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How to Address the Sustainability Transition of Farming Systems? A Conceptual Framework to Organize Research

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Abstract: Stakeholders from academic, political, and social spheres encourage the development of more sustainable forms of agriculture. Given its scale and scope, the sustainability transition is a challenge to the entire agricultural sector. The main question is, how to support the transition process? In this article, we explore how agricultural science can address the sustainability transition of farming systems to understand and support transition processes. We discuss the potential for articulating three research approaches: comprehensive analysis, co-design, and simulation modeling. Comprehensive analysis of the sustainability transition provides perspectives on the interplay between resources, resource management, and related performances of farming systems on the one hand and technical, economic, and sociocultural dimensions of change on the other. Co-design of the sustainability transition stimulates local-scale transition experiments in the real world and identification of alternatives for change. Simulation modeling explores future-oriented scenarios of management at multiple levels and assesses their impacts. We illustrate the articulation of research approaches with two examples of research applied to agricultural water management and autonomy in crop-livestock systems. The resulting conceptual framework is the first one developed to organize research to understand and support the sustainability transition of farming systems.

Keywords: sustainability; transition; simulation modeling; comprehensive analysis; co-design; mixed methods

1. 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 well-documented (e.g., [1] for the impacts of pesticide use on surface water). The agricultural sector faces global changes (e.g., climate change, market globalization and volatility, urbanization, pollution, new diseases and pests) that challenge the future relevance of mainstream agricultural models. Stakeholders from academic, political, and social spheres encourage development of more sustainable forms of agriculture, i.e., those less dependent on anthropogenic inputs and fossil fuels, resilient to global changes, producing sufficient and healthy food [2], and using practices that conserve biodiversity. Different forms of agricultural models have emerged that differ in their degree of institutionalization: organic farming [3], agroecology [4], eco-efficient agriculture [5], etc.

These forms of agriculture represent different concepts, paradigms, and visions about sustainability in agriculture [6]. Horlings and Marsden [7] developed the paradigms of weak and strong ecological modernization to categorize these forms of agriculture according to the way they consider the ecologization of agriculture. Weak ecological modernization of agriculture aims to increase the efficiency of synthetic input use to decrease production costs and environmental impacts. This can occur by implementing the most suitable management practices and using technological innovations such as improved plant cultivars and animal genotypes, sensors, etc. In contrast, strong ecological modernization of agriculture relies on increasing "agrobiodiversity across multiple spatial and/or temporal scales" in farming systems [8] to generate ecosystem services that replace synthetic inputs [9,10].

We focus mainly on this second type of modernization. Given its scale and scope, the sustainability transition is a challenge for the entire agricultural sector. It involves deep changes at multiple levels, from farming systems to food systems (due to a wider diversity of crops grown and offered to consumers) to new arrangements between ecological, economic, and social dimensions. These changes concern multiple aspects, including (i) revising farmers' objectives, values and motivations; (ii) redesigning farming systems, especially how agrobiodiversity components and other natural resources are integrated in space and time; (iii) changing the information systems and support provided to farmers; and (iv) encouraging societal changes in which consumers change their habits to more diverse and more sustainably-produced agricultural goods.

Considering current farming systems and the importance and complexity of the changes required, the main issue involves supporting the transition process. To date, the field of transition studies has been structured mainly around the theory of Transition management [11], the multi-level perspective (MLP) approach [12,13] and critiques of these approaches [14,15]. These studies have been applied most frequently to entire sectors such as energy and transport [16,17]. Highly integrated conceptual frameworks (e.g., multi-level, multi-dimensional, multi-stakeholder) have been developed, but they are not relevant or operational at the farm level. In addition, the main criticism is that these frameworks ignore the individual dimension of change, especially individuals' motivations for change and for breaking with the dominant system [15]. This is a crucial dimension of the sustainability transition of farming systems.

In the field of agricultural science, research has focused on developing knowledge and methods to support the design and evaluation of scenarios of more sustainable farming systems from the field to farm level, and up to the regional level [18]. This research is useful to provide exercises that engage stakeholders in a transition process and to go beyond "sketched" alternatives for change. However, it does not completely address the pathways to follow to transition to the scenario situations. These pathways are intrinsically uncertain, dynamic and multi-level because they are shaped by complex and changing interactions between the social, economic and environmental contexts [19]. Moreover, large-scale implementation of the transition can imply a large amount of information gathering, decision making, and operational and monitoring costs [20], which have been ignored by research even though they require democratic agreements among stakeholders. The entire community of agricultural scientists together with environmental, social, nutrition, and human health scientists faces the scientific challenge of improving understanding of and support for the sustainability transition of farming systems.

In this article, our objective is to develop a conceptual framework to address the problems surrounding the sustainability transition of farming systems. We discuss the potential for articulating research approaches, stances, objects, and scales to better understand and support transition processes. To illustrate this potential, we describe two examples of research conducted in our multidisciplinary (in the field of agricultural science: agronomy, animal science, and ecology) research group applied to agricultural water management and autonomy in crop-livestock systems.

2. Methods: Articulating Research Approaches

2.1. Conceptual Framework

Following Turnheim et al. [21], we believe a need exists to take advantage of the multiple views and approaches of agricultural science to better understand and support the sustainability transition of farming systems, which is as a complex, multi-dimensional and uncertain process. Three approaches that encompass different stances and methodological choices are considered key (Figure 1): comprehensive analysis, co-design, and simulation modeling. Each represents different viewpoints (constructivist vs. objectivist, past and present vs. projected) of the sustainability transition of farming systems and of factors that are critical to the transition. We posit that these three analytical perspectives are not incompatible and that they can and must be articulated to address transition issues. All three approaches adopt a systems perspective of the transition [22] 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" [23].

