power among them. We also observe that farm assessments do not sufficiently integrate social criteria or the full range of farmers' perceptions, and they are not developed or used enough to raise farmers' awareness of the need to change. These assessments also tend to misrepresent the complexity of agroecological systems and consider such systems over temporal horizons that are too short. More holistic, flexible, and dynamic assessment frameworks that explicitly address uncertainty are needed. We also come to the conclusion that support of farms during transitions to agroecology suffers from a lack of knowledge about farmers' change processes and a lack of monitoring methods and tools. Studies focusing on actual change processes, notably their temporal dimensions, are needed, as is the renewed use of experiments and DSS to support change.

When considering these challenges, it is clear that agricultural sciences must address cross-cutting challenges on this relatively recent topic of farm transitions to agroecology.

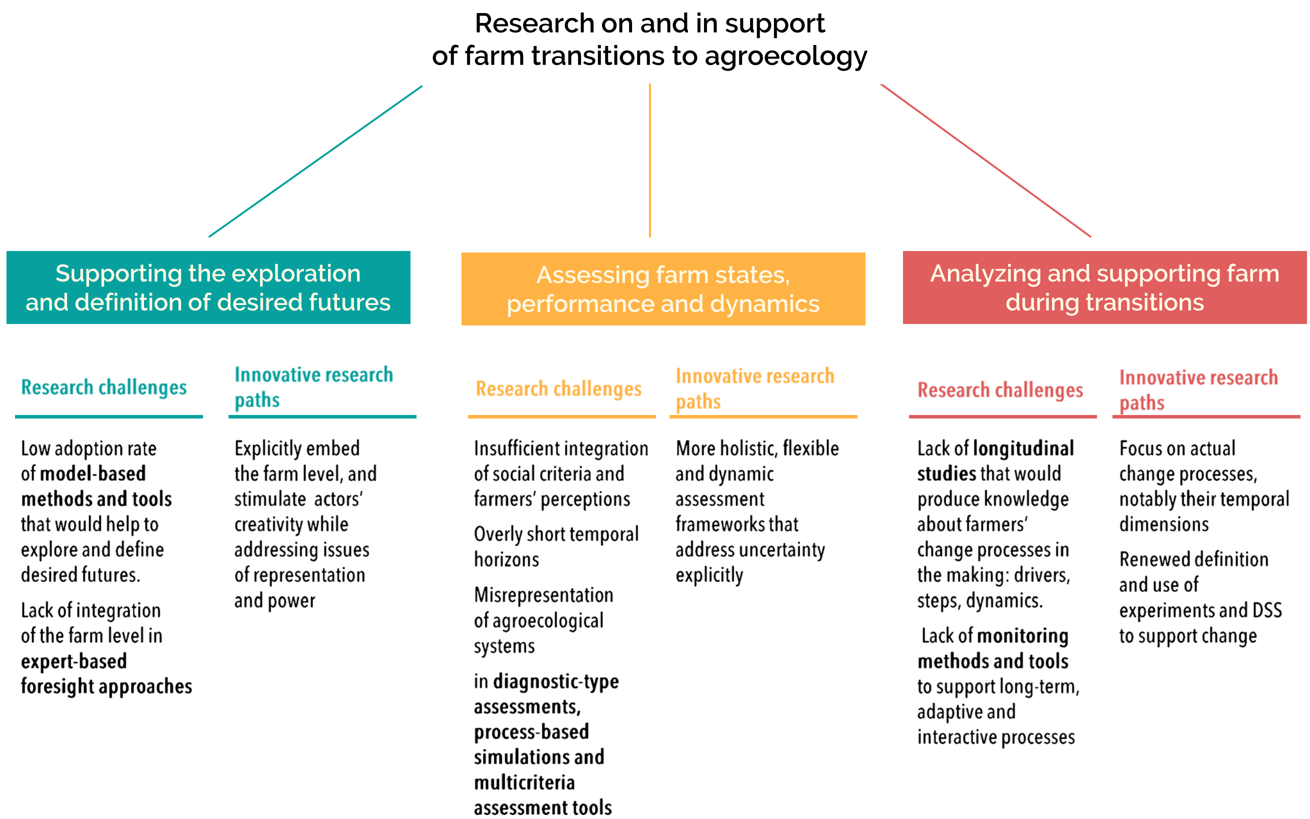

Fig. 3 Summary of findings across the three research activities that address farm transitions to agroecology. DSS: decision-support system.

Farm transitions to agroecology require reconsidering the system boundaries, studied dimensions, and site-, space-, and time-specificity of farm systems. They also require navigating across organizational levels (from the field to food system) to consider their imbrications, synergies, and antagonisms when combining innovations in the context of specific socio-technical systems, each with its own collective rules. Navigating short- and long-term temporal horizons emerges as another cross-cutting challenge overlooked by agricultural sciences. Navigating this is complex due to the unpredictable interactions between natural, technological, and social components of farm transitions. Because these interactions generate both predictable issues and surprises, farm transitions need to be considered as open-ended, evolutionary and adaptive processes. Finally, supporting farm transitions to agroecology requires building knowledge and tools whose content and layout are meaningful to farmers.

This interdisciplinary review built topical presentations during a webinar that helped identify research challenges and promising research pathways on farm transitions to agroecology. One of its limits is that although the review focused on advanced economies, all co-authors work in France, which could have resulted in overemphasizing research that addresses problems there. Another limit is that the review was restricted to research conducted in advanced economies; some additional challenges and pathways identified for low- and middle-income regions might also be relevant in advanced economies. A third limit is that the review focused on the farm level, whereas it is clear that farm transitions are influenced by the socio-technical context in which they are embedded. According to Anderson et al. (2021), "the large-scale transformation of food systems is actually many transformations, in which cultural shifts, policy changes, struggles and networks intervene in complex, dynamic, often contradictory ways", and farm transitions are just one of these transformations. Further research is needed to identify the complex relations between farms and their broader socio-technical systems, especially the market and policy regulations that can promote transition at scale.

The challenges involved in farm transitions to agroecology also challenge research organization and funding. Working on transitions means working on long-term processes. This requires visibility regarding the means assigned to research. More adaptive management of research projects is also needed to keep up with the reality of transition processes, which are themselves adaptive. This goes against current procedures in which research questions, partnerships and deliverables must be set before projects start. At the same time, research needs to be extremely responsive to emerging issues and explore them with agility. In particular, when research is oriented to support transitions, it should involve non-scientific actors and be organized for social learning and dynamic monitoring so the actors can adjust to emerging requirements while having time to establish solid collaborations. Acknowledging that most budgets for agricultural research are currently spent on projects, the question remains: are the current forms and requirements of these projects adapted to these challenges?

