How to address sustainability transition of farming systems? A position paper

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Abstract: *Stakeholders from academic, political or social spheres encourage the development of more sustainable forms of agriculture. Considering the scale and scope of the sustainability transition, it is challenging to the agricultural sector at large. The main question is how to support the transition process? In this communication, we expose how wicked problems related to the sustainability transition of farming systems can be addressed by agricultural science to better understand and support transition processes. We elaborate on the potential for articulation of three research approaches: comprehensive analysis, co-design and simulation modelling that refer to different stances and methodological choices. Comprehensive analysis of the sustainability transition of farming systems provides historical or snapshot perspectives on agricultural and institutional contexts and on the interplay between on one hand, the resources, their management and related performances of farming systems and on the other hand technical, economic and sociocultural dimensions of change. Co-design of the sustainability transition of farming systems stimulates local-scale experiments of transitions in the real world and the identification of alternatives for change from the farming system level to the territorial level. Simulation modelling consists of explorations of scenarios of management at different levels and assessment of their impacts. It offers a future-oriented perspective on transitions. We illustrate this potential for articulation of research approaches by taking the case of two examples of research conducted in our multidisciplinary research group applying to agricultural water management and autonomy in crop-livestock systems. The resulting conceptual framework is the first proposed to organize research to better understand and support sustainability transitions in the agricultural sector.*

Keywords: *sustainability, transition, simulation modelling, comprehensive analysis, co-design, mixed methods*

Introduction

Around the world, negative environmental impacts of agriculture (e.g. greenhouse gas emissions, water pollution, air pollution, species and habitat loss, soil erosion) are now well-documented (e.g. Stehle and Schulz, 2015 for the impacts of pesticide use on surface water). Moreover, the agricultural sector is confronted with global changes (climate change, market globalization and volatility, urbanization, pollutions, new diseases and pests) that question the relevance of mainstream agricultural models for tomorrow. Stakeholders from academic, political or social spheres encourage the development of more sustainable forms of agriculture i.e., less dependent on anthropogenic inputs and fossil fuels, resilient to global changes, producing sufficient and healthy food (Bommarco et al. 2013) and acting for biodiversity conservation. Different forms of agriculture have emerged in models differing according to their degree of institutionalization: organic farming (Niggli et al., 2015), agroecology (Francis et al., 2003), eco-efficient agriculture (Keating et al., 2010)...

These forms of agriculture represent different conceptions, paradigms and visions about sustainability in agriculture (Ollivier and Bellon, 2013). Horlings and Marsden (2011) proposed the paradigms of weak and strong ecological modernization to categorize these forms of agriculture according to the way they consider the ecologization of agriculture. The weak ecological modernization of agriculture aims to increase the efficiency of synthetic input use to decrease production costs and environmental impacts. This can be achieved through implementation of best management practices, use of technological innovations including improved plant cultivars and animal genotypes, sensors, etc. The strong ecological modernization of agriculture relies on an enhancement of *"agrobiodiversity across multiple spatial and/or temporal scales"* in farming systems (Kremen et al., 2012) to generate ecosystem services substituting to synthetic inputs (Malézieux, 2012; Therond et al., 2017).

We mainly focus on this second type of modernization. Considering the scale and scope of the sustainability transition, it is challenging to the agricultural sector at large. It involves deep changes at various levels from farming systems to food systems (due to a larger diversity of crops being cultivated and offered to consumers) towards new arrangements between ecological, economic and social dimensions. These changes concern a diversity of aspects including (i) the revision of farmers' objectives, values and motivations, (ii) the redesign of farming systems and more specifically of the way agrobiodiversity components and other natural resources are integrated over space and time, (iii) changes in the information systems and in the support provided to farmers and (iv) societal changes with consumers changing their habits towards more diverse and more sustainably-produced agricultural goods.

Considering the current farming systems and the importance and complexity of the changes required, the main question is how to support the transition process? So far, the field of transitions studies was mainly structured around the theory of Transitions Management (Kemp et al., 2007), the Multi-Level Perspective (MLP) approach (Kemp 1994; Geels, 2002) and critics of these approaches (Genus and Coles, 2008; Dentoni et al., 2017). These studies have most frequently been applied to entire sectors such as energy and transport (Barton et al., 2018, Geels, 2006). Highly integrated conceptual frameworks (multi-level, multi-dimensional, multi-stakeholder) have been developed but they are not very relevant nor operational at the level of a farm. In addition, the main criticism that can be made is that these frameworks neglect the individual dimension of change, and in particular the motivations of individuals for change and break with the dominant system (Dentoni et al., 2017). This is a crucial dimension of the sustainability transition of farming systems

In the field of agricultural science, research efforts have focused on the development of knowledge and methods to support the design and evaluation of scenarios of more sustainable farming systems from the field to the farm and up to the territory level (Martin et al., 2013). This research is useful to foresight exercises aimed at engaging stakeholders in a transition process and to go beyond "sketched" alternatives for change. However, it is insufficient to fully address the transition pathways towards the scenarized situations. Those pathways are intrinsically uncertain, dynamic, and multi-level as they are shaped by complex and changing interactions between the social, economic and environmental context (Duru et al., 2015). Moreover, large-scale implementation of the transition can imply high information-gathering, decision-making, operational and monitoring costs (Widmark et al. 2013) that have been neglected by research although they require democratic agreements. There is a scientific challenge for the community of agricultural scientists at large in getting a better understanding of and supporting the sustainability transition of farming systems.

In this communication, our objective is to develop a conceptual framework to address wicked problems related to the sustainability transition of farming systems. We elaborate on the potential for articulation of research approaches, stances, objects and scales to better understand and support transition processes. We illustrate this potential by taking the case of two examples of research conducted in our multidisciplinary (within the field of agricultural sciences: agronomy, livestock production science, ecology) research group applying to agricultural water management and autonomy in crop-livestock systems.

Articulation of research approaches

Conceptual framework

Following Turnheim et al. (2015), we consider there is a need to take advantage of the multiplicity of views and approaches of agricultural science for better understanding and supporting the sustainability transition of farming systems viewed as a complex, multi-dimensional and uncertain process. Three approaches are considered key (Fig. 1): comprehensive analysis, co-design and simulation modelling that refer to different stances and methodological choices. They each represent different viewpoints (constructivist vs. objectivist, past and present vs. projected) on the sustainability transition of farming systems and on the critical factors to this transition. We claim that these three analytical perspectives are not incompatible but that their articulation is possible and required to really address transition issues. All three approaches adopts a systems perspective on the transition (Darnhofer et al., 2012) and involve integrated assessment of farming systems, i.e. “the scientific ‘meta-discipline’ that integrates knowledge about a problem domain and makes it available for societal learning and decision making processes” (TIAS, 2018).

