Synthesis

Special Feature: Ecosystem Services for Agroecological Transitions

Agroecological Transitions: What Can Sustainability Transition Frameworks Teach Us? An Ontological and Empirical Analysis

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ABSTRACT

Transitioning toward more sustainable agricultural development paths requires extensive change, and not simply marginal technical adjustments as suggested by a strong conception of agroecology. To deal with transition, we believe that agroecology can be enriched by a deep analysis of Sustainability Transition frameworks and conversely, that preexisting theories can be questioned in light of the specificities of agroecological transitions (AET).

We first examine some of the main Sustainability Transition frameworks (resilience of social-ecological systems, institutional analysis, and development of social-ecological systems, and socio-technical transition). We identify their ontologies to question their ability to be combined without deep adjustments. In a second step, we analyze how these frameworks have been used and questioned by researchers from the life or social sciences in four AET studies.

We found that each framework is relevant in its systemic and dynamic approach to change, but also that there are limits concerning the balance between the various dimensions. The scales and processes linked to AET must be taken into account, as well as the way to jointly consider ecological, social-economic, and technological aspects. Moreover, it became clear that problems in dealing with agency are common to these approaches, which influences the way to model change. More broadly, sustainability transition frameworks need to better account for ecological and technological materialities and processes, the importance of emergent organizations in singular situations, and learning processes and the diversity of knowledge dynamics. Doing so is challenging

because it requires re-grounding theories in empirical observations as well as questioning disciplinary frontiers and ontologies.

Key words: agroecology; social-ecological systems; socio-technical systems; sustainability transition

INTRODUCTION

The ways in which agriculture has been developed have negatively affected the sustainability of global economies (IAASTD 2008). As the agrifood industry contributes to economic growth and is deeply connected to standards of living, it is crucial for sustainability. Until now, technological innovations have not been able to trigger the vital changes required; on the contrary, the industrialization of agriculture has increased the levels of throughput used in the global economy (Krausmann and Fischer-Kowalski 2013). To foster a transition toward more sustainable agriculture, alternative solutions have emphasized the positive role of (bio)diversification and the ecological processes and services they provide (Altieri 1999, Kremen et al. 2012). While technological solutions extend the productivist paradigm, the strong conception of agroecology we refer to requires extensive changes in agricultural practices, in the organization of production and distribution, in the nature of technologies used, and in re-conceptualizing the identity of 'farmer' (Francis et al. 2003, Hill and MacRae 1996, Lamine 2011, Nicholls et al. 2016). Ultimately, these changes involve other sets of social norms, requiring a different conception of the human-technology-environment than that prevailing in the productive-technology-intensive mode of agricultural production (Plumecocq et al. this issue). Agroecological transitions (AET) also imply cognitive aspects (IAASTD 2008). On the one hand, the knowledge used to manage technology-intensive production systems is no longer useful for informing individual and collective decision-making in agroecological systems; on the other hand, tackling the complexity of the AET has analytical and scientific consequences.

As in agroecology (Altieri 1995, Gliessman 2011), different research approaches to transition increasingly address the issue of sustainability. The main Sustainability Transition (ST) Frameworks belong to two families. The first, socio-technical transition (STT), includes many strands among which Transition Management (TM) and Multi-Level Perspective (MLP) are the most well-known (Markard et al. 2012). The second family of social-ecological system (SES) frameworks includes, among others (Binder et al. 2013), Institutional Analysis and Development (Ostrom 2009), and Resilience Thinking (Folke et al. 2010, Holling 1978). Both groups of approaches emphasize the need to consider interactions between technical innovations, the structure and type of social-economic system, and ecosystem functions and services at multiple levels. In addition, even though agroecology contributes to sustainability, AET is rarely addressed in any of these approaches (Markard et al. 2012, Ollivier 2015). Agroecologists have not considered transition in a broad, systemic, and multilevel way, as they have mainly conceptualized transition with the Efficiency-Substitution-Redesign model at farm scale. This model, considering phases with increasing costs of system reorganization and ecological features integration, is sometimes applied to institutional dimensions (e.g. organizational design or role of social movements) mainly through descriptive accounts rather than social science theories (Gliessman and Rosemeyer 2010, Hill and MacRae 1996, Nicholls et al. 2016).

ST frameworks seem relevant for improving our thinking about AET. However, to date, no study has analyzed the ontological and instrumental suitability of these approaches, combined or not, for addressing AET. Without trying to define a new integrated analytical framework, we seek here to identify some gaps and discuss future avenues for using and enhancing ST frameworks in transitioning agriculture towards sustainability.

In this paper, we argue that contrary to other types of transitions analyzed using ST frameworks, such as energy or water management, transiting to agroecological production systems faces the challenge of enrolling multiple and relatively isolated decision-makers as well as non-human entities. This means that the ways in which the multiple issues of AET are tackled need to adequately consider the interactions between multiple levels of decision-making, from a wide range of decentralized groups to more institutionalized organizations.

The paper is organized as follows. Section 2 analyzes some ontological mismatches of the main ST frameworks and identifies debates and gaps in current research. Instead of reinforcing the understanding of sustainability issues, we conclude that a hasty combination of frameworks without critical reflection on their ontologies generates theoretical inconsistencies and the accumulation of each approach's limitations. Then, section 3 presents how AET is addressed by ST frameworks, by investigating how they have been used in four studies on AET situations. These studies show that some adjustments of ST frameworks are required to better address AET. Based upon the analysis of framework ontologies and their use in studies of AET cases, section 4 discusses avenues to better analyze such transitions: strengthening the links between social-economic, ecological, and technical aspects; integrating more agency into social-system thinking; taking ecological dynamics into account; and taking technology seriously.

SUSTAINABILITY TRANSITION FRAMEWORKS ONTOLOGIES

This paper focuses on the main ST frameworks: Social-Ecological Systems (SES) frameworks, comprising

Resilience thinking (Gunderson et al. 1995, Holling 1973) and Ostrom's Institutional Analysis and Development (2009), and Socio-Technical Transition (STT). We chose them since, in recent years, they have been increasingly considered together, in publications, conferences, or international programs, in the larger field of Sustainability Science to explore the various aspects of Sustainability Transition (Kajikawa et al. 2014, Leach 2008, Ollivier 2015). Indeed, at first, the SES and STT literatures share many interesting features: interest in sustainability, in dynamic multilevel approaches to complex systems change, and in learning (Voss and Bornemann 2011) and governance issues (Smith and Stirling 2010, Van der Brugge and Van Raak 2007). Some authors have tried to combine them (e.g. Duru et al. 2014, Pahl-Wostl et al. 2007, Pant et al. 2015), considering these frameworks to be complementary, but others have combined them with other frameworks to counter their limitations (Bush and Marschke 2014, Dwiartama and Rosin 2014, Fabinyi et al. 2014, Stone-Jovicich 2015). Nevertheless, with other scholars (Leach 2008, Shove and Walker 2007), we call for caution in using, mixing or integrating these frameworks because of the risk of ontological mismatches and limitations.