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-022-00855-8.

Acknowledgements The authors acknowledge the financial and operational support of INRAE divisions ACT and AgroEcoSystem for organizing the webinar. Several studies mentioned in the review have benefitted from the dynamics of IDEAS (Initiative for Design in Agrifood Systems, https://www6.inrae.fr/ideas-agrifood). The authors deeply thank all participants of the webinar for their input, the editor and the reviewers for their constructive comments, and Michelle and Michael Corson for proofreading the English.

Authors' contributions Conceptualization, LP and GM; Methodology, LP and GM; Investigation, all authors; Original Draft, LP and GM; Writing – Review & Editing, all authors

Funding This work was funded by the INRAE divisions ACT and AgroEcoSystem.

Data availability Not applicable

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

References

Aare AK, Lund S, Hauggaard-Nielsen H (2021) Exploring transitions towards sustainable farming practices through participatory research – the case of Danish farmers' use of species mixtures. Agric Syst 189:103053. https://doi.org/10.1016/j.agsy.2021.103053

Agarwal B, Dorin B (2019) Group farming in France: why do some regions have more cooperative ventures than others? Environ Plan A 51:781–804. https://doi.org/10.1177/0308518X18802311

Aguilera E, Díaz-Gaona C, García-Laureano R et al (2020) Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review. Agric Syst 181:102809. https://doi.org/10.1016/J.AGSY.2020.102809

Alaoui A, Barão L, Ferreira CSS et al (2020) Visual assessment of the impact of agricultural management practices on soil quality. Agron J 112:2608–2623. https://doi.org/10.1002/agj2.20216

Altieri MA (1989) Agroecology: a new research and development paradigm for world agriculture. Agric Ecosyst Environ 27:37–46. https://doi.org/10.1016/0167-8809(89)90070-4

Anderson CR, Maughan C (2021) "The innovation imperative": the struggle over agroecology in the International Food Policy Arena. Front Sustain Food Syst 5:619185. https://doi.org/10.3389/fsufs.2021.619185

Anderson CR, Bruil J, Chappell MJ et al (2021) Power, governance and agroecology transformations. In: Anderson CR, Bruil J, Chappell MJ et al (eds) Agroecology now!: transformations towards more just and sustainable food systems. Springer International Publishing, Cham, pp 153–173

Ballot R, Loyce C, Jeuffroy M-H et al (2018) First cropping system model based on expert-knowledge parameterization. Agron Sustain Dev 38:33. https://doi.org/10.1007/s13593-018-0512-8

Barnaud C, Van Paassen A (2013) Equity, power games, and legitimacy: dilemmas of participatory natural resource management. Ecol Soc 18. https://doi.org/10.5751/ES-05459-180221

Bendfeldt E, McGonagle M, Niewolny K (2021) Rethinking farmer knowledge from soil to plate through narrative inquiry: an agroecological food systems perspective. J Agric Food Sys Community Dev 11:137–151. https://doi.org/10.5304/jafscd.2021.111.012

Benoit M, Joly F, Blanc F et al (2020) Assessment of the buffering and adaptive mechanisms underlying the economic resilience of sheep-meat farms. Agron Sustain Dev 40:34. https://doi.org/10.1007/s13593-020-00638-z

Bergez J-E, Colbach N, Crespo O et al (2010) Designing crop management systems by simulation. Eur J Agron 32:3–9. https://doi.org/10.1016/j.eja.2009.06.001

Bergez J-E, Carpy-Goulard F, Paradis S, Ridier A (2011) Participatory foresight analysis of the cash crop sector at the regional level: case study from southwestern France. Reg Environ Chang 11:951–961. https://doi.org/10.1007/s10113-011-0232-y

Bergez J-E, Audouin E, Therond O (eds) (2019) Agroecological transitions: from theory to practice in local participatory design. Springer International Publishing

Berntsen J, Petersen BM, Jacobsen BH et al (2003) Evaluating nitrogen taxation scenarios using the dynamic whole farm simulation model FASSET. Agric Syst 76:817–839. https://doi.org/10.1016/S0308-521X(02)00111-7

Berthet ET, Hickey GM (2018) Organizing collective innovation in support of sustainable agro-ecosystems: The role of network management. Agric Syst 165:44–54. https://doi.org/10.1016/j.agsy.2018.05.016

Berthet ETA, Barnaud C, Girard N et al (2016) How to foster agroecological innovations? A comparison of participatory design methods. J Environ Plan Manag 59:280–301. https://doi.org/10.1080/09640568.2015.1009627

Bezner Kerr R, Liebert J, Kansanga M, Kpienbaareh D (2022) Human and social values in agroecology: a review. Elem Sci Anth 10:00090. https://doi.org/10.1525/elementa.2021.00090

Boeraeve F, Dufrêne M, Dendoncker N et al (2020) How are landscapes under agroecological transition perceived and appreciated? A Belgian case study. Sustainability 12:2480. https://doi.org/10.3390/su12062480

Boone L, Roldán-Ruiz I, Van linden V et al (2019) Environmental sustainability of conventional and organic farming: accounting