Comprehensive analysis of the sustainability transition of farming systems provides perspectives (historical or in the making) on agricultural and institutional contexts and on the dynamic interplay between on one hand, agrobiodiversity and other natural resources, their management and related performances of farming systems and on the other hand technical, economic and sociocultural dimensions of change. Thus, the strengths and weaknesses of strategies to operate the sustainability transition as well as the drivers and barriers to the transition of farming systems can be identified. Co-design of the sustainability transition of farming systems stimulates local-scale experiments of transitions in the real world and the identification of alternatives for change from the farming system level to the territorial level. It requires implementing iterative design and assessment of options for the management of agrobiodiversity and other natural resources. If considered promising, these options can be implemented. Simulation modelling consists of explorations of scenarios of management of agrobiodiversity and other natural resources at different levels and assessment of their impacts. It offers a future-oriented perspective on transitions. It contributes to clarify the ability of different management options to achieve specific sustainability targets or to highlight counter-intuitive effects.

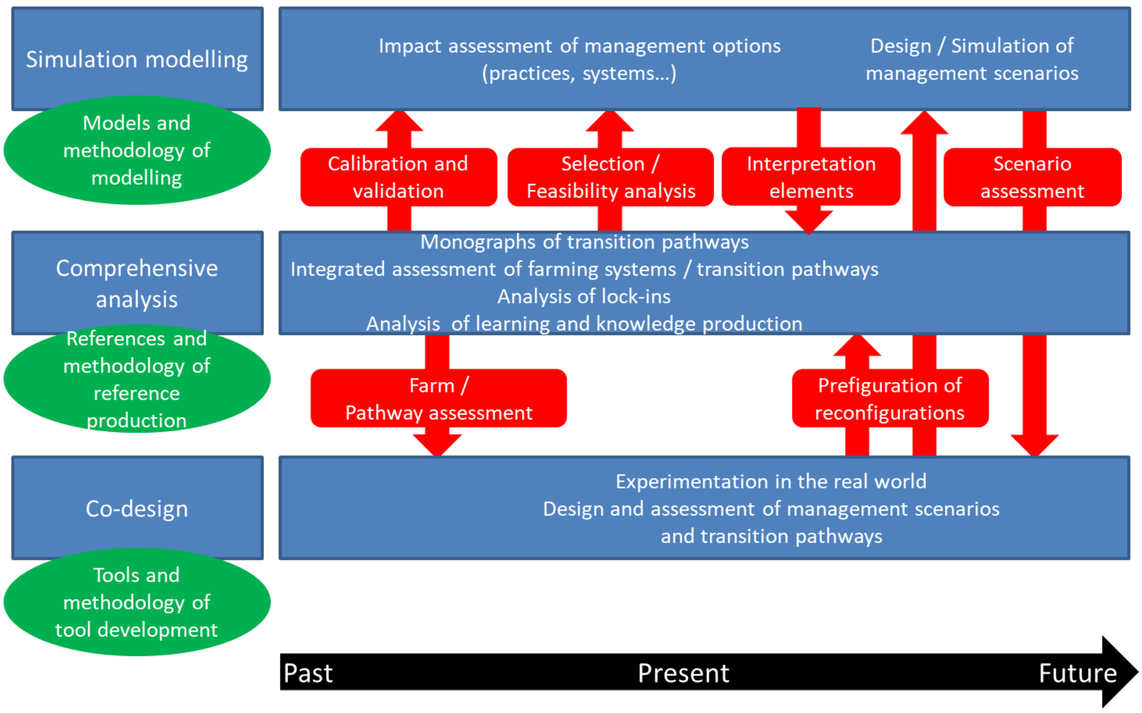

Figure 1: Articulation of research approaches to better understand and support transitions towards more sustainable forms of agriculture (adapted from Turnheim et al., 2015). The knowledge and methods produced are specified in the blue rectangles and green ovals respectively. The flows if information among research approaches are specified with red arrows and rectangles.

These three approaches emphasize specific aspects and views of transition processes. They also differ in the extent to which they integrate the specific features of situations (soil-climate context, actor networks, etc.). Thus, they can benefit each other. Comprehensive analysis provides simulation modelling with model specifications. It feeds models with data to calibrate and validate the crop, farm or land use models. It enables to select agrobiodiversity and other natural resources management options to be simulated. Comprehensive analysis also allows checking the feasibility of simulated options in the real world. It provides co-design with examples of transition pathways and corresponding integrated assessment of farming systems and territories. In return, simulation modelling feeds the comprehensive analysis with interpretation elements as it provides insights into the (biophysical, economic, etc.) processes underlying observed situations. Co-design provides comprehensive analysis with prefiguration of reconfigurations of farming systems to anticipate the decision upon those systems to be surveyed. Finally, simulation modelling can support co-design by helping stakeholders to position themselves regarding the different scenarios assessed, either to select one for implementation in the field or to enrich collective discussions.

Comprehensive analysis

Overview and corresponding stances, objects and scales

Comprehensive analysis aims to gain insight into the sustainability transition of farming systems and the agricultural and institutional contexts for this transition. This implies to adopt a systems perspective by paying attention to the interactions among system components, between the system and its environment, and to the dynamics of these interactions (Darnhofer et al., 2010). While mainstream agricultural science tends to reduce the lens to focus on specific aspects or sub-systems through *in vivo* or *in silico* experimental approaches, comprehensive analysis requires to keep “the ‘bigger picture’ in mind” (Darnhofer et al., ibid). This effort can best be supported by an interdisciplinary approach combining agronomy and livestock production science with conceptual and methodological frameworks from social sciences especially management science and agricultural economics (e.g. the institutional analysis and development framework; Ostrom et al., 1994). Moreover, comprehensive analysis is rooted in the real world. It relies on collaborations (mainly through surveys) with farmers who, by essence, deal with the bigger picture when managing their farms. The focus is on (i) existing farming systems that are diverse under the influence of different farmers’ objectives, opportunities and constraints (Magne et al., 2010) and (ii) the wider agricultural and institutional contexts that shape the windows of opportunities and constraints for farmers (Asai et al., 2018).