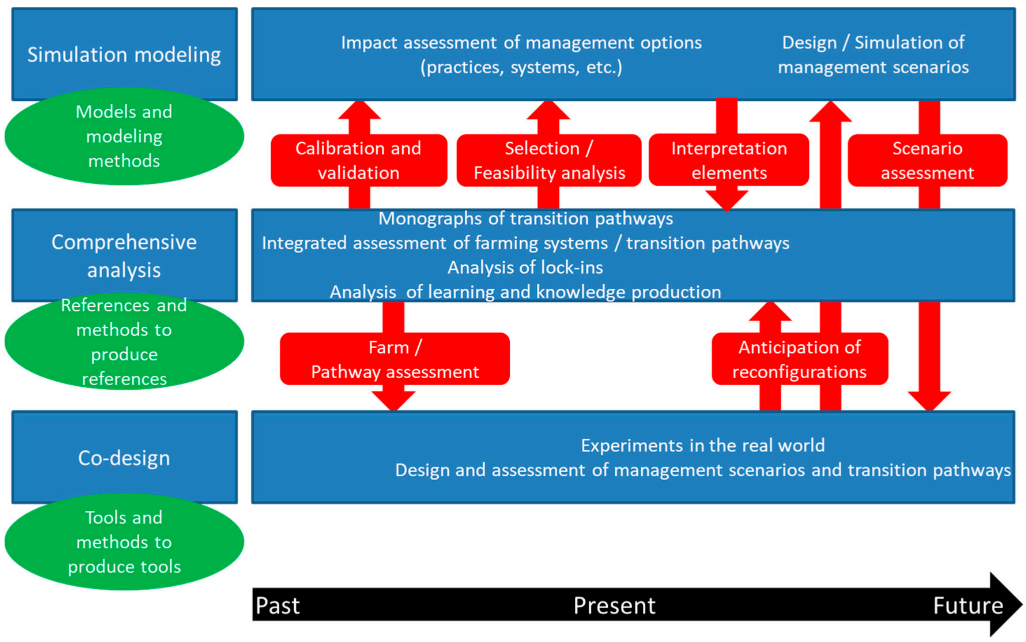

Figure 1. Articulating research approaches to better understand and support the transition to more sustainable forms of agriculture (adapted from [21]). Blue rectangles and green ovals indicate the knowledge and methods produced, respectively. Red arrows and rectangles indicate flows of information among research approaches.

2.2. Comprehensive Analysis

2.2.1. Overview and Corresponding Stances, Objects and Scales

Comprehensive analysis of the sustainability transition provides perspectives (historical or current) on agricultural and institutional contexts and the dynamic interplay between agrobiodiversity and other natural resources, agrobiodiversity and resource management, and related performances of farming systems on one hand and technical, economic, and sociocultural dimensions of change on the other. This implies adopting a systems perspective [24] by considering interactions among system components, between the system and its environment, and the dynamics of these interactions [22].

While mainstream agricultural science tends to focus on specific aspects or sub-systems through in vivo or in silico experimental approaches, comprehensive analysis requires keeping "the 'larger picture' in mind" [22]. This is best supported by an interdisciplinary approach that combines agronomy and animal science with conceptual and methodological frameworks from the social sciences, especially management science and agricultural economics (e.g., the institutional analysis and development framework [25]). Comprehensive analysis is rooted in the real world. It relies on collaboration (mainly through surveys) with farmers who, by essence, address the larger picture when managing their farms. The focus is on (i) existing farming systems, which are diverse due to the influence of farmers' objectives, opportunities and limitations [26]; and (ii) the wider agricultural and institutional contexts that shape farmers' windows of opportunities and limitations [27].

Comprehensive analysis has focused mainly on the cropping system, herd, and farm levels [28,29], although this kind of analysis is also applied at the regional level to understand interactions among farms [30,31] or between farmers and other stakeholders, such as those in the supply chain [32], advisors [26], or water managers. This kind of analysis generally focuses on evolution in interactions among farmers (with their histories, values, knowledge, objectives, and practices), farms (with their resources, assets, and limitations), and the environment (with its climatic and economic risks and opportunities, political regulations and incentives, and stakeholder networks) [22]. Along with understanding system functioning through these interactions and their dynamics, comprehensive analysis also assesses the sustainability of farming systems. This ranges from classic sustainability assessments [33,34] to more integrated approaches that assess the vulnerability or resilience of farming systems over time [35], i.e., their ability to cope with, adapt to or recover from effects of risks [36].

2.2.2. Strengths for Better Understanding and Supporting the Sustainability Transition

Implementing the sustainability transition is uncertain and challenging for most farmers, mainly because available scientific and empirical knowledge on the topic is scarce and the agricultural and institutional contexts are changing. These changes, as well as those in farmers' values, motivations, and objectives, can stimulate transition, which may disrupt their practices, performances, and professional networks [37]. The few documented experiences of the sustainability transition in farming systems [38–40] are too diverse to create a robust knowledge base for decision making. In most farming situations, the agricultural and institutional contexts allow for so many combinations of farmers' objectives and practices that choosing one can be difficult. Thus, comprehensive analysis of agricultural and institutional contexts and farming systems during the transition may provide insights into the strengths and weaknesses of strategies used to implement the sustainability transition in a given context and also identify some drivers for and barriers to implementing the transition [41,42].