for ecosystem services in life cycle assessment. Sci Total Environ 695:133841. https://doi.org/10.1016/j.scitotenv.2019.133841
Borrello M, Pascucci S, Caracciolo F et al (2020) Consumers are willing to participate in circular business models: a practice theory perspective to food provisioning. J Clean Prod 259:121013. https://doi.org/10.1016/j.jclepro.2020.121013
Borsato E, Zucchinelli M, D'Ammaro D et al (2020) Use of multiple indicators to compare sustainability performance of organic vs conventional vineyard management. Sci Total Environ 711:135081. https://doi.org/10.1016/j.scitotenv.2019.135081
Bos AP, Koerkamp PWGG, Gosselink JMJ, Bokma S (2009) Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. Outlook Agric 38:137–145
Boulestreau Y, Casagrande M, Navarrete M (2021) Analyzing barriers and levers for practice change: a new framework applied to vegetables' soil pest management. Agron Sustain Dev 41:44. https://doi.org/10.1007/s13593-021-00700-4
Bourgeois R, Sette C (2017) The state of foresight in food and agriculture: challenges for impact and participation. Futures. https://doi.org/10.1016/j.futures.2017.05.004
Bouttes M, Bize N, Maréchal G et al (2019a) Conversion to organic farming decreases the vulnerability of dairy farms. Agron Sustain Dev 39:19. https://doi.org/10.1007/s13593-019-0565-3
Bouttes M, Darnhofer I, Martin G (2019b) Converting to organic farming as a way to enhance adaptive capacity. Org Agr 9:235–247. https://doi.org/10.1007/s13165-018-0225-y
Bouttes M, Bancarel A, Doumayzel S et al (2020) Conversion to organic farming increases dairy farmers' satisfaction independently of the strategies implemented. Agron Sustain Dev 40:12. https://doi.org/10.1007/s13593-020-00616-5
Britz W, Ciaian P, Gocht A et al (2021) A design for a generic and modular bio-economic farm model. Agric Syst 191:103133. https://doi.org/10.1016/j.agsy.2021.103133
Brun J, Jeuffroy M-H, Pénicaud C et al (2021) Designing a research agenda for coupled innovation towards sustainable agrifood systems. Agric Syst 191:103143. https://doi.org/10.1016/j.agsy.2021.103143
Cabell JF, Oelofse M (2012) An indicator framework for assessing agroecosystem resilience. Ecol Soc 17:18
Carolan M (2020) Acting like an algorithm: digital farming platforms and the trajectories they (need not) lock-in. Agric Hum Values 37:1041–1053. https://doi.org/10.1007/s10460-020-10032-w
Catalogna M, Dubois M, Navarrete M (2018) Diversity of experimentation by farmers engaged in agroecology. Agron Sustain Dev 38:50. https://doi.org/10.1007/s13593-018-0526-2
Catalogna M, Dunilac Dubois M, Navarrete M (2022) Multi-annual experimental itinerary: an analytical framework to better understand how farmers experiment agroecological practices. Agron Sustain Dev 42:20. https://doi.org/10.1007/s13593-022-00758-8
Catarino R, Therond O, Berthomier J et al (2021) Fostering local crop-livestock integration via legume exchanges using an innovative integrated assessment and modelling approach based on the MAELIA platform. Agric Syst 189:103066. https://doi.org/10.1016/j.agsy.2021.103066
Cerf M, Jeuffroy M-H, Prost L, Meynard J-M (2012) Participatory design of agricultural decision support tools: taking account of the use situations. Agron Sustain Dev 32:899–910. https://doi.org/10.1007/s13593-012-0091-z
Chantre E, Cardona A (2014) Trajectories of French field frop farmers moving toward sustainable farming practices: change, learning, and links with the advisory services. Agroecol Sustain Food Syst 38:573–602. https://doi.org/10.1080/21683565.2013.876483
Chantre E, Cerf M, Le Bail M (2015) Transitional pathways towards input reduction on French field crop farms. Int J Agric Sustain 13:69–86. https://doi.org/10.1080/14735903.2014.945316
Chizallet M, Prost L, Barcellini F (2020) Supporting the design activity of farmers in transition to agroecology: towards an understanding. Le travail humain 83:33–59. https://doi.org/10.3917/th.831.0033
Ciaccia C, Ceccarelli D, Antichi D, Canali S (2020) Chapter 10 - Long-term experiments on agroecology and organic farming: the Italian long-term experiment network. In: Bhullar GS, Riar A (eds) Long-Term Farming Systems Research. Academic Press, pp 183–196
Colbach N, Colas F, Cordeau S et al (2021) The FLORSYS crop-weed canopy model, a tool to investigate and promote agroecological weed management. Field Crop Res 261:108006. https://doi.org/10.1016/J.FCR.2020.108006
Colnago P, Rossing WAH, Dogliotti S (2021) Closing sustainability gaps on family farms: combining on-farm co-innovation and model-based explorations. Agric Syst 188:103017. https://doi.org/10.1016/j.agsy.2020.103017
Compagnone C, Lamine C, Dupré L (2018) The production and circulation of agricultural knowledge as interrogated by agroecology. Revue d'anthropologie des connaissances 12-12. http://journals.openedition.org/rac/815
Coolsaet B (2016) Towards an agroecology of knowledges: recognition, cognitive justice and farmers' autonomy in France. J Rural Stud 47:165–171. https://doi.org/10.1016/j.jrurstud.2016.07.012
Coquil X, Béguin P, Dedieu B (2014) Transition to self-sufficient mixed crop–dairy farming systems. Renew Agr Food Syst 29:195–205. https://doi.org/10.1017/S1742170513000458
Coquil X, Dedieu B, Beguin P (2017) Professional transitions towards sustainable farming systems: the development of farmers' professional worlds. Work 57:325–337. https://doi.org/10.3233/WOR-172565
Coquil X, Cerf M, Auricoste C et al (2018) Questioning the work of farmers, advisors, teachers and researchers in agro-ecological transition. A review. Agron Sustain Dev 38:47. https://doi.org/10.1007/s13593-018-0524-4
Coteur I, Marchand F, Debruyne L et al (2016) A framework for guiding sustainability assessment and on-farm strategic decision making. Environ Impact Assess Rev 60:16–23. https://doi.org/10.1016/J.EIAR.2016.04.003
Crilly N (2019) Creativity and fixation in the real world: a literature review of case study research. Des Stud 64:154–168. https://doi.org/10.1016/j.destud.2019.07.002
Dardonville M, Urruty N, Bockstaller C, Therond O (2020) Influence of diversity and intensification level on vulnerability, resilience and robustness of agricultural systems. Agric Syst 184:102913. https://doi.org/10.1016/j.agsy.2020.102913
Dardonville M, Bockstaller C, Therond O (2021) Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive capacity of temperate agricultural systems. J Clean Prod 286:125456. https://doi.org/10.1016/j.jclepro.2020.125456
Dardonville M, Bockstaller C, Villerd J, Therond O (2022) Resilience of agricultural systems: biodiversity-based systems are stable, while intensified ones are resistant and high-yielding. Agric Syst 197:103365. https://doi.org/10.1016/j.agsy.2022.103365
Darnhofer I, Bellon S, Dedieu B, Milestad R (2010) Adaptiveness to enhance the sustainability of farming systems. A review. Agron Sustain Dev 30:545–555. https://doi.org/10.1051/agro/2009053
de Koeijer TJ, Wossink GAA, van Ittersum MK et al (1999) A conceptual model for analysing input–output coefficients in arable farming systems: from diagnosis towards design. Agric Syst 61:33–44. https://doi.org/10.1016/S0308-521X(99)00030-X
Dejoux J-F, Meynard J-M, Reau R et al (2003) Evaluation of environmentally-friendly crop management systems based on very early sowing dates for winter oilseed rape in France. Agronomie 23:725–736. https://doi.org/10.1051/agro:2003050
Delecourt E, Joannon A, Meynard J-M (2019) Work-related information needed by farmers for changing to sustainable cropping practices. Agron Sustain Dev 39:28. https://doi.org/10.1007/s13593-019-0571-5