Comprehensive analysis has mainly focused on the cropping system, herd and farm levels (Girard et al., 2008; Magne et al., 2016) although this kind of analysis also applies to the territory level to understand interactions among farms (Nowak et al., 2015; Couix et al, 2016) or between farmers and other actors such as supply chain actors (Magrini and Duru, 2015), advisors (Magne et al., 2010) or water managers. This kind of analysis is generally focused on the evolution of the interactions between the farmer with his/her own history, values, knowledge, objectives and practices, farms with the corresponding resources, assets and constraints and the environment characterized by climatic and economic hazards and opportunities, political regulations and incentives and actor networks (information network, sale network, etc.) (Darnhofer et al., 2010). Along with understanding system functioning through these interactions and their dynamics, comprehensive analysis also assesses the sustainability of farming systems. This ranges from classical sustainability assessments (Rasul and Thapa, 2004) towards more integrated approaches assessing the vulnerability or the resilience of farming systems over time (Martin et al., 2017), i.e. their capacity to cope with, adapt to, or recover from the effects of hazards (Smit and Wandel, 2006).

Strengths to better understand and support sustainability transitions

Implementing a sustainability transition is uncertain and challenging for most farmers mainly because available scientific and empirical knowledge on the topic is scarce and because the agricultural and institutional contexts are changing. A transition can be stimulated by changes in the agricultural and institutional contexts, farmers' values, motivations and objectives and it may result in major upsets of their practices, performances and professional networks (Lamine, 2011). The scarce documented experiences of sustainability transitions in farming systems (Chantre and Cardona, 2014; Chantre et al., 2015; Coquil et al., 2014) are too diverse to create a robust knowledge base for decision-making. In most farming situations, the space of combinations between farmers' objectives and practices allowed by the agricultural and institutional contexts is very large and choosing one might reveal difficult. Thus, comprehensive analysis of the agricultural and institutional contexts and of farming systems during the transition may provide insight on the strengths and weaknesses of strategies to operate the sustainability transition in a given context but also on some drivers and barriers to operate the transition (Basset, 2016; Ollion et al., 2018).

Comprehensive analysis of the agricultural and institutional contexts can rely on interviews with key informants or on participatory workshops to collectively produce an institutional analysis of the interactions between actors and resources (Etienne, 2014). When focusing on farming systems, comprehensive analysis stems on longitudinal farm surveys to collect data on several aspects of the transition across years: changes in farmers' objectives and underlying values, adaptations of farmers' practices and consequences on farm performances, farmers' experiments and learning... Based on this kind of surveys, quantitative analysis enables to characterize the sustainability, vulnerability or resilience of farming systems during the transition, and whether the transition yielded enhancements (Bouttes et al., 2018a). Such results can support farmers' decision-making regarding the sustainability transition. On the other hand, qualitative analysis enables to characterize changes in farmers' values and knowledge (Bouttes et al., 2018b) and practical knowledge gaps revealed by the transition and requiring further research. As it enables to address jointly technical and human aspects, comprehensive analysis offers the opportunity to assess farmers' adaptive capacity (Marshall et al., 2014) and to adjust accordingly the support offered to them during the transition.

Limits and inputs from other research approaches

Comprehensive analysis suffers from two main limits. First, it remains rather descriptive. If this is not a problem to characterize the most promising strategies for the sustainability transition, it can prove limiting to understand the biological or social mechanisms underlying the differences observed among farmers' strategies. This is where comprehensive analysis can benefit from a combination with simulation modelling. Data gathered for the purpose of comprehensive analysis can be used to feed simulation models that may provide interpretation elements to understand the differences observed among sustainability transition strategies (Fig. 1). Second, comprehensive analysis is rooted in past or current situations. In case the analysis reveals a risk of transition failure, it is not oriented on the exploration of alternative strategies. Combination with co-design can benefit comprehensive analysis. The former can feed co-design with problematic situations where sustainability transition strategies are in failure. In return, the latter provides alternative layouts for farming systems (Fig. 1).

Co-design

Overview and corresponding stances, objects and scales

The sustainability transition of farming systems based on a strong ecological modernization can be approached as a design activity. Since it is intended to value the local context for agricultural production (Duru et al., 2015), this design work has to be conducted with the actors of that context, especially farmers. These actors are a major and valuable source of knowledge about the situation to be transformed (Buur and Matthews, 2008). Their involvement appears necessary to increase the chances of producing locally-relevant solutions through dialogue with and feedback from the actors of the situation to be transformed (Waks, 2001). Moreover, their involvement is a way to engage them in the transition process by participating to the design of solutions that they may have to implement. Otherwise, the process may lead to lack of structure in problem framing because actors' goals and constraints, knowledge underpinning decisions, etc. would be uncertain, contested or even unknown (McCown, 2002). Bringing together pluralistic knowledge and perspectives (Bammer, 2005; Pretty, 1995) through participation may allow adequately integrating the diversity of backgrounds, values, knowledge, representations, goals, interests and opportunities (Sterk et al., 2009).

This approach takes the form of a problem-oriented design work. It can be conducted according to the 3 steps proposed by Nickerson et al. (2012): (1) problem finding, framing, and formulating, (2) problem solving, and (3) solution implementation. The first two stages correspond to what is commonly understood as design, *i.e.*, a phase of "thinking". It aims at integrating different sources of knowledge (conceptual, empirical and procedural, but also explicit and tacit knowledge) and their underlying epistemologies (Pohl and Hadorn, 2008). Co-design brings together a greater or lesser variety of actors (scientists from different disciplines, practitioners from different professions, policy-makers, users and citizens) that share and produce the knowledge needed to the design process. It is based on compromise and deliberation that must satisfy the requirements of inclusion, equality and freedom (Habermas, 1984).

The solution implementation, last step of this problem-oriented approach, bridges design and experience, "thinking" and "doing". At this stage, implementation outcomes often divert from expectations. Thus the co-design process is based on iterations of design and testing. Working with farmers allows monitoring these unexpected outcomes to progressively improve the design (Berthet et al., 2016). Co-design applying to the sustainability transition of farming systems can then take the form of a social experiment (Ansell and Bartenberger, 2016) that differs from other types of experiment because it is re-calibrated until it works (Stoker & John, 2009). Such a social experiment may transform both the actors (their values, knowledge, objectives and practices) of the co-design process and their situation of interaction, i.e. farming systems up to territories. At this stage, the challenge of co-design is to create the reflexive settings that allow learning from the experience of solution implementation (Pohl and Hadorn, 2008).

In some cases and contexts (e.g. when focusing on projected climate change), solution implementation is not feasible. It has to be replaced by forecasting mainly through simulation. In these cases, unexpected outcomes are difficult to capture, but changes in the beliefs and practices of the actors remain of interest.