Considering their ontologies, in the epistemological sense, we aim to identify the problems that remain with these frameworks, particularly in their use for AET analysis that we will examine in more detail below. Ontology is defined as the "foundational assumptions about the nature of the (social) world and its causal relationships" (Geels 2010) that underpin and frame ways of seeing transitions. Inspired by Binder et al. (2013) and Geels (2010) and considering history, anchorage, and critiques of frameworks, we identify in the following sections and in Table 1 the main ontologies, their basic conceptual units, and their relations, which allow them to model reality in various ways in terms of: disciplinary background, model of change, system delineation, and the social, ecological and technological entities considered.

Resilience Thinking of Social-Ecological Systems

The ontology of Resilience Thinking is based on recognizing the interdependence between people and nature (Folke et al. 2010), which is disruptive with traditional ecology in which this approach was originally grounded (Xu and Marinova 2013). Resilience is a rejection of the "Myth of Ecological Stability" (Holling 1978). This concept allows to understanding the non-linear dynamics of systems (Holling 1973), which constitutes a radical new way of seeing social-ecological reality.

For these scholars, an SES is resilient when, faced with disturbances, it remains relatively stable and evolves within a "stability domain" defined as a set of controlling variables (Folke et al. 2010), itself embedded in a stability landscape. Under certain conditions (external shocks, crises, or changes in internal cumulative properties) some thresholds are exceeded, in which case an SES can shift from one stability domain to another (Fig 1a).

Drawing on studies of ecosystem changes (Holling 1986) and Schumpeter's work on technical innovation and economic cycles (Allison and Hobbs 2004, Gunderson and Holling 2002), some authors have described an SES trajectory according to the metaphor of an adaptive cycle. This way of considering time involves four endogenously driven, interlinked phases of change in SES structures and functions (Walker et al. 2004), separated by critical transitions (Scheffer 2009). In the growth/exploitation (r) phase, resources are freely available. This phase then merges into the conservation phase (K) of slow capital accumulation, which then gradually becomes a rigid and low-flexibility phase in which most resources and novelty are locked-up and are responsive to external shocks (Folke et al. 2010). This phase would be "eventually, inevitably, followed by a chaotic collapse and release phase (Ω) that rapidly gives way to a phase of reorganization (α), which may be rapid or slow, and during which, innovation and new opportunities are possible" (Walker et al. 2004).

Moreover, the panarchy model (Gunderson and Holling 2002) considers change as the result of interactions of nested and multiscalar adaptive cycles (Fig 1b): rapid change at a small-scale (revolt) can affect upper-scales, but small-scale dynamics are also affected by upper-scales that stabilize and conserve the accumulated memory of system dynamics (Folke et al. 2010).

Fig. 1. Resilience Thinking representation of SES dynamics: a) ball and cup heuristic of the stability landscape and b) panarchy model of adaptive and resilient change (adapted from Gunderson and Holling 2002)

For these authors, the resilience of SES is the main goal for management (Berkes and Folke 1998, Olsson et al. 2004). However, some resilient systems may be locked-in in unsustainable states (Folke et al. 2010, Westley et al. 2011). SES authors thus moved from their initial conservative focus toward the concept of transformability, defined as the ability to create a fundamentally new system in order to shift to more sustainable states (Walker et al. 2004) and even change the nature of the stability landscape (Folke et al. 2010). Transformational change at smaller scales enables resilience at larger scales. Such transformations require radical regime shifts in values, patterns of social behavior, multilevel governance, and management regimes (Olsson et al. 2014).

As part of the resilience ontology and in response to the failure of "command and control" management (Holling and Meffe 1996), concepts of adaptive co-management (Olsson et al. 2004) and adaptive governance (Boyd and Folke 2011, Folke et al. 2005) were developed. These processes imply that individuals and institutions are able to organize themselves in a learning-by-doing way, e.g. allowing them to adjust their actions and rules with regards to knowledge extracted from their environment (Olsson et al. 2004). Adaptiveness means developing connections and feedback between SESs and scales to enable collective learning to identify traps, learn from conflicts, find "escape routes," and anticipate risks. Adaptive governance also points out two major challenges: i) overcoming legal and institutional barriers and ii) building bridges between current governance structures (Chaffin et al. 2016).

Institutional Analysis and the Development Framework of Social-Ecological Systems

The scope of SES as seen by Resilience Thinking was progressively broadened to reinforce the conceptualization of social entities and their governance issues (Binder et al. 2013, Brown 2014, Folke 2006, Xu and Marinova 2013), mostly thanks to Ostrom and her attendance at seminars at the Beijer Institute organized by some Resilience scholars (Cleveland et al. 1996, Ostrom 1993).

Ostrom conceived of Institutional Analysis and Development (IAD) as an SES diagnostic tool, operationally oriented and prescriptive, and analyzing a range of collective action and social dilemmas related to common pool resources (McGinnis and Ostrom 2014, Ostrom 2009). This framework is an SES with four interacting subsystems (Fig 2): the resource system, the resource units (also called the biophysical conditions), the governance system, and the actors (previously called "users") embedded in the social, economic, political, and ecological settings that influence focal action situations (McGinnis and Ostrom 2014, Ostrom and Cox 2010).

Fig. 2. IAD representation of SES (Ostrom and Cox 2010)

IAD includes strategies that go beyond nested property rights systems, considering concepts of social capital (trust, networks, cooperation), cultural capital for maintaining practices and learning, knowledge systems and mental models, enhancement of user rights, power and qualification, and access to market, capital, and investments (Ostrom 2009). By highlighting the danger of blueprint solutions (Ostrom and Cox 2010), IAD stresses the notions of "missing institutions" and of possible scale mismatches in the face of disturbances (Cleveland et al. 1996, Ostrom 2010). Beyond Markets and States, Ostrom puts forward the concept of polycentric governance to better contextualize multi-scale resource management (Ostrom 2010, Young et al. 2006). Polycentric governance emphasizes the co-existence of many centers of decision-making and power with authority divided amongst overlapping jurisdictions, which are formally independent of each other (McGinnis and Ostrom 2014). Polycentricity and networked forms of self-governance enable community users to develop rules and organizations at multiple levels and better mutual adjustments between social and ecological systems compared to monolithic, external, and imposed rules (Ostrom and Cox 2010).

Socio-technical Transition Frameworks

STT frameworks emerged in the Netherlands in the 1990s and have grown since the mid-2000s. Interest in them is now growing internationally through the Sustainability Transition Research Network (2009) and its journal, *Environmental Innovation and Societal Transitions* (2011). Its Board is a meeting point of various ST frameworks, especially STT, SES and Industrial Ecology (van den Bergh et al. 2011).