Comprehensive analysis of agricultural and institutional contexts can rely on interviews with key informants or participatory workshops to collectively produce an institutional analysis of interactions between stakeholders and resources [43]. When focusing on farming systems, comprehensive analysis is based on longitudinal farm surveys to collect data on several aspects of the transition over several years, including changes in farmers' objectives and underlying values, adaptations of farmers' practices and their consequences on farm performances, farmers' experiments and learning, etc. Based on these surveys, quantitative analysis can characterize the sustainability, vulnerability, and resilience of farming systems during the transition and whether the transition yielded improvements [44]. These results can help farmers make decisions about the sustainability transition. In contrast, qualitative analysis helps characterize changes in farmers' values and knowledge [45] and gaps in practical knowledge revealed by the transition that require further research because it simultaneously addresses technical and human aspects, comprehensive analysis assesses farmers' adaptive capacity [46], and allows adjusting the support provided during the transition.

2.2.3. Limitations and Inputs from Other Research Approaches

Comprehensive analysis has two main limitations. First, it remains rather descriptive. It can identify the most promising strategies for the sustainability transition and the factors promoting this transition. However, because it can hardly capture the dynamics of the interactions among these factors, it may provide little insight into the biological or social mechanisms underlying the differences between strategies. This is when comprehensive analysis can benefit from combination with simulation modeling. Data collected for comprehensive analysis can be used as input to simulation models that may provide interpretation elements to understand the differences observed among sustainability transition strategies (Figure 1). Second, comprehensive analysis is based on past or current situations. If it reveals that the transition may fail, it is unable to explore alternative strategies. Combining co-design with comprehensive analysis, however, can yield benefits: the latter can provide co-design with problematic situations in which sustainability transition strategies are failing. In return, the former can provide innovative reconfigurations of farming systems to anticipate the decisions that will be made about the systems surveyed (Figure 1).

2.3. Co-Design

2.3.1. Overview and Corresponding Stances, Objects and Scales

Sustainability transition of farming systems based on strong ecological modernization can be approached as a design activity. Since it is intended to value the local context of agricultural production [19], the design must include stakeholders from that context, especially farmers. These stakeholders are a major and valuable source of knowledge about the situation to be transformed [47]. They must be involved to increase the chances of producing locally relevant solutions through dialogue with and feedback from them [48]. Moreover, their involvement is a way for them to engage in the transition process by helping to design solutions that they may have to implement. Otherwise, the process may result in a lack of structure in framing the problem because stakeholders' goals and limitations, the knowledge underpinning decisions, etc., would be uncertain, contested or even unknown [49]. Combining pluralistic knowledge and perspectives [50,51] through participation may allow the diversity of backgrounds, values, knowledge, representations, goals, interests, and opportunities to be adequately integrated [52].

Co-design is problem-oriented. It can be performed according to the three stages developed by Nickerson et al. [53]: (i) problem finding, framing and formulating; (ii) problem solving; and (iii) solution implementation. The first two stages correspond to what is commonly understood as design, i.e., "thinking". Design integrates different sources of knowledge (e.g., conceptual, empirical, and procedural, but also explicit and tacit) and their underlying epistemologies [54]. Co-design brings together a variety of stakeholders (e.g., scientists from different disciplines, practitioners from different professions, policy-makers, users, and citizens) that share and produce the knowledge needed in the design process. It is based on compromise and deliberation that must satisfy the requirements of inclusion, equality and freedom [55].

Solution implementation, the last stage, bridges design and experience, i.e., "thinking" and "doing". In this stage, implementation outcomes often divert from expectations. Thus, co-design is based on iterations of design and testing. Working with farmers allows these unexpected outcomes to be monitored to progressively improve the design [56]. Applying co-design to the sustainability transition can then take the form of a social experiment [57] that differs from other types of experiments in that it is re-calibrated until it works [58]. This kind of social experiment may transform both the stakeholders (their values, knowledge, objectives and practices) participating in the co-design process and the products of their interactions (e.g., farming systems up to regions). At this stage, the challenge of co-design is to create the reflexive settings that facilitate learning from the experience of solution implementation [54]. When solution implementation is not feasible (e.g., when focusing on projected climate change), it must be replaced by forecasting, mainly through simulation. In these cases, unexpected outcomes are difficult to identify, but changes in the stakeholder beliefs and practices remain relevant.

2.3.2. Strengths for Better Understanding and Supporting the Sustainability Transition

Following the co-design approach before implementing the sustainability transition is beneficial for several reasons. The successive stages of problem finding and framing help to clarify the formulation of problems, which are frequently difficult at the beginning of the design process [59]. In most farming situations, the agricultural and institutional contexts allow for many alternative farming systems. Co-design stimulates the creativity of participants and integrates their respective knowledge to identify, discuss and select promising solutions for implementation [56]. Testing allows discrepancies between the expectations and effects of design implementation to be identified and recorded [60]. After testing, stakeholders can discuss whether the solutions are satisfactory enough for larger-scale implementation. Reflecting on unexpected outcomes leads to collective reflexivity and learning, which is central to the sustainability of the transition process.

Co-design is an operational approach to develop an open-ended sustainability transition that addresses uncertainty and knowledge gaps. It can generate original and innovative solutions. Researchers involved in co-design use conceptual and methodological frameworks from the social sciences to produce knowledge about technical or organizational aspects of the transition, as well as about cognitive, axiologic, and emotional aspects of the stakeholders involved. Co-design also highlights knowledge gaps and the research efforts needed. Since it is holistic and grounded in the problem situation, co-design helps researchers identify and learn from the co-evolution of technical, social and institutional aspects of the transition. This co-evolution, distinguished by the dynamics of agreement and conflict, also produces unpredictable outcomes [58] that provide insight to researchers and other stakeholders.