Strengths to better understand and support sustainability transitions

Implementation of the sustainability transition is preceded by a co-design process. This co-design is of major interests for several reasons. The successive stages of problem finding and framing enable to clarify the formulation of problems that are frequently wicked at the beginning of the design process (Bouma et al., 2011). In most farming situations, considering the agricultural and institutional contexts, the solution space for alternative farming systems is very large. The co-design process stimulates the creativity of participants and integrates their respective knowledge to identify, discuss and select promising solutions for implementation (Berthet et al., 2016). Testing allows revealing and recording any discrepancies between expectations and the effects of design implementation (Kilelu et al, 2013). After testing, actors can discuss whether the solutions are satisfactory enough for larger-scale implementation. Moreover, reflecting on unexpected outcomes leads to collective reflexivity and learning that is central to the sustainability of the transition process.

Co-design is an operational approach to develop an open-ended sustainability transition of farming systems, overcoming uncertainty and knowledge gaps. It can generate original and innovative solutions. The researcher involved in the co-design can produce knowledge on technical or organisational aspects of the transition as well as on cognitive, axiologic and emotional aspects of the embedded actors using conceptual and methodological frameworks from social sciences. It also highlights knowledge gaps and research efforts needed. Co-design being holistic and grounded in the problem situation, the researcher can capture and learn from the co-evolution between technical, social and institutional aspects of the transition. This co-evolution, marked by the dynamics of alignment and conflict, also produces unpredictable outcomes (Kilelu et al, 2013) that are insightful to researchers and other actors.

Limits and inputs from other research approaches

Being grounded in the problem situation is both a strength and a limit of the co-design approach. The results vary according to the actors involved, their bounded rationality and the specific features of the context. Thus the operational solutions and some of the knowledge produced are context-dependant and out-scaling may not be self-evident. The multiplication of experiences and the comparison of empirical results with theoretical frameworks will then allow the objectification necessary to the production of largely-applicable knowledge (Berthet et al., 2016). The input of scientific knowledge as well as the use of simulation models can foster the creativity and the relevance of this co-design process. Also, in some cases e.g. agricultural water management, iterations of design and testing can be extremely costly; simulation models offer an opportunity to experiment *in silico* the effects of proposed changes. However, simulation models may enable a better understanding of a limited range of unexpected side-effects, i.e. those that the model structure allows simulating.

Simulation modelling

Overview and corresponding stances, objects and scales

Simulation modeling refers to the use of numerical models to provide actors with information to make decisions about the sustainability transition of their practices, farming systems or even territory. Driven by the advances in IT technologies, agricultural system modeling has evolved along with agricultural science, leading to the development of process-based biophysical models of crops and livestock, statistical models based on observations, and economic models from field and regional to global levels (Jones et al., 2016). Another stream has emerged around the companion modelling (Commod) approach (Etienne et al., 2014). This approach entails the participatory development of the models before their use to address specific issues. These models are frequently multi-agent systems enabling to simulate interactions among actors concerned by a shared resource. Integrated assessment models (van Vuuren et al., 2015) is a recent approach largely used in climate change analysis. It draws on knowledge and strengths from various disciplines with disciplinary model components linked through a unified modeling platform.

At the levels considered in the sustainability transition of farming systems, data required to run simulation models is usually scarce. This justifies using parsimonious models that may make easier the sensitivity and uncertainty analysis of the model outputs (Constantin et al., 2015; Coucheney et al. 2015). Moreover, those models requiring less input data are more easily applicable in new agricultural and institutional contexts where available knowledge is limited. Participation of actors such as farmers in the modelling process may support the integration of their diversity of backgrounds, values, knowledge, representations, goals, interests and opportunities towards the overall relevance of the research (Sterk et al., 2009).

Applied to the sustainability transition of farming systems, simulation modeling implies to describe these systems as managed complex hierarchical systems and to pay attention to the interactions between their sub-systems. In addition to their own analytical interest, experimental data are required to develop, calibrate and evaluate the models. Simulation modelling allows calculating numerous variables difficult to measure in the field especially when it comes to scale changes to the farm and territory levels. This approach is useful to assess farming practices and systems across temporal and spatial scales and thereby inform actors engaged in the sustainability transition. For example, simulation modelling can be used to assess irrigation practices at field and farm levels (MODERATO: Bergez et al., 2001; Namaste: Robert et al., 2018). It can also be used to assess the impacts (e.g. on water management, nitrogen cycling, economics) of innovative practices (use of cover crops, crop diversification…) from the cropping system to the watershed level. It can also provide data on the different dimensions of sustainability and avoid a reductionist assessment centered on the productivity (Giuliano et al., 2016).

Strengths to better understand and support sustainability transitions

New approaches to modelling like companion modelling enable to match the problem framing of actors with conceptual and numerical models to ensure the relevance of the simulations. Thus, model development vary widely according to the systems studied and to the purpose of the study (Jones et al., 2016). Coupling experimental data with models allows simulating scenarios to estimate the impact of innovative practices (cover crops, crop diversification with introduction of legumes, or reduced soil tillage, etc.) or farming systems (organic farming, low-input cropping systems, etc.). Simulation models can estimate the impacts on agricultural production but also on other environmental outputs (nitrate leaching, greenhouse gas emissions; Tribouillois et al., 2018). Simulation results can support the reflection and discussions of actors engaged in a co-design process to plan and implement the sustainability transition of farming systems. This may stimulate social learning among local actors (Etienne et al., 2014) to increase the chances of consensus around the problem framing and the solution co-design and implementation. Being comprehensive, models can provide interpretation elements to the comprehensive analysis of farming systems in case observed phenomena remain unexplained from the data collected.

Limits and inputs from other research approaches

Different limits apply to the use of simulation modeling. A first limit is due to simulation modelling in itself and relates to black-box effects of models. However, developing models in the framework of participatory approaches might help actors to understand what is inside the models. Another limit relates to data acquisition over farming systems or territories to run simulation. In that case, combination with comprehensive analysis can facilitate the collection of the required data. Finally, applied to the sustainability transition of farming systems, the major limit of simulation models is that they are not suited to the novelty of some practices to be tested by simulation. These models are often calibrated and validated based on farming practices currently implemented and climate conditions currently encountered. The validity of the simulations of innovative practices in a future climate or under a different political and economic context might thus be questioned.

Application examples

Agricultural water management

Problem situation

In agricultural areas, droughts occur when low rains coincide with low stocks of water (in water bodies and soils) and high crop water needs (Amigues et al. 2006; Erdlenbruch et al. 2013). Recurring droughts reveal that the water demand structurally exceeds the water offer. Such water imbalance is unsustainable: it erodes ecosystem functioning (Gordon et al. 2010), drives water-use conflicts (Pimentel et al. 1997) and impacts agricultural production (Molden 2007). In Europe, even though water resources have a relatively high natural availability and storage capacities are well-developed, shortages of and conflicts over the water resource are common (EEA, 2012), in particular because of regulatory measures set up to promote environmentally sustainable management of natural resources (e.g. Water Framework Directive, 2000). For example, the river flow should not fall below a regulatory threshold (the “low-water regulating flow”, LWRF) supposed to ensure the proper functioning of the water environment and the satisfaction of all water uses. These regulatory measures for resource use call into question the sustainability of human activities that until then had been supported, such as irrigated agriculture.