STT scholars build conceptual frameworks to analyze the coevolution of society and technology, borrowing from many theories in the social sciences (Geels 2011, Markard et al. 2012, van den Bergh et al. 2011): constructivist science and technology studies (Bijker et al. 1987, Hughes 1983), evolutionary economics (Dosi 1982, Nelson and Winter 2002), new institutional economics (North 1990, Williamson 1996), and structuration theory (Giddens 1984). The two main STT frameworks are i) Multi-Level Perspective (MLP) (Geels 2002, 2011), which is an analytical framework for understanding past transitions (Fig. 3), and Transition Management (TM) (Rotmans et al. 2001), which deals with governing transition toward a specific sustainable goal. The TM approach is often discussed within the SES literature because of its approach to governance (Binder et al. 2013).

Fig. 3. The Multi-level View of Transitions (Geels 2011)

MLP analyzes transitions defined around a particular technology. As in the panarchy model, MLP conceptualizes nested levels of change but does so through interactions between three specific scales: the sociotechnical landscape, the regime, and niches (Fig 3). Transition is the process of regime reconfiguration under the action of the landscape and the ability of niches to be integrated in the dominant sociotechnical regime. The landscape level represents the exogenous economic, political, and cultural contexts beyond the influence of niche and regime actors (Geels 2002, 2011). Niches are defined as spaces on the margins of the dominant regime where small networks of actors develop radical innovations. For these scholars, in the dominant regime, established routines, practices, and rules within a set of coherent and interdependent dimensions (technology, policy, etc.) stabilize existing sociotechnical systems. Some studies in STT, based in evolutionary economics (Arthur 1989, Cowan and Gunby 1996, David 1985), also analyze transition failures through the processes of path dependency and of lock-in of the technological system, which explain the regime's stability (Berkhout 2002, Foxon 2011, Geels et al. 2014, Vanloqueren and Baret 2008).

Concluding remarks: the need to return to ontologies

Table 1 presents an overview of framework ontologies according to the items chosen in order to highlight some common points, but primarily the specificities, of each framework. This table identifies critical points for each framework, which are sometimes common to many of them (e.g. agency and power issues) and sometimes unique (e.g. lack of consideration for some dimensions). All these issues are limitations to fully integrating these frameworks.

Table 1: Framework ontology comparison

We will not comment on the entire table but rather identify some key ontological mismatches between frameworks that will be analyzed further in the general discussion. We have already noted that SES and STT make many analogous contributions, for instance on systemic or multilevel analysis.

In recent years, some scholars in each group have suggested convergences between ST frameworks. For instance, the notion of transformability in Resilience Thinking allows for some convergences with STT. Transition here seems analogous to the panarchy mechanism of revolt that contaminates upper levels and stabilizes system dynamics. Transition can also be compared to deliberate transformation or regime shift in the SES resilience framework (Moore et al. 2014). In some cases, the sociotechnical system can be so resilient in the SES sense that it is locked in an unsustainable state. Thus, technological lock-in analysis can be inspired by concepts of pathological states of poverty, rigidity, and lock-in traps of adaptive cycles in resilience thinking (Allison and Hobbs 2004).

Although such convergences may be promising, when analyzing their ontologies more deeply, we find that their conceptualizations of system, scales, model of change, and social and ecological entities are not identical. Moreover, they are sometimes contradictory, and there may be some confusion about concepts used in several approaches but with different meanings (e.g. niche, regime, or transition).

For instance, concerning system delineation, the defining criterion in each framework is not the same and the entities composing the systems are always partially considered in regards to particular conceptual and disciplinary ontologies. There are always some dimensions that are not fully taken into account, which leaves potential blind spots in system analysis (e.g. technology in Resilience or ecology in STT). STT approaches mainly focus on the relationship between technical and social-economic systems, while SES approaches tend to neglect the technical dimension of human-nature interactions.

These respective gaps and unknown or under-conceptualized entities can be seen as possible sources of complementarity between frameworks, for instance taking the ecological ontology of Resilience Thinking to reinforce STT approaches more focused on technology. Yet we argue that this kind of integration must be done carefully, because there are some ontological mismatches on many points between frameworks that must be considered.

For instance, concerning conceptions of change, when Resilience is considered as a finality for a system, this induces confusion with the concept of transition, which implies on the contrary a radical change, and not the stability of the system. There is also a mismatch on time conceptions between the cyclicality of panarchy, the teleology of STT, and the lack of temporality of IAD.

Concerning the multilevel conceptions, there is also a mismatch among, and even within, frameworks.

Indeed, even though there is a nested hierarchy in MLP, the functional qualification of levels differs from the hierarchy of nested scales of the panarchy model and the polycentricity of IAD. Geels (2011), in response to critics of MLP, mentions "theoretical inconsistencies" due to the progressive introduction of relationist and "flat ontologies" in this framework, which was first conceived as a nested hierarchy. These evolutions of MLP also refer to changes in the social ontologies it hybridizes by borrowing from various social science schools. The three frameworks considered also refer initially to a functionalist ontology (Geels 2010, Genus and Coles 2008, Gunderson and Holling 2002, Hatt 2013). Functionalism emphasizes structure, functions, and mechanisms that maintain the system's cohesion, consensus, and order, while conflict is denigrated (Catton and Dunlap 1980). Functionalist approaches are all criticized for their narrow conception of social-economic dynamics, particularly concerning issues of agency, conflict, and power relations (Shove and Walker 2007, Stone-Jovicich 2015), which prevents conceptualizing potential drivers of change.

ST frameworks offer conceptual and theoretical features to better tackle systemic and multilevel mechanisms of transition. Yet we argue that the integration of these frameworks needs reconceptualizations that take into account their ontologies, foundational assumptions, and possible mismatches.

In order to deepen the discussion about ways to enhance ST analysis, particularly in the case of agricultural sustainability, we present in section 2 how AET case studies challenge the use of these frameworks.

APPLYING ST FRAMEWORKS TO AGROECOLOGICAL TRANSITION SITUATIONS

In this section, we critically examine how research designs that question SES (IAD and Resilience versions) and STT (mainly MLP) frameworks have been used by researchers to address AET. Four studies were identified based on their academic publications (Bui 2015, Deconchat et al. 2007, Lamine 2012, Magrini et al. 2016, Souchère et al. 2010) and were supplemented with interviews with the main author about their use of and possible adjustments to ST frameworks. They were selected because together, they provide a broad and concrete overview of various aspects of AET as well as different ways to analyze it (Table 2 and Fig. 4). The objective was to reveal the practical limits and adjustments of these frameworks when used to address AET issues, in particular emphasizing: (i) their distinctive linking of social-economic, technical, and ecological dimensions and this to varying degrees (Fig. 4); and how they deal with (ii) technology; (iii) conflicts and power relationships; and (iv) ecological functioning. Each of these studies was conducted by researchers from different disciplines. Moreover, they also differed in their combinations of viewpoints and goals as a result of their epistemological posture, revealing different possible use of ST frameworks (Table 2 and Fig. 4). Table 2 synthetizes these studies according to items from ontological analysis and/or from comparing them.