2.3.3. Limitations and Inputs from Other Research Approaches

Being grounded in the problem situation is both a strength and a limitation of the co-design approach. The outcomes vary according to the stakeholders involved, their bounded rationality and the specific features of the context. Thus, the operational solutions and some of the knowledge produced are context-dependent and out-scaling may not be self-evident. Increasing the number of experiences and comparing empirical results to theoretical frameworks will provide the objectification necessary to produce knowledge that can be applied more widely [56]. The input of scientific knowledge and the use of simulation models can foster the creativity and relevance of the co-design approach. Comprehensive analysis provides co-design with examples of transition pathways and the corresponding integrated assessment of farming systems and regions and simulation modeling can support co-design by helping stakeholders take a position on the scenarios assessed, either to select one to implement in the field or to enrich group discussions. In some cases (e.g., agricultural water management), iterations of design and testing can be extremely expensive; simulation models provide an opportunity to explore, in silico, effects of proposed changes. However, simulation models may improve understanding of only a limited range of unexpected side-effects, i.e., those that the model structure can simulate.

2.4. Simulation Modeling

2.4.1. Overview and Corresponding Stances, Objects, and Scales

Simulation modeling is the use of mathematical models to explore scenarios of management of agrobiodiversity and other natural resources at different levels and estimates their impacts. Driven by advances in information technology, agricultural system modeling has evolved along with agricultural science, resulting in the development of process-based biophysical models of crops and livestock, statistical models based on observations, and economic models at field, regional, and global levels [61]. Another approach has emerged around companion modeling (ComMod) [62], which entails participatory development of models before using them to address specific issues. These models are frequently multi-agent systems that simulate interactions among stakeholders concerned with a shared resource. Using integrated assessment models [63] is a recent approach widely used in climate change analysis. It draws on knowledge and strengths from multiple disciplines by linking discipline-specific submodels through a unified modeling platform.

The data required to run simulation models are usually scarce at the levels considered in the sustainability transition of farming systems. This justifies using parsimonious models, i.e., simple yet robust models that are simple to use in participatory settings, that may facilitate sensitivity and uncertainty analysis of model outputs [64,65]. Models that require fewer input data are easier to apply in new agricultural and institutional contexts, for which available knowledge is limited. Participation of stakeholders such as farmers in the modeling process can help integrate their diverse knowledge and representations, increasing the overall relevance of the research [52].

When applied to the sustainability transition of farming systems, simulation modeling implies describing the systems as complex managed hierarchical systems and considering interactions between their sub-systems. Experimental data, besides having intrinsic analytical utility, are required to develop, calibrate, and evaluate the models. Simulation modeling can estimate many variables that are difficult to measure in the field, especially when upscaling to the farm and regional levels. This approach is useful for assessing farming practices and systems across temporal and spatial scales and thus for informing stakeholders engaged in the sustainability transition. For example, simulation modeling can assess irrigation practices at field and farm levels (MODERATO: [66]; Namaste: [67]). It can also assess impacts (e.g., on water management, nitrogen cycling, economics) of innovative practices (use of cover crops, crop diversification, reduced soil tillage, etc.) from the cropping system to watershed level. It can also provide data on the multiple dimensions of sustainability and avoid a reductionist assessment centered on productivity [68].

2.4.2. Strengths for Better Understanding and Supporting the Sustainability Transition

New modeling approaches, such as companion modeling, help align stakeholders' problem framing with conceptual and quantitative models to ensure the relevance of simulations. Thus, model development varies widely depending on the system studied and the purpose of the study [61]. Combining experimental data with models helps simulate scenarios that estimate impacts of innovative practices or farming systems (organic farming, low-input cropping systems, etc.). Simulation models can estimate impacts on agricultural production and other environmental outputs (e.g., nitrate leaching, greenhouse gas emissions; [69]). This way, simulation modelling offers a future-oriented perspective on the transition and clarifies the ability of different management options to achieve specific sustainability targets or to highlight counter-intuitive effects.

Simulation results can support reflections and discussions of stakeholders engaged in the co-design process to help them plan and implement the sustainability transition of their practices, farming systems or even the region. This may stimulate social learning among local stakeholders [60] involved to increase the chances that they reach consensus on problem framing and solution co-design and implementation. Because they are comprehensive, models can provide interpretation elements to comprehensive analysis of farming systems when the data collected cannot explain the phenomena observed. They can also be used to assess the relevance of outscaling promising strategies for the sustainability transition identified through comprehensive analysis in different contexts.

2.4.3. Limitations and Inputs from Other Research Approaches

Simulation modeling has certain limitations, such as its "black-box" effects. Developing models in the framework of participatory approaches, however, may help stakeholders understand what the models represent. Comprehensive analysis can also provide model specifications. Another limitation is the amount of data required calibrate and validate crop, farm, or land-use models. In this case, adding comprehensive analysis can facilitate collection of the required data. This kind of analysis also enables selection of which agrobiodiversity and other natural resource management options to simulate. At this stage, models are not always suited for simulating innovative practices. The fact that models are often calibrated and validated based on existing farming practices and climate conditions can challenge the validity of estimations of innovative practices in a future climate or under different political and economic contexts. To verify the relevance of simulation modeling results, further comprehensive analysis can help assessing the real-world feasibility of the options simulated.