"Crisis" measures, such as water-use restrictions, occur when river flow falls below the LWRF, but they are considered inaccurate to resolve water imbalance. To limit the occurrence of water crises, the 2006 Water and Aquatic environment French Act established a water quota for irrigated agriculture within each watershed. In many watersheds, mainly in Southwestern France, this newly established water quota is much lower than the water withdrawn in the past dry years, which leads (or should lead) farmers to re-think their farming systems, at short or longer term. Such changes participate to the profound changes in water management and governance promoted by several authors (Pahl-Wostl et al. 2007; EEA 2012; Erdlenbruch et al. 2013;) and which should include rethinking the approach ("participatory", "prospective", "integrated", "adaptive" etc) and the orientation ("demand management", "agroecological practices", "locally-adapted cropping systems", etc.).

Articulation of research approaches

We have been working on quantitative water management for coping with water scarcity problems for more than 25 years, but the year 2003 can be considered as a pivotal year for works at the territorial scale. The sharp drought occurring that year as well as a public debate on the Charlas dam construction changed the mind of both water managers and researchers about the need for tools to explore and assess alternatives to the current land uses and farming practices. Our research group participated to the Charlas public debate and then to various meetings dealing with water management all along the period which led to the 2006 Water and Aquatic environment French Act and its implementation (A1: Debril and Therond, 2012). Several interviews of water users and water managers were also conducted. A comprehensive analysis of these meetings and interviews revealed the need for developing modelling tools to assess the potential environmental (particularly on the river flows) and economic (particularly on the farming systems) impacts of large-scale changes in land uses and farming practices (A2 : Guines, 2003; A3: Balestrat and Therond, 2014).

A following series of individual and collective works of students (e.g. A4: Cheynier, 2010; A5: Gaulupeau, 2010) allowed us to understand the water management situations in several watersheds, with an emphasis (i) on the interactions between actors (water users and water managers) and between actors and the biophysical environment, and (ii) on the decision-making processes of each type of actor. These comprehensive analyses were synthesized through cognitive maps for interactions between actors and resources, and through UML activity diagrams for decision processes (A6: Mayor et al., 2012). This allowed us to identify the entities and processes to integrate in a model of the water management situation with water imbalance problems and the spatial and temporal resolutions and level of functional complexity (e.g. farm) to be represented.

Accordingly, we developed a multi-agent modelling platform called MAELIA (A7: Therond et al., 2014) which allows representing dynamic interactions between human activities (farming practices), ecological processes (hydrology and crop growth), and governance systems (water regulations and releases from dams) at fine spatiotemporal resolutions. MAELIA includes three types of agent: farmer, dam manager and state services (software) agents. A specific modelling work led us to select AqYield as the crop growth module of MAELIA, for its low parameter needs and its performance (A8: Constantin et al., 2015).

MAELIA was developed to handle actual problems of water managers and issues of the main water users (farmers) in agricultural landscapes. We first applied it on the downstream part of the Aveyron watershed (South-Western France). The instantiation of the model on this watershed required the collaboration of local experts to add local knowledge to generic data bases in order to adequately distribute soils and cropping systems within the watershed (A9: Murgue et al., 2016). For parameterising farmers' decisions for irrigating and other agricultural operations, we surveyed several farmers and conducted a transversal analysis to yield generic decision rules for each combination cropping system x soil x irrigation equipment situation (A10: Hipolito, 2012). A further work was conducted to develop a faster method, based on interviews of few key-informants, in order to apply MAELIA to several other watersheds (A11: Rizzo, 2018).

In parallel, with local stakeholders, we designed scenarios, as alternatives to the current situation, aiming at improving the water balance of the study watershed (A12: Murgue et al., 2015). Thanks to a necessary translation step from stakeholders' narratives into model inputs (Alacamo, 2008), these scenarios, based on moderate changes in land use, crop rotations and agricultural practices, were simulated with MAELIA. Nevertheless they appeared as far from solving the local water imbalance problem. Thus, we conducted another iteration of scenario design and assessment to explore more innovative or radical changes. In a new co-design workshop, we asked local stakeholders to select scenarios they considered as most interesting to learn (but not necessarily most wished). To be able to run MAELIA with these new scenarios, we had to conduct new modelling developments to simulate correctly new crops (e.g. winter crops) and new farming practices (long rotations) (A13: Tribouillois et al., 2018, submitted).

Simulation runs of MAELIA (A14: Allain et al., 2018b) allowed us to quantify, for each new scenario, indicators listed by experts to meet the evaluation criteria demanded by local stakeholders. In separate "evaluation workshops", homogeneous groups of stakeholders (i.e. sharing the same stakes and objectives) were asked to evaluate each scenario for each criteria using the simulated indicators they consider relevant in addition to their own expertise (A15: Allain, 2018a). An analysis of all workshops was conducted using Kerbabel tool (Frame and O'Connor, 2011) and presented in a collective meeting. The evaluation of the different scenarios by the different groups, the indicators chosen as arguments and the diverging and converging positions among stakeholder groups were highlighted in order to share positions and let emerge new scenarios.

Synthesis and insights

Figure 2 summarises the various steps of our research on agricultural water management at the territory level. It highlights the back-and-forths over time between co-design and simulation modelling. Comprehensive analysis was an essential preliminary step of our research process to promote the sustainability transition in water management: it guided our participatory stance and allowed us to structure the overall problem by helping model specification (processes, components and scales), identification of participants to the co-design exercises, and definition of evaluation criteria and indicators. The conjunctive use of simulation modelling and participatory design and evaluation exercises allowed us to improve our understanding of the local water situation by clarifying debate points but also by arising converging points between actors with diverging stakes in conflictual context.