Fig. 4 : Position of the selected studies according to the social-economic, ecological, and technological dimensions studied

The Gascony Hillside Forest Management Study

This study analyzed forestry practices in the Gascony hill country in southwestern France. In this agricultural region, forest management provides pest regulation services and reduces farmers' dependence on chemicals. The aim of the study, grounded in a vision of the AET at landscape level, was to understand how standard management of a coppice (the main silvicultural system in the Gascony region) could contribute to both sustainable agriculture and forestry. The SES Resilience approach was used to describe the forest (both as a shelter, a support for biodiversity protection, and an object of management) (Deconchat et al. 2007). Thus, the forest was conceptualized as an SES, linking ecological functions and properties (biodiversity, population regulation, etc.) with social dimensions (forest as a heritage site, as a production system, as product of practices, etc.). The study focused on landscape management practices because they were seen as a link between social systems and ecosystems. More precisely, the authors studied how several biodiversity patterns were influenced to varying degrees by human practices (mainly logging) and natural factors (e.g., edaphic conditions, dispersal).

Various adaptations were needed in applying the Resilience approach:

1. First, at the epistemological level, the resilience framework was not completely adopted by the authors because they thought it would not provide an analytical basis for establishing nor testing their hypothesis (i.e. that forest management can contribute to biodiversity at the landscape level and limit the use of chemicals in surrounding agriculture). In general, they agreed it was not possible to use hypothetico-deductive reasoning in the Resilience approach when dealing with large-scale issues or landscape matters. According to the authors, this is due to the fact that (i) it is not possible to control all parameters described in this framework at a larger/landscape scale; and (ii) complexity makes it unsuited for revealing chains of causality (interlinks of direct and indirect effects). Instead, the Resilience approach was used in a more inductive and exploratory way to frame the interdisciplinary work among sociologists, geographers, landscape ecologists, and entomologists. This approach also facilitated agreements on the shared ideas underlying the study, e.g. acknowledging that social systems and forest ecosystems coevolve because the rules of

management are co-determined.

2. Second, the authors found that identifying multiple levels was not helpful when dealing with AET. When considering the large scale, biodiversity management issues required taking into account multiple scales and the ways in which these scales were interconnected. In particular, specialized land-uses at local scales (e.g. forest or agriculture) may reveal a much more diverse patchwork at larger scales. In the Resilience framework, multilevel connections are conceptualized as hierarchical (see the nested adaptive cycle from the panarchy model). Therefore, it misses the effects of leaps across scales and patchwork effects. However, a greater plasticity in interpreting connections at various scales is important for plant biodiversity and is even more crucial for animal biodiversity as they are mobile.

3. Third, ecological system thinking needed refinement. The study highlighted the importance of the fringes of different land-use areas and geographical units (e.g. edges of the woodlots or parcel rims) in which significant social-ecological issues arise. If we do not explicitly take into account fringe areas, we cannot truly understand how biodiversity operates as a link across various areas.

4. Finally, social-economic system thinking was found to be too cursory. The study found that the rules conventionally accepted by ecologists in order to manage the forest and biodiversity in an ecologically rational way were not applied by the stakeholders, who kept doing as they had always done. Extensive ethnological research indicated that the 'less rational' management rules that forest managers chose for themselves were based on vernacular practices deeply rooted in systems of beliefs and modes of representation of the forest, e.g. as a heritage site in which socio-cultural characteristics are embedded, rather than as capital to be exploited. The authors noted that researchers need to consider the effects of confronting the regulation system with the belief system, as the latter is considered irrational from an ecologist's perspective.

The Pays de Caux Soil Run-Off Study

This study analyzed the management of soil run-off at the watershed level in the northwest European belt region (Pays de Caux, Normandy, France) (Souchère et al. 2010). This region is one of the most productive agricultural areas of France with highly specialized crop systems. It is also subject to erosive phenomena involving episodic deathly muddy floods, as well as pollution of the water supplied to surrounding large cities. The study sought to find ways to improve territorial organization to better manage erosion and soil run-off through an agroecological perspective. To this end, the authors used companion modelling (COMMOD) methodology grounded in Ostrom's SES approach (Etienne 2014), using Multi-Agent Modelling and Role-Playing Games (Janssen and Ostrom 2006).

Using the COMMOD methodology had two aims. The first was to push stakeholders to establish a clear, realistic, and agreed-upon vision of possible changes in situated contexts through a visioning and anticipating exercise. The second objective was to help a diverse group of stakeholders with multiple and conflicting views work together. The goal was to foster collective decision-making by allowing the participants to assess the collective effects of individual decisions and of neighborly relationships on problems of soil run-off in a large cereal-growing area. The authors built a conceptual model of the Social-Agro-Ecological system used during the role-playing game by drawing on recent advances in soil science and agronomy as well as social, economic and political inputs and related ecosystem variables (Ostrom 2009).

The role-playing game (RPG) presented a watershed area. Three farms were located there. The outflow of their water catchment was located in a built area of a village. The spatial grid was 400 m² per pixel and included all the parceled plots of the three farms. A three-crop rotation system was applied for each land plot with wheat, potatoes, and peas. Depending on the crop management sequence, different levels of soil run-off were modeled (for example, for rolled and non-rolled peas). The price was fixed by the cooperative. As rolled peas are considered 'greener', they were given a price premium. The computing simulation model then calculated the transfer of run-off from one land plot to another at a lower level. Depending on the volume of run-off observed, technical solutions (change farmers' crop management sequences or install hydraulic infrastructure such as grass strips or rainwater collection reservoirs) or economic solutions (taxes for bad practices, financial compensation for good practices, etc.) were designed. Six people participated in the role-playing game. It started with the co-construction of a conceptual model from the knowledge they acquired in education programs on soil erosion. In a second phase, the game followed a two-step sequence: first defining crop management rotation over a three-year period at an individual level, and then modifying decisions after concertation and negotiation.

The social-economic system was represented by the different relevant stakeholders needed for preventing and resolving soil run-off: the farmers located in the watershed, the watershed technical manager, the representatives of local public authorities (village, city, large metropolis), NGOs (consumers), landowner unions, an agricultural council, and the river basin agency. All of these stakeholders defined the action arena modeled during the cooperative role-playing game. The model was first tested in a small area before changing scale and being applied to other watersheds in the river basin, thus covering a larger geographical area.