Deytieux V, Burstin J, Lemanceau P et al (2018) CA-SYS: a long term experimental platform on agroecology at various scales. In: XV European Society for Agronomy Congress, Innovative cropping and farming systems for high quality food production systems. Genève, Suisse

Diserens F, Choptiany J, Barjolle D et al (2018) Resilience assessment of Swiss farming systems: piloting the SHARP-tool in Vaud. Sustain 10:4435. https://doi.org/10.3390/su10124435

Dogliotti S, García MC, Peluffo S et al (2014) Co-innovation of family farm systems: a systems approach to sustainable agriculture. Agric Syst 126:76–86. https://doi.org/10.1016/j.agsy.2013.02.009

Dumont AM, Wartenberg AC, Baret PV (2021) Bridging the gap between the agroecological ideal and its implementation into practice. A review. Agron Sustain Dev 41:32. https://doi.org/10.1007/s13593-021-00666-3

Duru M, Therond O, Fares M (2015a) Designing agroecological transitions; a review. Agron Sustain Dev 35:1237–1257. https://doi.org/10.1007/s13593-015-0318-x

Duru M, Therond O, Martin G et al (2015b) How to implement biodiversity-based agriculture to enhance ecosystem services: a review. Agron Sustain Dev 35:1259–1281. https://doi.org/10.1007/s13593-015-0306-1

Duval JE, Blanchonnet A, Hostiou N (2021) How agroecological farming practices reshape cattle farmers' working conditions. Agroecol Sustain Food Syst 45:1480–1499. https://doi.org/10.1080/21683565.2021.1957062

Eames M, McDowall W (2010) Sustainability, foresight and contested futures: exploring visions and pathways in the transition to a hydrogen economy. Technol Anal Strateg Manag 22:671–692. https://doi.org/10.1080/09537325.2010.497255

EIP-Agri (2017) Horizon 2020 - multi-actor projects. In: https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_brochure_multi-actor_projects_2017_en_web.pdf

Elzen B, Bos B (2019) The RIO approach: design and anchoring of sustainable animal husbandry systems. Technol Forecast Soc Chang 145:141–152. https://doi.org/10.1016/j.techfore.2016.05.023

Eurostat (2021a) Agri-environmental indicator - specialisation - statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_specialisation. Accessed 2 Dec 2021

Eurostat (2021b) Agri-environmental indicator - mineral fertiliser consumption - statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_mineral_fertiliser_consumption. Accessed 2 Dec 2021

Eurostat (2021c) Extra-EU trade in agricultural goods - statistics explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Extra-EU_trade_in_agricultural_goods. Accessed 2 Dec 2021

Eurostat (2021d) Glossary:agricultural holding. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Agricultural_holding. Accessed 12 Apr 2022

Ewert F, Rötter RP, Bindi M et al (2015) Crop modelling for integrated assessment of risk to food production from climate change. Environ Model Softw 72:287–303. https://doi.org/10.1016/J.ENVSOFT.2014.12.003

Falconnier GN (2016) Trajectories of agricultural change in southern Mali. Wageningen University

Falconnier GN, Descheemaeker K, Van Mourik TA et al (2017) Co-learning cycles to support the design of innovative farm systems in southern Mali. Eur J Agron 89:61–74. https://doi.org/10.1016/j.eja.2017.06.008

FAO (2018) The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems. https://www.fao.org/documents/card/en/c/I9037EN/. Accessed 12 Oct 2021

FAO (2022) Scaling up agroecology to achieve the sustainable development goals. https://www.fao.org/agroecology/overview/agroecology-and-the-sustainable-development-goals/en/. Accessed 12 Oct 2021

Ferguson BG, Maya MA, Giraldo O et al (2019) Special issue editorial: what do we mean by agroecological scaling? Agroecol Sustain Food Syst 43:722–723. https://doi.org/10.1080/21683565.2019.1630908

Fieldsend AF, Cronin E, Varga E et al (2021) 'Sharing the space' in the agricultural knowledge and innovation system: multi-actor innovation partnerships with farmers and foresters in Europe. J Agric Educ Ext 27:423–442. https://doi.org/10.1080/1389224X.2021.1873156

Francis C, Lieblein G, Gliessman S et al (2003) Agroecology: the ecology of food systems. J Sustain Agric 22:99–118. https://doi.org/10.1300/J064v22n03_10

Freibauer A, Mathijs E, Brunori G et al (2011) Sustainable food consumption and production in a resource-constrained world summary findings of the EU SCAR third foresight exercise. EuroChoices 10:38–43. https://doi.org/10.1111/j.1746-692X.2011.00201.x

Gamache G, Anglade J, Feche R et al (2020) Can living labs offer a pathway to support local agri-food sustainability transitions? Environ Innov Soc Transit 37:93–107. https://doi.org/10.1016/j.eist.2020.08.002

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Polic 31:1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels FW, Kemp R (2007) Dynamics in socio-technical systems: typology of change processes and contrasting case studies. Technol Soc 29:441–455. https://doi.org/10.1016/j.techsoc.2007.08.009

Giller KE, Leeuwis C, Andersson JA et al (2008) Competing claims on natural resources: what role for science? Ecol Soc 13

Giller KE, Corbeels M, Nyamangara J et al (2011) A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crops Research 124:468–472. https://doi.org/10.1016/j.fcr.2011.04.010

Girard N (2015) Knowledge at the boundary between science and society: a review of the use of farmers' knowledge in agricultural development. J Know Manag 19:949–967. https://doi.org/10.1108/JKM-02-2015-0049

Girard N, Magda D (2020) The interplays between singularity and genericity of agroecological knowledge in a network of livestock farmers. J Rural Stud 73:214–224. https://doi.org/10.1016/j.jrurstud.2019.11.003

Gliessman S (2016) Transforming food systems with agroecology. Agroecol Sustain Food Syst 40:187–189. https://doi.org/10.1080/21683565.2015.1130765

Global Yield Gap and Water Productivity Atlas (2021) Global yield gap and water productivity atlas. https://www.yieldgap.org/. Accessed 2 Dec 2021

Goulet F (2013) Narratives of experience and production of knowledge within farmers' groups. J Rural Stud 32:439–447. https://doi.org/10.1016/j.jrurstud.2013.09.006

Guzmán GI, López D, Román L, Alonso AM (2013) Participatory action research in agroecology: building local organic food networks in Spain. Agroecol Sustain Food Syst 37:127–146. https://doi.org/10.1080/10440046.2012.718997

Guzmán GI, Aguilera E, García-Ruiz R et al (2018) The agrarian metabolism as a tool for assessing agrarian sustainability, and its application to Spanish agriculture (1960-2008). Ecol Soc 23:art2. https://doi.org/10.5751/ES-09773-230102