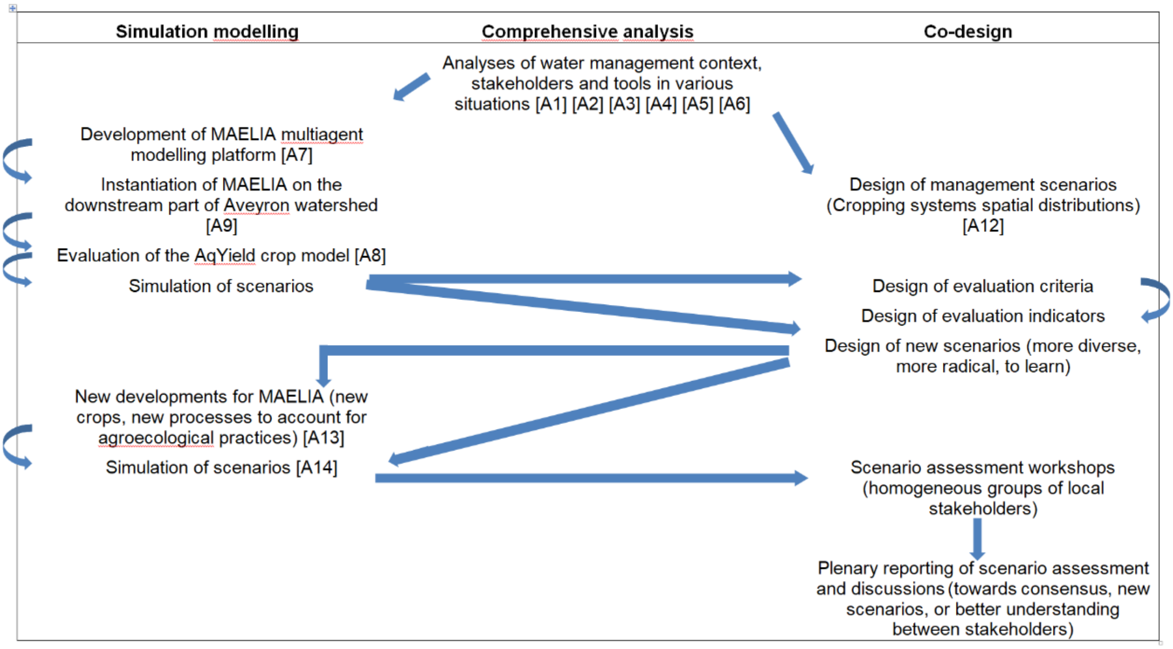

Figure 2: Overview of the articulation among the three research approaches in the agricultural water management example

Autonomy in crop-livestock systems

Problem situation

In Europe, the dependence of farming systems to synthetic inputs has increased dramatically in the last 50 years. As an illustration, 8.3 TgN of synthetic fertilizer are spread on croplands each year in Europe (Billen et al., 2014). Livestock production systems share similar problems as they are increasingly dependent on imported feed from a small number of countries (USA, Argentina and Brazil). Each year, net imports of feed correspond to 2.34 GgN in Europe (Lassaletta et al., 2014). This situation questions the sustainability of European agriculture and more specifically its vulnerability to increases in synthetic nitrogen and feed prices.

As a response to these issues, several authors suggest developing more integrated forms of agriculture to restore the autonomy and the sustainability of agricultural systems (Bell and Moore, 2012; Hendrickson et al., 2008). Diversified and (horizontally) integrated agricultural systems promote ecological interactions over space and time between system components (e.g. crops, grasslands and animals) and create opportunities for synergistic resource transfers between them (Hendrickson et al., 2008). Crop–livestock systems are suggested as a theoretical ideal for implementing the principles of diversified and (horizontally) integrated agriculture (Hendrickson et al., 2008; Lemaire et al., 2014) to reduce the dependence of European agriculture on synthetic nitrogen and imported feed inputs.

Articulation of research approaches

Over the last years, our research efforts have focused on understanding how crop-livestock integration can contribute to increase farm autonomy at the farm and territory levels (Fig. 3).

In a French area that tends to specialize towards crop production, we conducted a comprehensive analysis to identify farmers' strategies that allowed the survival of mixed crop-livestock farming (B1: Ryschawy et al., 2013). We analyzed the trajectories of the entire farm population from 1950 to 2005 based on six 10-year time steps. Two complementary strategies appeared to be suitable to express the theoretical advantages of mixed crop-livestock systems and preserve farm sustainability. The first one was maximizing autonomy by smartly integrating crops, pastures and livestock so as to promote internal recycling of nutrients and reduce the dependence on inputs. The second one was agricultural diversification to exploit economies of scope and protect the farm against market fluctuations. Engaging farmers in a sustainability transition based on diversification and enhanced autonomy was challenging as it tended to go against the trends observed in the field.

We developed a participatory board game supported by a computer model called Forage Rummy (B2: Martin et al., 2011). It is intended to be used by agricultural consultants and/or researchers with small groups of 2 to 4 farmers during workshops lasting from 2 to 4 hours. Workshops include collectively and iteratively designing (with material objects e.g. cards) and evaluating (with a simulation model) crop-livestock systems to adapt to new contextual challenges (e.g. volatility of input prices) and new farmers' objectives (e.g. transition to organic farming). Throughout these iterations, it aims at developing farmers' adaptive capacity to implement sustainability transitions by stimulating their reflections and discussions. Forage Rummy was successfully used with hundreds of farmers and extension agents were trained to using it (B4: Berthet et al., 2016). The development of Forage Rummy also led to simulation modelling efforts as it required selecting or developing process-based models (e.g. B3: Duru et al., 2009) displaying robustness when being scaled out and requiring a low number of input parameters to be informed.

Forage Rummy workshops revealed two different limits to the widespread adoption of integrated crop-livestock systems. First farmers are not always aware of the risks to which they are exposed and thus they might be reluctant to implement sustainability transitions. Second, due to specific constraints (e.g. land availability, topography), some farms do not have much room for diversification and enhanced autonomy at the farm level. Following these observations, we developed two new strains of research: comprehensive analysis of the vulnerability of crop-livestock systems to climatic and economic variability and co-design and simulation modelling of crop-livestock integration beyond the farm level.

To sensitize farmers to the least vulnerable strategies for crop-livestock systems in the current context, we developed an integrated method to assess farm vulnerability and explain how this vulnerability can best be reduced according to farmers' adaptations over time (B5: Martin et al., 2017a). This method defines that the lowest farm vulnerability is obtained through a combination of high values of measurements, a stable or increasing trend and low variability for all vulnerability variables considered. We applied our method to several datasets including farms in a routine management regime (B6: Bouttes et al., 2018c; B5: Martin et al., 2017a) and farms operating a sustainability transition (B7: Bouttes et al., 2018a). For the latter case, farms were surveyed (2008-2013) prior, during and after their conversion to organic dairy farming. Our analysis showed that farms that decreased most their vulnerability had drastically reoriented their strategies for integrating crop and livestock from systems based on silage maize dependent on imported soymeal to autonomous pasture-based systems placing grazing at the core of the farming system. This kind of comprehensive analysis is being replicated to support farmers with sector-specific and local insights about most promising strategies to implement sustainability transitions.