Diverse limitations emerged with the COMMOD methodology as an IAD approach of SES:

1. First, whereas ecological system thinking and technology seem to be integrated, the AET analyzed in and promoted by this study was primarily driven by the reflexive learning and local

adaptive management of the SES. This was the case with regards to specific agronomic practices (crop rotation, cover crops) and the infrastructure needed to prevent soil run-off (grass strips, rainwater collection reservoir), as well as the economic trade-offs at stake. The initial design of the conceptual model played a key role in the COMMOD methodology, questioning both the nature of the "ecological knowledge" included in the conceptual model and the way it was built and experienced by stakeholders (Folke 2006).

2. Second, the outcomes of the role-playing game largely depended on the ability of the research team to pre-identify potential sources of conflict and power relations and to involve the various key stakeholders in solving the ecological issues identified. Without accurate pre-identification, the solutions identified during the role-playing game may not be effectively implemented in the field if barriers to their implementation have not been removed.

3. Third, the multiple levels of time and space and their interconnections remained challenging. Over time, the authors identified a number of issues in maintaining a shared collective and spatial representation of erosion problems. This was especially true as the context involved changes in people and society (a farmer's retirement, resignation of watershed managers, elections) and in farming practices. This in turn affected the efficiency of the solutions identified in different time frames, as well as their possible extension to a larger geographical scale across multiple interdependent watersheds with different water supply agencies and local authorities. The underlying model of change within the SES was incremental, addressing the micro-situational variables affecting farmers' decision-making and local patterns of collective action. Pre-analytical choices might have meant the silencing of radical change within the socio-agro-ecological systems, through the interactions among social-economic, technical, and ecological aspects. Instead, local actors were left free to individually and collectively negotiate and decide on the solutions they wanted to implement. Nevertheless, path dependencies imposed by the broader social-economic, institutional, and political context were not challenged in modelling the SES and its sustainability over time.

The Biovallée Study

This study examined the development of organic farming (OF) in the Drôme valley, a mountainous rural area in southeastern France. Due to the diversity of local farming systems (field crops, seeds, fruits, garlic, goat, sheep, aromatic and medicinal plants, vegetables and wine), there is little intensive use of chemicals in this area's farms, except in the flat valley area. This region was one of the birthplaces of organic farming in the 1970s in France. In the early 1990s, the area was affected by rural exodus, lack of competitiveness, and agricultural crises. OF then became a way to sustain local agriculture. According to stakeholders, local policies were implemented in order to turn this "hinterland of productivism" into "a pioneer of the quality turn." Between 2009 and 2014, the four communities of towns in the valley implemented a public program named Biovallée to boost sustainable development. This strategy involved linking several domains in technology and ecology, such as eco-building or farming and food, which were key areas for action.

The study examined the factors that fostered OF and the extent to which this transition process involved several components of the region's agrifood system; i.e., not only farming practices, but also processing, retailing, consumption practices (Bui 2015, Lamine 2012). The analysis was partly based on the MLP framework used to study the AET mechanisms. Following the evolution of public policies over the last four decades, as well as several key initiatives launched by the local agricultural cooperatives and by diverse actors within the local civil society, the study uncovered changes in the visions of and the rules within the agrifood regime over time. The study found that OF progressively became an option on which the diverse actors in this territorial agrifood system converged, although in two different paradigms: one outside the regime (the paradigm of radical ecologization, endorsed by civil society actors), and one inside it (an ecological modernization paradigm endorsed by more conventional economic stakeholders such as the cooperatives). Both paradigms were also supported by local public policies. The study thus showed that AET at the scale of a territorial agrifood system resulted from a combination of private and civil society initiatives and tailored public policies, which in turn, led to a further legitimation of both ecologization paradigms.

However, the researchers had to address some shortcomings of the MLP approach:

1. First, MLP does not give enough attention to social or organizational innovations, which were decisive in the Biovallée agroecological transition. Whereas MLP primarily focuses on technological innovation and considers that niches can influence the regime by selection through technological competition, the researchers also included social innovations in their study in order to capture the complex process of AET in this area.

2. Moreover, this study found that niches were not in competition as would be expected from MLP. Rather, the transition involved diverse niches that coexisted and interacted with the regime (separately or together). These different initiatives were able to influence the regime because each of them affected several (different) components of the territorial agrifood system (farming practices, processing, retailing, consumption practices, extension services, research), even though each initiative may have significantly affected only 1 or 2 components.

3. The third and probably most important point deals with one of the main criticisms of the MLP approach, i.e., the fact that it neglects power relationships. The authors addressed this issue by

using Actor Network Theory to study enrolment processes and alliances. They showed that in Biovallée, AET was made possible because alternative actors progressively gained more influence (especially with the local authorities), which resulted in redefining power relationships within the territorial agrifood system, especially between mainstream and alternative agricultural actors.

In sum, this study showed that transition processes did not result from technological innovation developed within niches, but rather from various initiatives that generated social innovations and through a profound redefinition of the visions and the power relationships, which were territorially grounded.

The French Legumes Agrifood Study

This study analyzed the legume agrifood chain (from production to distribution) in France (Magrini et al. 2016). Though legume crops can contribute to AET through the nutritional (protein) and ecological (nitrogen fixation) benefits they provide, their cultivated areas in France are decreasing. The MLP approach was used to examine how to revive legume crops. This framework was considered adequate for describing the problem at hand: how can a beneficial although marginal crop emerge from organizational or technical innovations (e.g. extruded protein for livestock alimentation, or legume-durum wheat pastas)? MLP was also used as a heuristic framework to facilitate interdisciplinary research: economists and agronomists agreed on the elements involved in the transitions described in MLP. As the study progressed, however, it became clear to the authors that understanding how to revive this crop required analyzing why it had decreased in the first place and the factors that locked legume crops in a marginal position. The authors thus decided that a more in-depth examination of the historical processes leading to this lock-in was necessary. In this respect, the MLP proved to be relatively insufficient, because it does not fully clarify how socio-technical systems become locked-in. Therefore, as the research moved toward examining these lock-in mechanisms, the authors drew more on evolutionary economics, in particular Arthur (1989), and the notion of anchorage (of niches within regimes).

In the kind of AET analyzed in this study, the emergence of niches and their evolution played a significant role. In the MLP, niches are perceived as places where innovation takes place, which can change the course of a socio-technical regime. For this reason, the authors of this study were limited in their use of the MLP framework in several different ways.

1. First, in MLP, emphasis is placed on the role of technological innovations, but tends to neglect other kinds of (social) innovation. Innovations require networking the actors and organizing collective action. Yet forms of social organization may also be considered as innovative; for

instance, they can be designed to provide, justify, and support the provision of agronomical services (e.g. using legume as an intercrop or as a service-plant for nitrogen fixation). This required a broader understanding of the variables through which niches influence regimes than the ones offered in the MLP framework (and not only technological).