3. Results: Examples of Application in Two Research Domains

3.1. Agricultural Water Management

3.1.1. Problem Situation

In agricultural areas, droughts occur when low rainfall coincides with low water stocks (in water bodies and soils) and high crop water needs [70,71]. Recurring droughts reveal that water demand structurally exceeds water supply. This water imbalance is unsustainable: it erodes ecosystem functioning [72], drives water-use conflicts [73], and impacts agricultural production [74]. In Europe, natural availability of water resources is quite high, and water storage capacities are well-developed. However, shortages of and conflicts over water resources are common [75], in particular due to regulatory measures established to promote environmentally sustainable management of natural resources (e.g., [76]). For example, river flow should not fall below a regulatory threshold (the "low-water regulating flow", LWRF), which is designed to ensure the proper functioning of the water environment and to satisfy all water uses. These regulatory measures for resource use challenge the sustainability of human activities that until recently were encouraged, such as irrigated agriculture.

"Crisis" measures, such as water-use restrictions, occur when river flow falls below the LWRF, but they are considered inappropriate for resolving water imbalances. To decrease the occurrence of water crises, the 2006 Water and Aquatic Environment Act in France established a water quota for irrigated agriculture within each watershed. In many watersheds, mainly in southwestern France, this quota is much lower than the water withdrawn in past dry years, which encourages (or should encourage) farmers to rethink their farming systems, in the short or longer term. These changes contribute to profound changes in water management and governance promoted by several authors [71,75,77], which should include rethinking the approach ("participatory", "prospective", "integrated", "adaptive", etc.) and the orientation ("demand management", "agroecological practices", "locally-adapted cropping systems", etc.).

3.1.2. Articulating Research Approaches

For more than 25 years, we have studied quantitative water management to address water scarcity problems. The year 2003 can be considered pivotal for studies at the regional scale. The extreme drought that occurred in 2003, as well as the public debate about construction of the Charlas dam, changed the minds of water managers and researchers about the need for tools to explore and assess alternatives to current land uses and farming practices. Our research group participated in the Charlas dam public debate and attended multiple meetings about water management throughout the period that led to the 2006 Water and Aquatic Environment Act and its implementation (A1: [78]; A1 starts the numbering of the outputs produced in this research series represented on Figure 2). Several interviews were conducted with water users and water managers. Comprehensive analysis of these meetings and interviews revealed the need to develop modeling tools to assess the potential environmental impacts (particularly on river flows) and economic impacts (particularly on farming systems) of large-scale changes in land uses and farming practices (A2: [79]; A3: [80]).

The resulting series of individual and collective studies by graduate students (e.g., A4: [81]; A5: [82]) helped us to understand water management situations in several watersheds, with an emphasis on (i) interactions among stakeholders (water users and water managers) and between stakeholders and the biophysical environment and (ii) the decision-making processes of each type of stakeholder. These comprehensive analyses were summarized via cognitive maps for interactions between stakeholders and resources and via Unified Modeling Language activity diagrams for decision processes (A6: [83]). This helped us to identify which entities and processes to include in a model of a water management situation with water imbalance problems and which spatial and temporal resolutions and level of functional complexity (e.g., farm) to represent.

Accordingly, we developed a multi-agent modeling platform called MAELIA (A7: [84]). It allows simulating the interactions between human activities (farming practices), ecological processes (hydrology and crop growth), and governance systems (water regulations and releases from dams) over time at fine spatiotemporal resolutions. MAELIA includes three types of agents: farmers, dam managers, and state services. A specific modeling study helped us to select AqYield as the crop growth module of MAELIA, due to its low input data requirements and high robustness (A8: [64]).

MAELIA was developed to address problems of water managers and issues of the main water users (farmers) in agricultural landscapes. We first applied it to the downstream portion of the Aveyron watershed (southwestern France). Parameterization of the model for this watershed required collaborating with local experts to add local knowledge to generic databases to adequately distribute soils and cropping systems within the watershed (A9: [85]). To parameterize farmers' decisions about irrigating and other agricultural operations, we surveyed several farmers and conducted a transversal analysis to define generic decision rules for each combination of cropping system × soil × irrigation equipment situation (A10: [86]). An additional study was conducted to develop a faster method, based on interviews with a few key informants, to apply MAELIA to several watersheds (A11: [87]).

In parallel, along with local stakeholders, we designed alternative scenarios of the current situation with the objective to improve the water balance of the study watershed (A12: [88]). After translating stakeholders' narratives into model inputs [89], these scenarios, representing moderate changes in land use, crop rotations, and agricultural practices, were simulated with MAELIA. Nevertheless, they were 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 the most interesting to learn about (but not necessarily the most desired). To simulate these new scenarios with MAELIA, we modified AqYield to accurately simulate new crops (e.g., winter crops) and new farming practices (long rotations) (A13: [90]).

For each new scenario, MAELIA simulations (A14: [91]) enabled us to quantify indicators that experts had identified to meet the evaluation criteria that the local stakeholders had demanded. In separate "evaluation workshops", homogeneous groups of stakeholders (i.e., sharing the same issues and objectives) were asked to evaluate each scenario for each criterion using the simulated indicators they considered relevant, in addition to their own expertise (A15: [92]). The KerBabel Decision Support Tool [93] was used to analyze all evaluation workshops, and its results were presented in a meeting of all of the groups. The groups' evaluations of the scenarios, the indicators chosen as arguments and the diverging and converging positions among stakeholder groups were highlighted to share positions and allow new scenarios to emerge.

3.1.3. Summary and Insights

We diagrammed our series of research on agricultural water management at the regional level (Figure 2), which highlights the iterations over time between co-design and simulation modeling. Comprehensive analysis was an essential preliminary step in promoting the sustainability transition of water management: it guided our participatory stance and allowed us to structure the overall problem by facilitating model specification (processes, components, and scales), identifying participants for the co-design approach, and defining evaluation criteria and indicators. The articulated use of simulation modeling, co-design and evaluation exercises improved our understanding of the local water situation by clarifying debate points but also by allowing converging viewpoints among stakeholders with diverging interests to emerge in a context of conflict.