Hazard L, Steyaert P, Martin G et al (2018) Mutual learning between researchers and farmers during implementation of scientific principles for sustainable development: the case of biodiversity-based agriculture. Sustain Sci 13:517–530. https://doi.org/10.1007/s11625-017-0440-6

Hazard L, Couix N, Lacombe C (2021) From evidence to value-based transition: the agroecological redesign of farming systems. Agric Hum Values. https://doi.org/10.1007/s10460-021-10258-2

Hémidy L, Maxime F, Soler L-G (1993) Instrumentation et pilotage stratégique dans l'entreprise agricole. Cahiers d'Economie et Sociologie rurales 28:91–118. https://www.persee.fr/doc/reae_0755-9208_1993_num_28_1_1364

Hernandez-Aguilera JN, Mauerman M, Herrera A et al (2020) Games and fieldwork in agriculture: a systematic review of the 21st century in economics and social science. Games 11:47. https://doi.org/10.3390/g11040047

Hill SB, MacRae RJ (1996) Conceptual framework for the transition from conventional to sustainable agriculture. J Sustain Agric 7:81–87. https://doi.org/10.1300/J064v07n01_07

Hochman Z, Rees H v, Carberry PS et al (2009) Re-inventing model-based decision support with Australian dryland farmers. 4. Yield Prophet® helps farmers monitor and manage crops in a variable climate. Crop Pasture Sci 60:1057–1070. https://doi.org/10.1071/CP09020

Holt-Giménez E, Altieri MA (2013) Agroecology, food sovereignty, and the new green revolution. Agroecol Sustain Food Syst 37:90–102. https://doi.org/10.1080/10440046.2012.716388

Ingram J (2008) Agronomist–farmer knowledge encounters: an analysis of knowledge exchange in the context of best management practices in England. Agric Hum Values 25:405–418. https://doi.org/10.1007/s10460-008-9134-0

Ingram J (2010) Technical and social dimensions of farmer learning: an analysis of the emergence of reduced tillage systems in England. J Sustain Agric 34:183–201. https://doi.org/10.1080/10440040903482589

Ingram JSI, Wright HL, Foster L et al (2013) Priority research questions for the UK food system. Food Sec 5:617–636. https://doi.org/10.1007/s12571-013-0294-4

Iocola I, Angevin F, Bockstaller C et al (2020) An actor-oriented multicriteria assessment framework to support a transition towards sustainable agricultural systems based on crop diversification. Sustain 12:5434. https://doi.org/10.3390/su12135434

Janker J, Mann S (2020) Understanding the social dimension of sustainability in agriculture: a critical review of sustainability assessment tools. Environ Dev Sustain 22:1671–1691. https://doi.org/10.1007/s10668-018-0282-0

Jeuffroy M-H, Loyce C, Lefeuvre T et al (2022) Design workshops for innovative cropping systems and decision-support tools: learning from 12 case studies. Eur J Agron 139:126573. https://doi.org/10.1016/j.eja.2022.126573

Jones L, Tanner T (2017) 'Subjective resilience': using perceptions to quantify household resilience to climate extremes and disasters. Reg Environ Change 17:229–243. https://doi.org/10.1007/s10113-016-0995-2

Keating BA (2020) Crop, soil and farm systems models – science, engineering or snake oil revisited. Agric Syst 184:102903. https://doi.org/10.1016/J.AGSY.2020.102903

Keating BA, Carberry PS, Bindraban PS, et al. (2010) Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci 50:S–109–S–119. https://doi.org/10.2135/cropsci2009.10.0594

Kemp R, Loorbach D (2006) Transition management: a reflexive governance approach. reflexive governance for sustainable development. Edward Elgar, Cheltenham, UK and Northampton, MA, USA, pp 103–130

Klerkx L, Seuneke P, de Wolf P, Rossing WAH (2017) Replication and translation of co-innovation: the influence of institutional context in large international participatory research projects. Land Use Pol 61:276–292. https://doi.org/10.1016/j.landusepol.2016.11.027

LaCanne CE, Lundgren JG (2018) Regenerative agriculture: merging farming and natural resource conservation profitably. PeerJ 6:e4428. https://doi.org/10.7717/peerj.4428

Lacombe C, Couix N, Hazard L (2018) Designing agroecological farming systems with farmers: a review. Agric Syst 165:208–220. https://doi.org/10.1016/j.agsy.2018.06.014

Lacoste M, Cook S, McNee M et al (2022) On-farm experimentation to transform global agriculture. Nat Food 3:11–18. https://doi.org/10.1038/s43016-021-00424-4

Lamine C (2011) Transition pathways towards a robust ecologization of agriculture and the need for system redesign. Cases from organic farming and IPM. J Rural Stud 27:209–219. https://doi.org/10.1016/j.jrurstud.2011.02.001

Le Bellec F, Rajaud A, Ozier-Lafontaine H et al (2012) Evidence for farmers' active involvement in co-designing citrus cropping systems using an improved participatory method. Agron Sustain Dev 32:703–714. https://doi.org/10.1007/s13593-011-0070-9

Le Gal P-Y, Dugué P, Faure G, Novak S (2011) How does research address the design of innovative agricultural production systems at the farm level? A review. Agric Syst 104:714–728. https://doi.org/10.1016/j.agsy.2011.07.007

Le Gal P-Y, Andrieu N, Bruelle G et al (2022) Modelling mixed crop-livestock farms for supporting farmers' strategic reflections: The CLIFS approach. Comput Electron Agric 192:106570. https://doi.org/10.1016/j.compag.2021.106570

Leclere M, Loyce C, Jeuffroy M-H (2018) Growing camelina as a second crop in France: a participatory design approach to produce actionable knowledge. Eur J Agron 101:78–89. https://doi.org/10.1016/j.eja.2018.08.006

Leclere M, Jeuffroy M-H, Loyce C (2021) Design workshop with farmers as a promising tool to support the introduction of diversifying crops within a territory: the case of camelina in northern France to supply a local biorefinery. OCL Oilseed Fats Crops Lipids 28:40. https://doi.org/10.1051/ocl/2021023

Leeuwis C (2000) Learning to be sustainable. Does the Dutch agrarian knowledge market fail? J Agric Educ Ext 7:79–92. https://doi.org/10.1080/13892240008438809

Leippert F, Darmaun M, Bernoux M, Mpheshea M (2020) The potential of agroecology to build climate-resilient livelihoods and food systems. FAO and Biovision

Lemaire G, Franzluebbers A, Carvalho PC d F, Dedieu B (2014) Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric Ecosyst Environ 190:4–8. https://doi.org/10.1016/j.agee.2013.08.009