2. Second, this framework overlooks power structures and relations. This study presented a case in which regime actors themselves designed technical innovations to supply "niche markets." These mainstream actors had both the network connections and the power to support niche actors in organizing or in providing them with resources. They also had the capacity to influence the norms, the institutional settings, and the modes of regulation that formed the landscape level. Yet the MLP framework does not explain these influence relationships between regime actors, niche actors, and the institutional landscape (e.g. through lobbying).

3. Third, implications of the ecological system's functioning are not thoroughly explored. For the authors, MLP reduces the 'ecological system' to a biological support for technological innovations (e.g. getting the protein out of legumes) in a very restrictive way.

4. Finally, the ways in which the framework links together multiple levels was not helpful when dealing with AET. Small networks of actors alone cannot explain how nor why niches and regimes become compatible and coevolve. The authors felt it was important to understand the nature of the regime as well as its constitutive elements (e.g. a particular market or outlet, or a type of quality certification), because they are points of anchorage between niches and regimes.

In that respect, the authors found that MLP incompletely describes the ways in which the levels presented in the framework - niches, regimes, and the landscape - are connected. This, in turn, has implications for the missing variables to consider, which determines the form and the boundary of the socio-technical system at hand.

Concluding remarks on study outcomes

In this section, we address the critical points identified in these studies in their use of ST frameworks with regards to AET. By examining the practical implementations of these frameworks in actual situations, these four studies deepen our understanding of the interrelations of social-economic, technological, and ecological factors in AET. Table 2 summarizes the key aspects in each study, especially the research questions addressed, and some ontological items found in Table 1: the time scale and contours of the system, the underlying models of change and multilevel conception, and specifying the technological, social-economic, and ecological system. Table 2 highlights the gaps and limitations of the ST framework used to analyze each AET situation.

Table 2: Comparison of agroecological transition studies

Table 2 highlights the variety of AET situations and of the ways they are conceptualized according to some privileged dimensions of the ST frameworks used and to the authors' discipline and epistemological posture. In each case, we observed that ST frameworks had to be adapted to AET situations in order to become heuristic and operational. At a more general level, there is a need for the majority of AET case studies to ground their analyses at micro-levels, i.e. territories, individual mental models, actions, and interactions, as well as grounded collective actions.

A number of caveats remain with these studies, suggesting the need for a better understanding of the underlying models of change and their drivers. The STT studies show that we must deepen our understanding of lock-in regimes, of niche-regime and landscape-niche interrelations, as well as the role of conflicts and power relations and changes in rules and practices. In SES studies, designing relevant conceptual models remains complex, thereby imposing limitations on their replication and scale extension (Etienne 2014, Janssen and Ostrom 2006). Another major challenge involves the need to move away from a static vision of the grammar of rules to better understand institutional dynamics and their causality in polycentric governance systems (McGinnis and Ostrom 2014). While AET is often viewed exclusively through the lens of technological innovation, these studies also highlight the key role of social and institutional innovations in supporting such transitions. Given the diversity of possible interpretations of agroecological goals, understanding the socio-political debates around transition objectives and paths has to be part of any research on the subject. We found that the relative weight given to technology and technical agricultural practices, the modelling of social-economic systems, and the representations of the ecological system also need to be re-examined. Moreover, beyond taking into account resources as limited, the way to integrate ecological aspects remained a key issue in all these agroecosystem studies.

More generally, this examination of actual uses clearly showed that both the discipline of the researcher and the epistemology chosen were determinant for how these frameworks were used, as well as for their limitations. This illustrates how difficult it is to address the multiple aspects involved in the AET while also combining STT and SES in an integrated framework.

DISCUSSION: AVENUES TO DEAL WITH THE MULTIPLE DIMENSIONS OF (AGROECOLOGICAL) TRANSITIONS

Analyzing STT and SES frameworks through their ontologies as well as their use in field studies shows that they cannot thoroughly address the issues involved in AET. From this comparative analysis of frameworks, we would like to highlight some key issues for further research on sustainability transitions.

Strengthening a three-dimensional approach

This study confirmed that none of the frameworks fully addresses all the main dimensions involved in AET. Agroecology, defined as an ecology of sustainable food systems (Francis et al. 2003), proposes a paradigm shift in the way to analyze and manage ecological, technical, and social-economic aspects at multiple scales (Dalgaard et al. 2003). AET requires addressing interactions among ecology, technology, and socio-economy. The AET studies therefore revealed the difficulties that existing frameworks have taking into account all three dimensions and exploring new interdependencies between them. Some authors have already suggested considering "socio-eco-technical systems" (Pant et al. 2015), "social-ecological-technological systems" (Olsson et al. 2014) or "socio-ecological-technological system" approaches (McGinnis and Ostrom 2014) in several kinds of sustainability transitions.

Nevertheless, views of the social-economic, technological and ecological dimensions are still uneven. For instance, for many critics the Resilience approach is unappealing to the social sciences because of the misconception of social-economic systems resulting from the problematic application of ecological concepts to society (naturalization) (Brown 2014, Bush and Marschke 2014, Cote and Nightingale 2012, Davidson 2010, Hatt 2013, Smith and Stirling 2010, Stone-Jovicich 2015). Paradoxically, as with STT, Resilience Thinking does not consider the ecological system as an explicit dimension in the transition process, although at minimum biological materiality and its specific spatial and temporal organizations should be taken into account in transition processes (Coenen et al. 2012, Grin et al. 2010, Markard et al. 2012). Achieving the integration of social and ecological interactions is still an important issue for the SES approach (Schoon and Van der Leeuw 2015). In Resilience Thinking, technology is also weakly addressed and thus undertheorized; it is mostly seen as a mediator in human-environment interactions and exogenous to SESs (Westley et al. 2011).

By requiring three-dimensional system thinking (social-economic, ecological, and technical), the AET emphasizes the importance of exploring new interactions, which can only be partially done using the ST frameworks considered, even in a complementary way (Olsson et al. 2014, Ostrom and Cox 2010, Pant et al. 2015). We will now turn to discuss avenues for enhancing research on the co-evolution of social-economic, ecological, and technological systems through debates about each of these dimensions.

Integrating More Agency into Social-Economic System Thinking and Reconsidering Models of Change

Our analysis of different AET situations suggests that ST models of change do not fit all transition situations. We found that each framework first expresses an *a priori* vision with a predefined model of social change. These frameworks define both the contours of the system and the process of change by choosing the dimensions, scales, mechanisms, and type of connections considered as the main drivers of the transition.