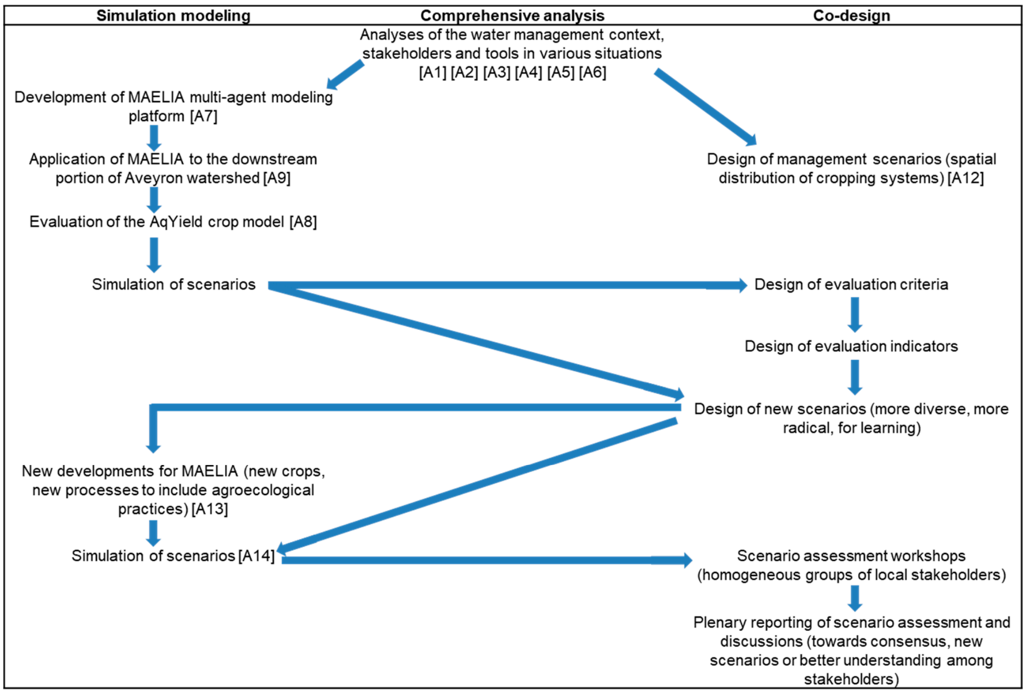

Figure 2. Overview of the articulation over time (from top to bottom) among the three research approaches for the example of agricultural water management. A1, A2, etc. refer to the outputs of the research listed in the text.

3.2. Autonomy in Crop-Livestock Systems

3.2.1. Problem Situation

In Europe, the dependence of farming systems on synthetic inputs has increased dramatically in the past 50 years. As an illustration, 8.3 TgN of synthetic fertilizer are spread on croplands each year in Europe [94]. Livestock production systems have similar problems since they increasingly depend on feed imported from a few countries (USA, Argentina and Brazil). Each year, net imports of feed to Europe equal 2.34 GgN [95]. This situation challenges the sustainability of European agriculture, especially its vulnerability to increases in prices of synthetic nitrogen and feed.

In response to these issues, developing more integrated forms of agriculture appears to be a promising option to restore the autonomy and sustainability of agricultural systems [96,97]. Diversified and (horizontally) integrated agricultural systems promote ecological interactions between system crops, grasslands, and animals in space and time and create opportunities for synergies between them through resource transfers [97]. Thus, crop-livestock systems are well-suited for implementing the principles of diversified and (horizontally) integrated agriculture [97,98] to reduce the dependence of European agriculture on synthetic nitrogen and imported feed inputs.

3.2.2. Articulating Research Approaches

In recent years, our research has focused on understanding how crop-livestock integration can increase farm autonomy at farm and regional levels (Figure 3). In the piedmont of the French central Pyrenees that tends to specialize in crop production, we performed comprehensive analysis to identify farmers' strategies that allow mixed crop-livestock farming to survive (B1: [99]; B1 starts the numbering of the outputs produced in this research series represented on Figure 3). We analyzed trajectories of the

the area's entire farm population from 1950–2005 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 maximized autonomy by integrating crops, pastures, and livestock to promote internal nutrient recycling and reduce the dependence on inputs. The second used agricultural diversification to exploit economies of scope to protect the farm against market fluctuations. Engaging farmers in a sustainability transition based on diversification and increased autonomy was challenging since 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: [100]). Agricultural advisors and/or researchers can use it with small groups of farmers during half-day workshops. During these workshops, farmers collectively and iteratively design (with material objects, e.g., cards) and evaluate (with a simulation model) crop-livestock systems to adapt to contextual hazards (e.g., a sudden and sharp increase in input prices) and new farmers' objectives (e.g., converting to organic farming). Throughout these iterations, the aim is to develop farmers' adaptive capacity to implement the sustainability transition by stimulating their discussions and reflections. Forage Rummy was successfully used with hundreds of farmers, and extension agents were trained to use it (B4: [56]). The development of Forage Rummy also led to simulation modeling studies since it required selecting or developing process-based models (e.g., B3: [101]) that were robust when scaled out and required few input data.