To assess the scope for integrating crops, pastures and livestock beyond the farm level, we developed a conceptual framework defining three forms of integration: local coexistence, complementarity, and synergy, each with increasingly stronger temporal, spatial and organizational coordination among farms (B8: Martin et al., 2017b). In parallel, we developed a method for co-design and assessment of integrated crop-livestock systems beyond the farm level and applied it with a group of organic farmers specialized in crop or livestock production (B9: Moraine et al., 2017; B10: Ryschawy et al., 2017). First, we analyzed the strengths and weaknesses of agricultural systems to identify the potential for new crop-livestock interactions between farms. This analysis was discussed with farmers and served as a basis to design crop-livestock integration scenarios with them. Using a multicriteria assessment grid, we assessed these scenarios regarding their sustainability and the results were presented to farmers to discuss their feasibility We paid particular attention to the trade-offs between individual and collective benefits related to scenario implementation. The selected scenario resulted in enhanced autonomy for fertilizers, feed and decision-making at both the individual and the collective levels. Yet, with this method, the trade-offs between individual and collective benefits were not easy to catch for farmers, and some key dimensions of crop-livestock integration beyond the farm level like its logistics were neglected. To address these issues, we developed a serious game called Dynamix (B11: Ryschawy et al., 2018) to support the collective design of scenarios of crop-livestock integration beyond the farm level. This serious game integrates a simulation model itself based on previous work including the simulation model of Forage Rummy (B2: Martin et al., 2011). It is being used with farmer groups in several French regions.

Synthesis and insights

As for the agricultural water management example, our research included back-and-forths between research approaches, especially between co-design and comprehensive analysis (Fig. 3). However, in this case, it was the co-design that was central to the orientation of further research approaches. It guided the type of methodological efforts to conduct on comprehensive analysis of farm trajectories and on co-design itself. It was also crucial in the simulation modelling choices that we made with priority given to parcimonious models, i.e. simple yet robust models easy to use in participatory settings.

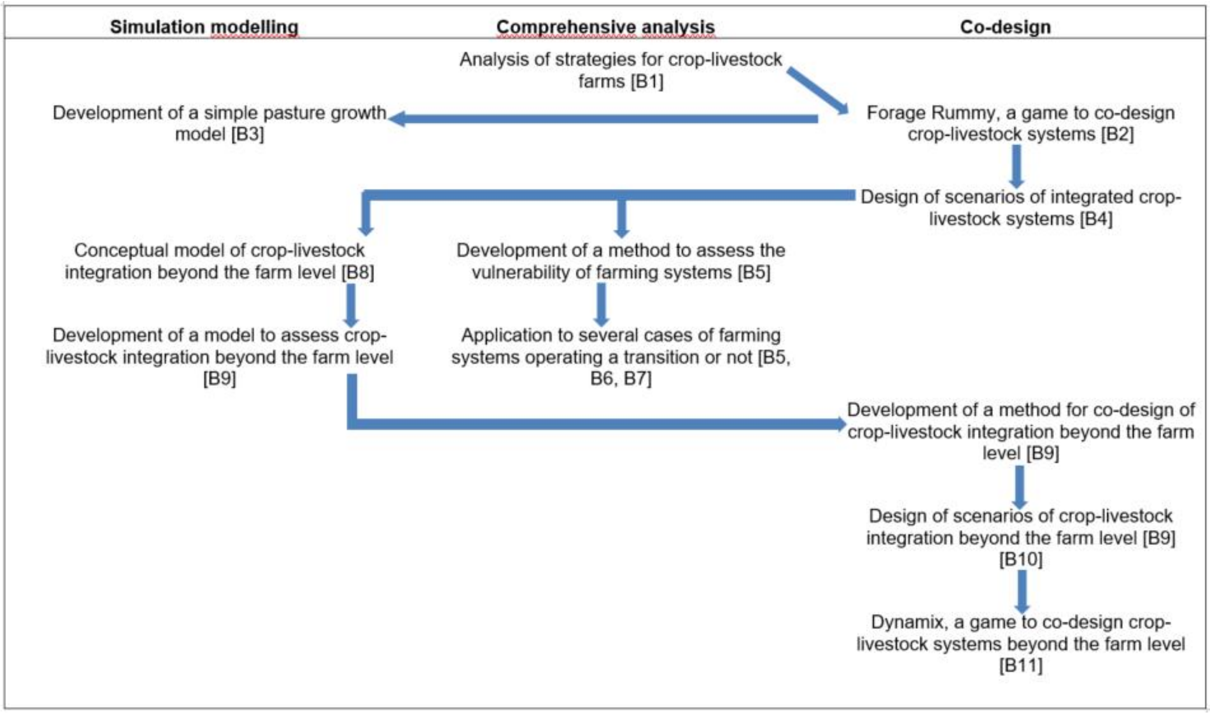

Figure 3: Overview of the articulation among the three research approaches in the autonomy in crop-livestock systems example

Discussion and conclusions

Ex-post analysis of the pros and cons of the conceptual framework

As suggested by Turnheim et al. (2015) for the transition to sustainable and low-carbon societies, the combination of the three research approaches, comprehensive analysis, co-design and simulation modelling, over two case studies enabled to address wicked problems related to the sustainability transition of farming systems. The two case studies showed the interdependencies among approaches that required aligning problem frames among approaches. Scaling over space and time as well as criteria and indicators used for the evaluation of observed or imagined scenarios were defined consistently. In addition, the levels of details in each approach were decided to complement one another regarding the complexity of the farming systems represented. For example, in the agricultural water management case study, the simulation models were developed to match the requirements of the co-design process according to the outcomes of the comprehensive analysis (Fig. 2).

In both case studies, comprehensive analysis was the starting point prior to simulation modelling and co-design. It allowed getting a better understanding of the problem situation which is needed for developing simulation models or facilitating co-design processes (McCown, 2002). As already suggested (Martin, 2015), co-design was strongly related to simulation modelling: simulation models played a key informative role during co-design. In particular, at the farm up to the territory level, information-gathering costs can be quite high and sometimes the infromation gathered may be poorly reliable due to difficulty of measurements. Simulated data can then provide actors with information they have never been confronted to on the current farming systems or on co-designed scenarios. Thus, simulation models enabled participating actors to deepen their search for solutions of sustainability transition (Martin et al., 2013). These models also promoted social learning on the pros and cons of scenarios involving a range of actors be it on agricultural water management or on crop-livestock integration beyond the farm level.