In the vast and complex question of how to describe social-economic systems, power and agency must be addressed. Underestimating certain forms of agency, i.e. the ability of individuals and groups to act, define strategies, and produce new meanings, has been highlighted as a problem in critiques of STT (Beymer-Farris et al. 2012, Geels 2010, 2011), and of SES about the way the latter deals with agency and power (Boonstra 2016, Dwiartama and Rosin 2014, Fabinyi et al. 2014). These debates draw partly on broader ones that have resulted from the fragmentation of the social sciences, particularly over functionalist ontology, which is the foundation of the ST frameworks considered here. By emphasizing the maintaining of order, functionalism "limits the understanding of social processes that influence change and transition, notably social dynamics, agency, and innovation" (Bush and Marschke 2014).

Some authors advocate analyzing power dynamics and asymmetries (Geels 2011, Leach 2008, Markard et al. 2012, Smith and Stirling 2010). Olsson et al. (2014) argue that adaptive management and governance concepts embed agency and power, and the IAD deals explicitly with power relationships and conflict resolution. In SES, some research has already been done in this direction, for instance by examining shadow networks, institutional leadership, and power issues, often using supplementary frameworks such as Political Ecology or Actor-Network Theory (Boonstra 2016, Dwiartama and Rosin 2014, Fabinyi et al. 2014, Olsson et al. 2014, Smith and Stirling 2010, Stone-Jovicich 2015, Voss and Bornemann 2011).

Current debates over the different visions of agroecology, which often oppose a model based on technological solutions to one based on ecological and social innovations, place the role of institutions and emergent collective organizations (agency) at the core of the transition process. These debates also stress the political nature of the transformations underlying these different visions. This political dimension of transition has not been sufficiently taken into account in ST frameworks (Brown 2014, Fabinyi et al. 2014, Grin et al. 2010, Shove and Walker 2007, Smith and Stirling 2010, Voss and Bornemann 2011). Some authors have identified disagreements about the transition targets (Brown 2014, Smith and Stirling 2010), about the actors governing transition, the system frameworks to adopt, and the targets and the means for change (Shove and Walker 2007). Others note that the transition process is embedded within broader political contexts that limit the possibilities for change (Voss and Bornemann 2011).

Considering agency also affects the conception of social-economic system change, regarding the opposition between flat and hierarchical ontologies (Geels 2011) already mentioned as well as the type of historicity, either structural-mechanistic or event-oriented (Giddens 1984). The AET studies examined here indicate that change is driven by more emergent and unpredictable dynamics, requiring more inductive and constructivist analytical approaches. The studies show that stakeholders' capacity for action is not only framed by institutions, but also that actors' choices reinforce those institutions. Individual and collective grassroots actors are key to triggering changes at the forefront of transition mechanisms; they create social-economic, ecological or technological innovation processes but cannot predict the type, trajectory, and importance of the change they may trigger (Bui 2015). Therefore, following other authors and considering the potential multileveled organization of systems, we argue for more inductive, empirically grounded, constructivist (Genus and Coles 2008) and pragmatist epistemologies (Bui et al. 2016, Bui et al. 2015, Popa et al. 2015). They give attention to agency within society (Davidson 2010, Leach 2008, Smith and Stirling 2010, Stone-Jovicich 2015) and also recognize the social benefits of conflicts and controversies in producing social signification, agreements, and change.

Taking Ecological Processes into Account

The AET highlights the importance of ecology in designing agriculture that works *with* nature, and not just avoids or limits its environmental impacts. This ecological aspect is thus a component of the system with its own agency, process, and scales. In this vision, we have to dig deeper within the properties, organization, and process of ecological systems, and not limit ourselves to the sole notions of natural resources or ecological objectives. SES frameworks are the only ones that significantly recognize ecology, biophysical materiality, and spatiality as organizing principles of the sustainability transition. However, in SES, ecological processes are rarely explicitly described nor is the way to integrate them with social-economic or technological dimensions. For instance, IAD considers natural elements as resource units described by biophysical indicators (McGinnis and Ostrom 2014) and not as ecological processes. We find that although the ecological dimension is generally absent from the STT approach, it is also paradoxically lacking within SES frameworks. This underestimation of ecological processes in ST is partly due to a historical dispute about the way social scientists deal with nature (Bruckmeier 2011, Caillé 2001). Classical sociology does not study natural, or even technological, artefacts, considering that society is distinct from any biological determinism and that social states can only be explained by social factors (Caillé 2001). The nature-society dualism has nevertheless been questioned in various emerging approaches across the social sciences (such as Political Ecology, Actor-Network Theory, etc.). These competing approaches conceptualize human-nature interactions between two polarities of tension within the social sciences: the socialization of the environment and the naturalization of society (Bruckmeier 2011, Caillé 2001, Catton and Dunlap 1980, Stone-Jovicich 2015). Some currents have developed integrative conceptions of this relationship, such as materialist-metabolic approaches (de Molina and Toledo 2014, Haberl et al. 2011). Yet they often work at a global scale and are focused on material and energy flows rather than living beings and their ideal and material aspects. In addition, Political Ecology considers the environment as an arena in which various social actors with asymmetrical power compete for control of natural resources (Bruckmeier 2011). Yet in all the studies, as we see with the STT and SES approaches that have particular positions on social-ecological interactions, there is debate about how to consider human/non-human associations symmetrically as well as on how to integrate ecology (Beymer-Farris et al. 2012, Stone-Jovicich 2015, Vayda and Walters 1999).

The AET also introduces controversies between actors about the different ways they take ecological goals into account in their management. One issue, illustrated in the Pays de Caux study, is how to address the diversity of definitions and representations of nature according to the actors and transition levels considered, and how ecology is collectively and socially constructed at the interface between the sciences and empirical knowledge. Maintaining and developing local ecological knowledge, as well as creating, reevaluating, and reshaping individual and collective management practices, rules, and organizational structures, is a continual challenge (Olsson et al. 2004). Linking social-economic and ecological issues, and possibilities for interdisciplinarity, means considering a limited constructivism that recognizes a non-determinist and non-essentialist ecological materiality affecting humans. It also means recognizing the variability of conceptions of and interactions with such a reality (Caillé 2001, Stone-Jovicich 2015).