Forage Rummy workshops revealed two limitations to widespread adoption of integrated crop-livestock systems. First, farmers are not always aware of the risks to which they are exposed and thus might be reluctant to implement the sustainability transition. Second, due to specific constraints (e.g., land availability, topography), some farms do not have much capacity to diversify and increase autonomy at the farm level. Following these observations, we developed two new areas of research: comprehensive analysis of the vulnerability of crop-livestock systems to climatic and economic variability, and co-design and simulation modeling 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 a method to assess farm vulnerability and to explain how this vulnerability can best be reduced by farmers' adaptations over time (B5: [34]). According to the method, farm vulnerability is minimized when high values, a stable or increasing trend and low variability is found for all vulnerability variables considered. We applied our method to several datasets, including farms with a routine management regime (B6: [102]; B5: [34]) and farms that were implementing a sustainability transition (B7: [44]). For the latter, farms were surveyed (2008–2013) before, during and after their conversion to organic dairy farming. Our analysis showed that farms that decreased their vulnerability the most had drastically reoriented their strategies for integrating crops and livestock, from systems based on silage maize and dependent on imported soybean meal to autonomous pasture-based systems based on grazing. This kind of comprehensive analysis is being replicated to support farmers with sector-specific and local insights into the most promising strategies for implementing the sustainability transition.

To assess the scope for integrating crops, pastures and livestock beyond the farm level, we developed a conceptual framework that defines three forms of integration: local coexistence, complementarity and synergy. These three forms correspond to a gradient of stronger temporal, spatial and organizational coordination among farms (B8: [103]). In parallel, we developed a method to co-design and assess integrated crop-livestock systems beyond the farm level and applied it to a group of organic farmers specialized in crop or livestock production (B9: [104]; B10: [105]). First, we analyzed these 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 the sustainability of these scenarios and presented the results to farmers to discuss their feasibility. We focused particularly on trade-offs between individual and collective benefits of implementing the scenarios. The selected scenario resulted in increased autonomy for fertilizers, feed and decision making at both individual and collective levels. With this method, however, farmers had difficulty identifying trade-offs between individual and collective benefits, and certain key dimensions of crop-livestock integration beyond the farm level were ignored, such as logistics. To address these issues, we developed a serious game called Dynamix (B11: [106]) to support collective design of scenarios of crop-livestock integration beyond the farm level. This serious game integrates a simulation model that is based on previous studies, including the simulation model of Forage Rummy (B2: [100]). It is currently used with farmer groups in several French regions.

3.2.3. Summary and Insights

Like for the agricultural water management example, our research on autonomy in crop-livestock systems included iterations between research approaches, especially co-design and comprehensive analysis (Figure 3). In this case, however, co-design was central for orienting subsequent research approaches. It guided the type of methods used to conduct the comprehensive analysis of farm trajectories and the co-design itself. It was also crucial in the simulation modeling choices we made, with priority given to parsimonious models.

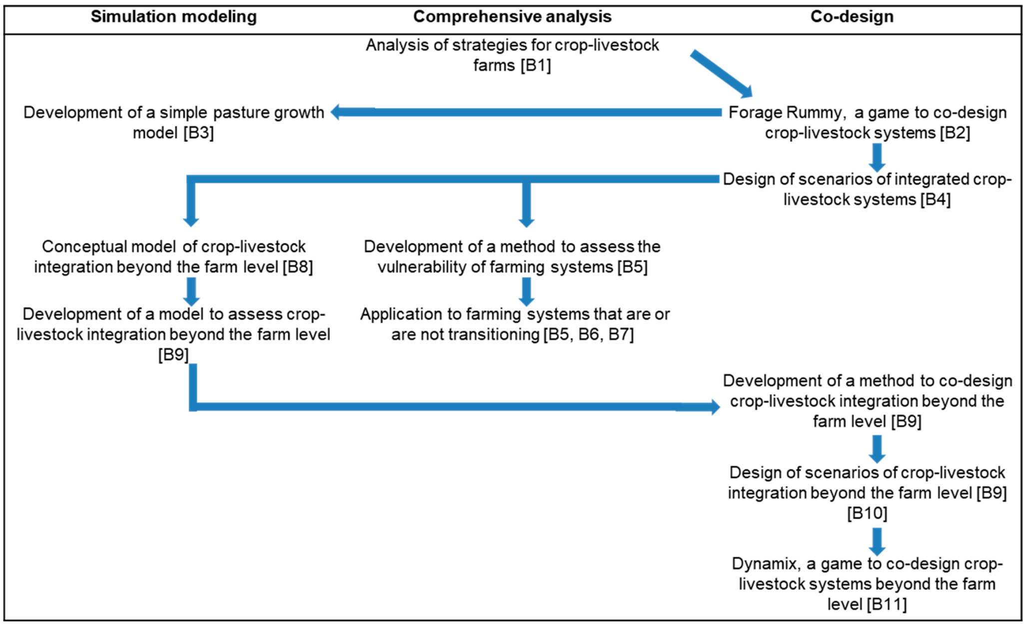

Figure 3. Overview of the articulation over time (from top to bottom) among the three research approaches for the example of autonomy in crop-livestock systems. B1, B2, etc. refer to the outputs of the research listed in the text.

4. Discussion and Conclusions

4.1. Ex-Post Analysis of Pros and Cons of the Conceptual Framework

The two case studies showed interdependence among the research approaches—comprehensive analysis, co-design and simulation modeling—whose problem frames required alignment to address problems related to the sustainability transition of farming systems. Spatial and temporal scaling was consistently defined, as were criteria and indicators used to evaluate observed or hypothetical scenarios. In addition, the approaches' levels of detail were designed to complement one other to represent the complexity of the farming systems. For example, in the agricultural water management case study, the simulation models were developed to meet requirements of the co-design approach according to the outcomes of the comprehensive analysis (Figure 2).