Another key aspect of the articulation of research approaches in the case studies was the space given to the analysis of counter-intuitive effects (Kilelu et al., 2013). Diverging and converging positions among actors were highlighted whenever possible to enrich the co-design processes. For example, in the autonomy in crop-livestock systems case study, farmers co-designed scenarios of crop-livestock integration beyond the farm level to achieve win-win solutions. With an objective of fairness among participants, these scenarios included manure transfers among farms based on the regular price of manure in the area. Unexpectedly, scenario simulations showed that using this price, one of the farmers was sharply disadvantaged compared to the others. Thus farmers decided to fix a higher price for manure till reaching a win-win situation. Considering the scale and scope of the changes considered, unexpected outcomes are inherent to sustainability transitions. They are also insightful to learn and improve the design of future solutions. Tracking these outcomes and creating the reflexive settings allowing to learn from them is crucial in the proposed conceptual framework.

In the end, over the two case studies, these combined perspectives between comprehensive analysis, co-design and simulation modelling allowed to “zoom in and out” between levels of analysis and to “zip back and forth” in time taking into account diverging and converging positions among actors. The combination of approaches on transitions “in the making” and of future-oriented approaches intended to feed the reflections on transitions allowed the production of knowledge and methods for all stages of the sustainability transition process sparing the positions of each actor.

Our overall approach was driven by Bammer’s (2005) principles of integration and implementation science to address complex societal issues: systems thinking and complexity science, participatory methods and knowledge management, exchange and implementation. Implementation of these principles provided us with a robust understanding of the sustainability transition of farming systems and led us to produce concept, knowledge and methods that were used with actors (farmers, water managers, farm advisors, etc.) to support transition processes. Outcomes of these processes were clear in both case studies with adoption of the tools by actors in their daily work (e.g. Forage Rummy by agricultural consultants) or continuous request to researchers to maintain their investment (e.g. to feed simulation-based discussions of actors having diverging positions on agricultural water management). The tools developed allowed decreasing information-gathering, decision-making, operational and monitoring costs to make sustainability transitions easier.

Still, it should be clear that we also faced issues throughout the two case studies. The main one relates to the generalization of our findings beyond our case studies. These findings tend to be situation-dependent and only the multiplication of experiences will allow the production of generic knowledge. Still, we took care that all the methods developed were not situation-dependent. But that raises the issue of their development and calibration. Developing an integrated assessment model like MAELIA is a long process: after a stage of comprehensive analysis stage, the model has to be developed, calibrated and validated which is not trivial with that kind of large-scale model, and then tested with actors. And in some cases, it might not be able to simulate the scenarios they would be interested to test. Another issue relates to the complexity of scale changes in the decisions. At the territory level, it might be more difficult to get a fair representation of all the actors concerned by the sustainability transition in the participatory processes.

Guiding principles for applying the conceptual framework

We conclude with a set of guiding principles for the combination of these three approaches to support sustainability transition processes and ensure the credibility, salience and legitimacy of the research (Cash et al., 2003):

(i) The overall research should start with a succession of problem finding, framing, and formulating stages. There is no single correct understanding of problem situations (Pretty, 1995). These understandings are framed by individual interpretations that themselves depend on knowledge and beliefs acquired during life. At a very early stage of a project, problem farming is thus essential to ensure that all actors (including researchers and farmers) share their definitions of the problem situation (Pahl-Wostl and Hare, 2004). Otherwise, the risk is to take definitions of problem situations for granted, leading to farmers' goals and constraints, knowledge underpinning decisions as well as farming system states being uncertain, contested or even unknown (Groot and Rossing, 2011; McCown, 2002).

(ii) All three approaches should adopt a systems perspective on the transition and involve integrated assessment of farming systems (Darnhofer et al., 2010; Giampetro, 2010) to integrate their complexity across their different agronomic, ecological, economic, sociological, temporal and spatial dimensions (Giller et al., 2008). To ensure the complementarity and compatibility of the outcomes, it is crucial to clearly define the focus, the multiplicities of temporal and spatial scales and the boundaries of each approach (Adam et al., 2012). This is a precondition to a smooth integration of the data and results of one approach into another.

(iii) The overall research should be interdisciplinary. If conducted from the side of agricultural science, it should be opened to insights from the social sciences (Giller et al., 2008). For instance, modelling farmer decision-making processes can best benefit from the advances of management science and artificial intelligence. And this modelling is needed to enhance the reliability and accuracy of plant growth simulations (Martin et al., 2012). Similarly, characterization of farmers' learning during the sustainability transition is a key concern to enhance the support provided to farmers. This necessarily builds on agricultural scientists trained to the concepts and methods of social sciences or on collaborations with social scientists.

(iv) Combining research approaches on transitions "in the making" through comprehensive analysis and approaches intended to feed the reflections on transitions through simulation modelling and co-design allows the production of knowledge and methods required for all stages of the sustainability transition process. The combination of approaches should be conducted iteratively (Giller et al., 2008). Over the long term, a chain of interactions is created, generating concept, knowledge and methods attuned to the needs of actors. These interactions may be continuous or periodic, the latter responding to specific windows of opportunity (policy decisions, farmer associations request, etc.).

(v) Throughout the combination of research approaches, it is essential integrate the human component of the transition (e.g. actors motivations) to ensure the relevance of the research for the decision-making of actors embedded in the transition situations (Garcia et al., 2005). The three approaches offer different yet complementary ways to address the complexity and the dynamics of this human component in farming systems: by exploring the response of farming system management to projected constraints, by identifying promising management strategies to operate sustainability transitions, by revealing the gap between expectations on promising solutions and outcomes of their implementation, etc.

(vi) Considering the changes related to a sustainability transition especially in terms of objectives, norms and values of the actors involved, it is essential to include a re-definition of performance criteria for farming systems. When dealing with complex issues such as the sustainability transition of farming systems, the contribution of science lies in bringing together pluralistic knowledge and perspectives (Bammer, 2005; Pretty, 1995). Hence participation of actors such as farmers in research approaches is essential to adequately integrate the diversity of backgrounds, values, knowledge, representations, goals, interests and opportunities (Sterk et al., 2009). Actors are no longer viewed as adopters of scientific recommendations but rather as experts capable of bringing new perspectives on performance (Röling and Wagemakers, 1998).

(vii) The research should pay attention to the possibilities of outscaling. Farming is definitely a "situated" activity - characterized by a diversity of climatic, spatial, social, institutional and economic conditions defining constraints at different levels (Giller et al., 2008). As a result, farmers have situated management practices and situated management problems (McCown et al., 2009). For this reason, the knowledge produced may tend to be situation-dependent and only the multiplication of experiences and the comparison of empirical results will allow the objectification necessary for the production of generic knowledge. Yet, the methods produced should be flexible enough to accommodate a large range of institutional and agricultural contexts.

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