Lesur-Dumoulin C, Laurent A, Reau R et al (2018) Co-design and ex ante assessment of cropping system prototypes including energy crops in Eastern France. Biomass Bioenerg 116:205–215. https://doi.org/10.1016/j.biombioe.2018.06.013

Lobell DB, Field CB, Cahill KN, Bonfils C (2006) Impacts of future climate change on California perennial crop yields: model projections with climate and crop uncertainties. Agric For Meteorol 141:208–218. https://doi.org/10.1016/J.AGRFORMET.2006.10.006

López-Ridaura S, Masera O, Astier M (2002) Evaluating the sustainability of complex socio-environmental systems. the MESMIS framework. Ecol Indic 2:135–148. https://doi.org/10.1016/S1470-160X(02)00043-2

Lotter DW (2003) Organic agriculture. J Sustain Agric 21:59–128. https://doi.org/10.1300/J064v21n04_06

Luján Soto R, de Vente J, Cuéllar Padilla M (2021) Learning from farmers' experiences with participatory monitoring and evaluation of regenerative agriculture based on visual soil assessment. J Rural Stud 88:192–204. https://doi.org/10.1016/j.jrurstud.2021.10.017

MAAF (French ministry of agriculture, agrifood and forestry) (2016) The agroecology project in France. https://agriculture.gouv.fr/sites/minagri/files/1604-aec-aeenfrance-dep-gb-bd1.pdf. Accessed 24 Apr 2022

Magrini M-B, Anton M, Cholez C et al (2016) Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood

system. Ecol Econ 126:152–162. https://doi.org/10.1016/j.ecolecon.2016.03.024
Marchand F, Debruyne L, Triste L et al (2014) Key characteristics for tool choice in indicator-based sustainability assessment at farm level. Ecol Soc 19:46. https://doi.org/10.5751/ES-06876-190346
Marinus W, Descheemaeker KKE, van de Ven GWJ et al (2021) "That is my farm" – an integrated co-learning approach for whole-farm sustainable intensification in smallholder farming. Agric Syst 188:103041. https://doi.org/10.1016/j.agsy.2020.103041
Martin G, Felten B, Duru M (2011) Forage rummy: a game to support the participatory design of adapted livestock systems. Environ Model Softw 26:1442–1453. https://doi.org/10.1016/j.envsoft.2011.08.013
Martin G, Barth K, Benoit M et al (2020) Potential of multi-species livestock farming to improve the sustainability of livestock farms: a review. Agric Syst 181:102821. https://doi.org/10.1016/j.agsy.2020.102821
Mason RE, White A, Bucini G et al (2021) The evolving landscape of agroecological research. Agroecol Sustain Food Syst 45:551–591. https://doi.org/10.1080/21683565.2020.1845275
Mawois M, Vidal A, Revoyron E et al (2019) Transition to legume-based farming systems requires stable outlets, learning, and peer-networking. Agron Sustain Dev 39:14
McCown RL (2001) Learning to bridge the gap between science-based decision support and the practice of farming: evolution in paradigms of model-based research and intervention from design to dialogue. Aust J Agric Res 52:549–571. https://doi.org/10.1071/AR00119
Méndez VE, Bacon CM, Cohen R (2013) Agroecology as a transdisciplinary, participatory, and action-oriented approach. Agroecol Sustain Food Syst 37:3–18. https://doi.org/10.1080/10440046.2012.736926
Merot A, Alonso Ugaglia A, Barbier J-M, Del'homme B (2019) Diversity of conversion strategies for organic vineyards. Agron Sustain Dev 39:16. https://doi.org/10.1007/s13593-019-0560-8
Merot A, Belhouchette H, Saj S, Wery J (2020) Implementing organic farming in vineyards. Agroecol Sustain Food Syst 44:164–187. https://doi.org/10.1080/21683565.2019.1631934
Meynard J-M, Dedieu B, Bos AP (Bram) (2012) Re-design and co-design of farming systems. An overview of methods and practices. In: Darnhofer I, Gibbon D, Dedieu B (eds) Farming Systems Research into the 21st Century: The New Dynamic. Springer Netherlands, pp 405–429
Meynard J-M, Jeuffroy M-H, Le Bail M et al (2017) Designing coupled innovations for the sustainability transition of agrifood systems. Agric Syst 157:330–339. https://doi.org/10.1016/j.agsy.2016.08.002
Meynard J-M, Charrier F, Fares M et al (2018) Socio-technical lock-in hinders crop diversification in France. Agron Sustain Dev 38:54. https://doi.org/10.1007/s13593-018-0535-1
Milestad R, Dedieu B, Darnhofer I, Bellon S (2012) Farms and farmers facing change: the adaptive approach. In: Farming Systems Research into the 21st century: The new dynamic. Springer, pp 365–385
Mora O, Mouël CL, Lattre-Gasquet M d et al (2020) Exploring the future of land use and food security: a new set of global scenarios. PLoS ONE 15:e0235597. https://doi.org/10.1371/journal.pone.0235597
Mottet A, Bicksler A, Lucantoni D et al (2020) Assessing transitions to sustainable agricultural and food systems: a tool for agroecology performance evaluation (TAPE). Front Sustain Food Syst 4:252. https://doi.org/10.3389/fsufs.2020.579154
Nemecek T, Hayer F, Bonnin E et al (2015) Designing eco-efficient crop rotations using life cycle assessment of crop combinations. Eur J Agron 65:40–51. https://doi.org/10.1016/J.EJA.2015.01.005
Nguyen G, Purseigle F (2012) The corporate challenge to the family farm. Etudes rurales 190:99–118
Padel S, Levidow L, Pearce B (2020) UK farmers' transition pathways towards agroecological farm redesign: evaluating explanatory models. Agroecol Sustain Food Syst 44:139–163. https://doi.org/10.1080/21683565.2019.1631936
Paut R, Sabatier R, Tchamitchian M (2020) Modelling crop diversification and association effects in agricultural systems. Agric Ecosyst Environ 288:106711. https://doi.org/10.1016/j.agee.2019.106711
Paut R, Sabatier R, Dufils A, Tchamitchian M (2021) How to reconcile short-term and long-term objectives in mixed farms? A dynamic model application to mixed fruit tree - vegetable systems. Agric Syst 187:103011. https://doi.org/10.1016/j.agsy.2020.103011
Pelzer E, Bonifazi M, Soulié M et al (2020) Participatory design of agronomic scenarios for the reintroduction of legumes into a French territory. Agric Syst 184:102893. https://doi.org/10.1016/j.agsy.2020.102893
Peri C (2006) The universe of food quality. Food Qual Prefer 17:3–8. https://doi.org/10.1016/J.FOODQUAL.2005.03.002
Périnelle A, Meynard J-M, Scopel E (2021) Combining on-farm innovation tracking and participatory prototyping trials to develop legume-based cropping systems in West Africa. Agric Syst 187:102978. https://doi.org/10.1016/j.agsy.2020.102978
Perrin A, Cristobal MS, Milestad R, Martin G (2020) Identification of resilience factors of organic dairy cattle farms. Agric Syst 183:102875. https://doi.org/10.1016/j.agsy.2020.102875
Pissonnier S, Lavigne C, Le Gal P-Y (2017) A simulation tool to support the design of crop management strategies in fruit tree farms. Application to the reduction of pesticide use. Comput Electron Agric 142:260–272. https://doi.org/10.1016/j.compag.2017.09.002
Pissonnier S, Dufils A, Le Gal P-Y (2019) A methodology for redesigning agroecological radical production systems at the farm level. Agric Syst 173:161–171. https://doi.org/10.1016/J.AGSY.2019.02.018
Poux X, Aubert P-M (2018) An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise. IDDRI Study N°09/18 SEPTEMBER 2018. https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Etude/201809-ST0918ENtyfa.pdf. Accessed 24 Apr 2022
Pretty J, Sutherland WJ, Ashby J et al (2010) The top 100 questions of importance to the future of global agriculture. Int J Agric Sustain 8:219–236. https://doi.org/10.3763/ijas.2010.0534
Prost L (2021) Revitalizing agricultural sciences with design sciences. Agric Syst 193:103225. https://doi.org/10.1016/j.agsy.2021.103225
Prost L, Reau R, Paravano L et al (2018) Designing agricultural systems from invention to implementation: the contribution of agronomy. Lessons from a case study. Agric Syst 164:122–132. https://doi.org/10.1016/j.agsy.2018.04.009
Pullens JWM, Sørensen P, Melander B, Olesen JE (2021) Legacy effects of soil fertility management on cereal dry matter and nitrogen grain yield of organic arable cropping systems. Eur J Agron 122:126169. https://doi.org/10.1016/J.EJA.2020.126169
Quinio M, Guichard L, Salazar P et al (2022) Cognitive resources to promote exploration in agroecological systems design. Agric Syst 196:103334. https://doi.org/10.1016/j.agsy.2021.103334
Ravier C, Jeuffroy M-H, Gate P et al (2018) Combining user involvement with innovative design to develop a radical new method for managing N fertilization. Nutr Cycl Agroecosyst 110:117–134. https://doi.org/10.1007/s10705-017-9891-5
Rivero MJ, Evans ACO, Berndt A et al (2021) Taking the steps toward sustainable livestock: our multidisciplinary global farm platform journey. Anim Front 11:52–58. https://doi.org/10.1093/af/vfab048
Robin MH, Colbach N, Lucas P et al (2013) Injury profile SIMulator, a qualitative aggregative modelling framework to predict injury profile as a function of cropping practices, and abiotic and biotic environment. II. Proof of concept: design of IPSIM-Wheat-Eyespot. PLoS ONE 8:e75829. https://doi.org/10.1371/journal.pone.0075829