In both case studies, comprehensive analysis was the starting point, performed before simulation modeling or co-design. It improved understanding of the problem situation, which is necessary to develop simulation models or facilitate the co-design approach [49]. As already suggested [107], co-design was strongly related to simulation modeling: simulation models played a key informative role during co-design. In particular, from farm to regional levels, costs of information gathering may be high, and sometimes that information may have low reliability due to measurement difficulties. Simulated data can provide stakeholders with information they have not encountered in current farming systems or in co-designed scenarios. Thus, simulation models enabled participating stakeholders to deepen their search for solutions for the sustainability transition [18]. These models also promoted social learning about pros and cons of scenarios involving a range of stakeholders, whether for agricultural water management or for crop-livestock integration beyond the farm level.

Another key aspect of articulating research approaches in the case studies was the analysis of counter-intuitive effects [60]. Diverging and converging positions among stakeholders were highlighted whenever possible to enrich the co-design process. 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. Aiming for 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 this price put one farmer at a great disadvantage compared to the others. Consequently, the farmers decided to set a higher price for manure until they all reached a win-win situation. Given the scale and scope of the changes considered, unexpected outcomes are inherent to the sustainability transition. They also provide insights into learning about and improving the design of future solutions. Tracking these outcomes and creating the reflexive settings to learn from them is crucial in the conceptual framework developed.

Ultimately, in the two case studies, the combined perspectives of comprehensive analysis, co-design and simulation modeling enabled us to "zoom in and out" between levels of analysis and to "zip back and forth" in time by considering diverging and converging positions among stakeholders. The combination of (i) approaches for the transition "in the making" and (ii) future-oriented approaches designed to encourage reflection about the transition helped to produce knowledge and methods for all stages of the sustainability transition. As a result, outcomes of the research were clear in both case studies, with stakeholders adopting the tools in their daily work (e.g., Forage Rummy by agricultural advisors) or continuous requests to researchers to maintain their investment (e.g., to encourage simulation-based discussions of stakeholders with differing positions on agricultural water management). The tools developed decreased costs of information gathering, decision making, operation and monitoring, which eases the sustainability transition.

Nonetheless, we also faced challenges during the two case studies, the main one being generalization of our findings beyond the case studies. The findings tend to be situation-dependent. We were careful to ensure, however, that none of the methods developed was situation-dependent. Still, this raises the challenge of their development and calibration. Developing an integrated assessment model such as MAELIA is a long process: after comprehensive analysis, the model must be developed, calibrated, and validated (an elaborate process with such a large-scale model) and then tested with stakeholders. In some cases, the model might not be able to simulate scenarios of interest. Another challenge was the complexity of scale changes in the decisions. At the regional level, it might be more difficult to fairly involve all the stakeholders concerned by the sustainability transition in the participatory processes.

4.2. Guiding Principles for Applying the Conceptual Framework

We conclude with a set of guiding principles for articulating the three approaches to support sustainability transition processes and ensure the credibility, salience, and legitimacy of the research [108].

(i) The overall research should start with a succession of problem finding, framing and formulating stages. Problem situations can be regarded from a diversity of perspectives resulting in a diversity of understandings [51]. At the beginning of a project, problem framing is thus essential to ensure that all stakeholders (farmers, researchers, etc.) express their definitions of the problem situation [109]. Otherwise, they risk assuming that they share the same definitions of problem situations, resulting in farmers' goals and limitations, the knowledge on the problem situations being uncertain or contested [49,110].

(ii) All three approaches should adopt a systems perspective on the transition and involve integrated assessment of farming systems [22,111] to integrate their complexity in the agronomic, ecological, economic, sociological, temporal and spatial dimensions [112]. To ensure the complementarity and compatibility of the outcomes, it is crucial to clearly define the focus, the multiple temporal and spatial scales, and the boundaries of each approach [113]. This is a precondition to smoothly integrate the data and results of one approach into another.

(iii) The overall research should be interdisciplinary. Although conducted from the perspective of agricultural science, it should be open to insights from the environmental, social, nutrition and human health sciences [112]. For example, modeling farmer decision making can benefit most from advances in management science and artificial intelligence. In addition, this type of modeling is needed to increase the reliability and accuracy of plant growth simulations [114]. This necessarily relies on agricultural scientists trained in the concepts and methods of other fields of science or collaboration with scientists from these fields.

(iv) Combining research approaches on the transition "in the making" through comprehensive analysis and approaches intended to encourage reflection on the transition through simulation modeling and co-design produces the knowledge and methods required for all stages of the sustainability transition. The approaches should be combined iteratively [112]. In the long term, a chain of interactions is created that generates concepts, knowledge, and methods attuned to stakeholder needs. These interactions among approaches may be continuous or occasional, the latter responding to specific opportunities (policy decisions, farmer association requests, etc.).

(v) Given the changes involved in the sustainability transition, especially in objectives, norms and values of the stakeholders involved, it is essential to redefine the performance criteria of farming systems. When addressing complex issues such as the sustainability transition of farming systems, scientists have to integrate pluralistic knowledge and perspectives [50,51]. To this end, they have to organize the participation of farmers to the research to integrate their various backgrounds, knowledge, representations, values, interests, goals, and opportunities [52].

(vi) The research should focus on the potential of outscaling. Farming is a "situated" activity. It is embedded into climatic, economic, social, and institutional conditions that define constraints applying at different levels [112]. As a result, farmers' management practices and management problems are embedded into the causalities of situations too [115]. For this reason, although the knowledge produced may tend to be situation-dependent, the methods produced should be flexible enough to accommodate a wide range of institutional and agricultural contexts.

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