Rodriguez D, Cox H, deVoil P, Power B (2014) A participatory whole farm modelling approach to understand impacts and increase preparedness to climate change in Australia. Agric Syst 126:50–61. https://doi.org/10.1016/j.agsy.2013.04.003

Rose DC, Sutherland WJ, Parker C et al (2016) Decision support tools for agriculture: towards effective design and delivery. Agric Syst 149:165–174. https://doi.org/10.1016/j.agsy.2016.09.009

Rossing WA, Meynard J-M, Van Ittersum MK (1997) Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. Eur J Agron 7:271–283. https://doi.org/10.1016/S1161-0301(97)00042-7

Rossing WAH, Albicette MM, Aguerre V et al (2021) Crafting actionable knowledge on ecological intensification: Lessons from co-innovation approaches in Uruguay and Europe. Agric Syst 190:103103. https://doi.org/10.1016/j.agsy.2021.103103

Rotmans J, Kemp R, van Asselt M (2001) More evolution than revolution: transition management in public policy. Foresight 3:15–31. https://doi.org/10.1108/14636680110803003

Ryschawy J, Moraine M, Péquignot M, Martin G (2019) Trade-offs among individual and collective performances related to crop–livestock integration among farms: a case study in southwestern France. Org Agr 9:399–416. https://doi.org/10.1007/s13165-018-0237-7

Sabatier R, Oates LG, Jackson RD (2015) Management flexibility of a grassland agroecosystem: a modeling approach based on viability theory. Agric Syst 139:76–81. https://doi.org/10.1016/J.AGSY.2015.06.008

Sabatier R, Joly F, Hubert B (2017) Assessing both ecological and engineering resilience of a steppe agroecosystem using the viability theory. Agric Syst 157:146–156. https://doi.org/10.1016/j.agsy.2017.07.009

Sadok W, Angevin F, Bergez J-E et al (2009) MASC, a qualitative multi-attribute decision model for ex ante assessment of the sustainability of cropping systems. Agron Sustain Dev 29:447–461. https://doi.org/10.1051/agro/2009006

Salembier C, Segrestin B, Sinoir N et al (2020) Design of equipment for agroecology: coupled innovation processes led by farmer-designers. Agric Syst 183:102856. https://doi.org/10.1016/j.agsy.2020.102856

Salembier C, Segrestin B, Weil B et al (2021) A theoretical framework for tracking farmers' innovations to support farming system design. Agron Sustain Dev 41:61. https://doi.org/10.1007/s13593-021-00713-z

Silva EM, Tchamitchian M (2018) Long-term systems experiments and long-term agricultural research sites: tools for overcoming the border problem in agroecological research and design. Agroecol Sustain Food Syst 42:620–628. https://doi.org/10.1080/21683565.2018.1435434

Simon S, Lesueur-Jannoyer M, Plenet D et al (2017) Methodology to design agroecological orchards: Learnings from on-station and on-farm experiences. Eur J Agron 82:320–330. https://doi.org/10.1016/j.eja.2016.09.004

Slimi C, Prost M, Cerf M, Prost L (2021) Exchanges among farmers' collectives in support of sustainable agriculture: from review to reconceptualization. J Rural Stud. https://doi.org/10.1016/j.jrurstud.2021.01.019

Soulé E, Michonneau P, Michel N, Bockstaller C (2021) Environmental sustainability assessment in agricultural systems: a conceptual and methodological review. J Clean Prod 325:129291. https://doi.org/10.1016/j.jclepro.2021.129291

Sutherland WJ, Fleishman E, Mascia MB et al (2011) Methods for collaboratively identifying research priorities and emerging issues in science and policy. Method Ecol Evol 2:238–247. https://doi.org/10.1111/j.2041-210X.2010.00083.x

Sutherland L-A, Burton RJF, Ingram J et al (2012) Triggering change: Towards a conceptualisation of major change processes in farm decision-making. J Environ Manag 104:142–151. https://doi.org/10.1016/j.jenvman.2012.03.013

Teixeira HM, Van den Berg L, Cardoso IM et al (2018) Understanding farm diversity to promote agroecological transitions. Sustain 10:4337. https://doi.org/10.3390/su10124337

ten Napel J, van der Veen AA, Oosting SJ, Koerkamp PWGG (2011) A conceptual approach to design livestock production systems for robustness to enhance sustainability. Livest Sci 139:150–160. https://doi.org/10.1016/j.livsci.2011.03.007

Tittonell P (2020) Assessing resilience and adaptability in agroecological transitions. Agric Syst 184:102862. https://doi.org/10.1016/j.agsy.2020.102862

Toffolini Q, Jeuffroy M-H, Prost L (2016) Indicators used by farmers to design agricultural systems: a survey. Agron Sustain Dev 36:1–14. https://doi.org/10.1007/s13593-015-0340-z

Toffolini Q, Jeuffroy M-H, Mischler P et al (2017) Farmers' use of fundamental knowledge to re-design their cropping systems: situated contextualisation processes. NJAS-Wagen J Life Sci 80:37–47. https://doi.org/10.1016/j.njas.2016.11.004

Toffolini Q, Capitaine M, Hannachi M, Cerf M (2021) Implementing agricultural living labs that renew actors' roles within existing innovation systems: a case study in France. J Rural Stud 88:157–168. https://doi.org/10.1016/j.jrurstud.2021.10.015

van Apeldoorn DF, Kok K, Sonneveld MPW, Veldkamp TA (2011) Panarchy rules: rethinking resilience of agroecosystems, evidence from Dutch dairy-farming. Ecol Soc 16. https://doi.org/10.5751/ES-03949-160139

van der Meulen B, de Wilt J, Rutten H (2003) Developing futures for agriculture in the Netherlands: a systematic exploration of the strategic value of foresight. J Forecast 22:219–233. https://doi.org/10.1002/for.851

van der Ploeg JD, Barjolle D, Bruil J et al (2019) The economic potential of agroecology: Empirical evidence from Europe. J Rural Stud 71:46–61. https://doi.org/10.1016/J.JRURSTUD.2019.09.003

van der Werf HMG, Petit J (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agric Ecosyst Environ 93:131–145

van der Werf HMG, Knudsen MT, Cederberg C (2020) Towards better representation of organic agriculture in life cycle assessment. Nat Sustain 3:419–425. https://doi.org/10.1038/s41893-020-0489-6

Vanloqueren G, Baret PV (2009) How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. Res Policy 38:971–983. https://doi.org/10.1016/j.respol.2009.02.008

Velasco-Muñoz JF, Mendoza JMF, Aznar-Sánchez JA, Gallego-Schmid A (2021) Circular economy implementation in the agricultural sector: definition, strategies and indicators. Resour Conserv Recycl 170:105618. https://doi.org/10.1016/j.resconrec.2021.105618

Vogl CR, Kummer S, Schunko C (2016) Farmers' experiments and innovations: a debate on the role of creativity for fostering an innovative environment in farming systems. In: Proceedings of the 2th European IFSA Symposium, Shropshire, UK, pp 21–25

Wezel A, Bellon S, Doré T et al (2009) Agroecology as a science, a movement and a practice. A review. Agron Sustain Dev 29:503–515. https://doi.org/10.1051/agro/2009004

Wezel A, Brives H, Casagrande M et al (2016) Agroecology territories: places for sustainable agricultural and food systems and biodiversity conservation. Agroecol Sustain Food Syst 40:132–144. https://doi.org/10.1080/21683565.2015.1115799

Zira S, Rydhmer L, Ivarsson E et al (2021) A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden. Sustain Prod Consum 28:21–38. https://doi.org/10.1016/j.spc.2021.03.028

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Lorène Prost[1] · Guillaume Martin[2] · Rémy Ballot[3] · Marc Benoit[4] · Jacques-Eric Bergez[2] · Christian Bockstaller[5] · Marianne Cerf[1] · Violaine Deytieux[6] · Laure Hossard[7] · Marie-Hélène Jeuffroy[3] · Margot Leclère[3] · Marianne Le Bail[1] · Pierre-Yves Le Gal[8,9] · Chantal Loyce[3] · Anne Merot[10] · Jean-Marc Meynard[1] · Catherine Mignolet[11] · Nicolas Munier-Jolain[12] · Sandra Novak[13] · Virginie Parnaudeau[14] · Xavier Poux[15] · Rodolphe Sabatier[16] · Chloé Salembier[1] · Eric Scopel[17] · Sylvaine Simon[18] · Marc Tchamitchian[16] · Quentin Toffolini[3] · Hayo van der Werf[14]

[1] Université Paris-Saclay, AgroParisTech, INRAE, UMR-SADAPT, F-78850 Thiverval-Grignon, France

[2] Université de Toulouse, INRAE, UMR AGIR, F-31320 Castanet-Tolosan, France

[3] Université Paris-Saclay, AgroParisTech, INRAE, UMR-Agronomie, F-78850 Thiverval Grignon, France

[4] Université Clermont Auvergne, INRAE, VetAgro Sup, UMR Herbivores, F-63122 Saint-Genès-Champanelle, France

[5] Université de Lorraine, INRAE, UMR LAE, F-68000 Colmar, France

[6] INRAE, UE115 Domaine Expérimental d'Epoisses, F-21110 Bretenière, France

[7] INRAE, University of Montpellier, UMR Innovation, F-34060 Montpellier, France

[8] CIRAD, UMR INNOVATION, F-34398 Montpellier, France

[9] Innovation, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

[10] INRAE, CIRAD, Institut Agro, CHEAM-IAMM, UMR ABsys, F-34060 Montpellier, France

[11] INRAE, ASTER, F-88500 Mirecourt, France

[12] Agroécologie, L'Institut Agro Dijon, INRAE, Univ. Bourgogne, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France

[13] INRAE, FERLUS, F-86600 Lusignan, France

[14] INRAE, Institut Agro, UMR SAS, F-35000 Rennes, France

[15] ASCA-IDDRI, F-75010 Paris, France

[16] INRAE, UR 767 Ecodéveloppement, F-84000 Avignon, France

[17] CIRAD, UPR AIDA, F-34398 Montpellier, France

[18] INRAE, UERI Gotheron, F-26320 Saint-Marcel-lès-Valence, France