Taking Technology Seriously

Among SES scholars, there has been a growing interest in technologies, especially with the Anthropocene debate. Yet until now, SES has considered technologies as artifacts shaped outside the SES (Westley et al. 2011). Resilience authors consider technology to be a double-edged sword: some view it as a source of destruction, while others question whether technical innovations can reverse the trends challenging the earth system. However, information, nano- or bio-technologies, or geo-engineering, can only improve our lives if we consider ecological integrity and human needs (Galaz 2012, Westley et al. 2011). Using STT and SES, these authors propose moving beyond the technology-biosphere opposition by transforming institutions, incentives (support for institutional entrepreneurs, for knowledge integration), and the supply-driven innovation system. Some IAD studies do integrate technology (Anderies et al. 2004). They consider that institutions coordinate investments in infrastructure and production technologies, which in turn influence ecosystems and production in a way that affects the relationships between users and the ecosystem. McGinnis and Ostrom (2014) suggest that IAD can also be applied to the governance of artificially constructed technological systems and can be extended to Social-Ecological-Technical Systems (SETS). On this side, STT frameworks offer the most advanced conceptualization of technology because they specifically focus on analyzing social and technological co-evolution (mainly in energy and transport) thanks to conceptually borrowing STS concepts in a systemic manner (Geels 2011).

However, ST studies actually consider large technological systems and neglect situated technical practices (Shove and Walker 2007). They also neglect the processes and scales that are involved in anchoring those practices in local territories (Coenen et al. 2012) and in actors' learning and skills development. There is also little consideration of the active role of users in shaping technology, although some STS scholars (Star 1991, Woolgar 1991) have shown how technology affects users: they may be liberated but also marginalized due to the standardized script that technology embeds, to its cost, and also to the skills it requires to be used. As McGinnis and Ostrom (2014) acknowledge, technologies create new power asymmetries and possible social cleavage given the high level of technicity necessary for technology's development and maintenance.

As for agroecology, in its strong conception, ST frameworks are insufficient because transition differs from the adoption of large, fully-developed technological packages. We advocate taking technology seriously via situated technical practices. AET needs to reflect on the creation and the assessment of situated technologies and technical practices, which would allow for aligning farmers' needs (technical efficiency, painfulness, profitability, etc.) and ecosystem processes with their specificities, integrity, and services supplied, as well as with societal needs and demands (health impact, food price, labor justice, etc.). If we do not consider these situated practices, reflections about the potential social or ecological impacts of technologies will remain insufficient. Doing so, however, would enable a more concrete understanding of social-ecological interactions, which is particularly crucial for AET. Technology is a constitutive element of agricultural systems. Agricultural sciences, particularly agronomy, examine interactions between ecological processes in controlled ecosystems and technologies (and technical practices) with varying degrees of complexity (Gras et al. 1989). Yet farming practices cannot be reduced to a purely technological component. Some agronomists, following agroecologists (Dalgaard et al. 2003, Francis et al. 2003), broaden the concept of the traditional agroecosystem (mainly the plot) to better integrate farmers' practical knowledge, mimetism with natural ecosystems, and considering agroecosystems as an SES (Doré et al. 2011). Explicitly describing practices within this technical dimension requires taking into account the representations, values, knowledge, and know-how that farmers mobilize and develop in their farm management. Doing so would emphasize the individual dimension, often overlooked by ST frameworks, as crucial for innovation and new knowledge transition. Moreover, individuals may also be a source of technological or epistemic lock-in, for instance because of risk aversion or actions of some powerful "merchants of doubt," as shown by agnotology scholars (Dedieu and Jouzel 2015, Proctor and Schiebinger 2008).

Replacing individuals in ST frameworks would also recognize the political dimension of technologies. Indeed, Political Agronomy, a nascent discipline inspired by Political Ecology and STS, studies the relationships and processes that link political, economic, and social forces with the creation and use of agronomic knowledge and technologies in terms of asymmetric power relations and struggles (Sumberg et al. 2013). In this sense, the Appropriate Technology movement, related to agroecology (Fressoli and Arond 2015), also seeks to redefine technology as a tool for autonomous development.

CONCLUSION

The agroecological transition, and more broadly the sustainability transition, involve a great diversity of processes and aspects that cannot be encompassed in a single and integrated model or framework. We need to deepen and adjust the conceptualization of ecological, social-economic, and technological factors and their interconnections proposed by ST frameworks. Most previous work on these frameworks, whether combining them or not, has acknowledged the relevance of their systemic, dynamic, and multi-level approaches; yet it has also identified their limits in accounting for one of the dimensions or processes involved (such as social or ecological) and thus their limits for exploring key analytical aspects of transition (such as those linked to agency).

Moreover, STT and Resilience frameworks propose a hierarchical conception of systems that strongly limits the paths through which transition can occur and the ways we think about management and governance of transition. A non-hierarchical and interdependent point of view on relationships between transition levels is central for conceptualizing transition management and governance. Considering the importance of bottom-up and adaptive processes in transition and the diversity of types (eco, socio, techno) of links between dimensions, the multilevel aspects of AET must be explored from a broader perspective. We suggest breaking away from a systematic ordering of the different transition levels in established models, in order to better explore in practice the range of levels involved and the diversity of relationships between them, as well as their synergies.

To study AET, we believe that there is no ready-made framework, given the internal limitations we have noted. The integration of existing ST frameworks is hampered by some ontological mismatches and by the relevance to the empirical situations analyzed. To avoid theoretical inconsistencies and blindly imposing a theoretical model on an observed situation, such a combination of ST frameworks must be carefully done and continuously grounded in empirical and diverse situations, such as in the four cases we reviewed. Doing so, one must be aware of the ways in which each theory frames the way we see transition due to its ontology, beyond merely analyzing privileged dimensions. Moreover, we advocate moving beyond traditional disciplinary boundaries and epistemic postures that dictate the ways interdependencies are studied between dimensions, scales, and the place given to empirical knowledge. Indeed, connecting transition dimensions remains challenging for the disciplinary and practical organization of research.

Sustainability transitions, in general and particularly for the agroecological transition, require developing inter- and transdisciplinary dialogue, both among scientists from different disciplines and between scientists and nonscientist, plural epistemologies (Dalgaard et al. 2003, Popa et al. 2015). There is a lack of knowledge integration across the boundaries of the social and natural sciences, due to the specialization of theories and their competing forms of explanation and interpretation. Beyond scientific disciplinary debates, however, transition requires increasing knowledge production through experiential learning and social learning processes within transdisciplinary research that recognizes the plurality of ontologies, knowledge, and power distribution.

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Table 1. Framework ontology comparison

Ontological entities	STT	SES frameworks	
	Mainly MLP	Resilience	IAD
Disciplinary background	A middle-range framework composed of social science theoretical hybridization	A pluridisciplinary approach first grounded in ecology and later integrating economics and social science disciplines	Political science and institutional economics
System delineation	Defined by the technology analyzed, so it is continuously redefined through the connections between levels	Defined by physical materiality so the contours do not change	Defined by a natural resource and social dilemma treated within an action arena
Multilevel conception	MLP triptych: landscape, regime, and niche, mainly focused on niche and regime co-evolutions	Panarchy: interconnectedness, nested adaptive cycles and interactions within and across scales (Folke et al. 2010)	Polycentricity of nested socio-ecological, economic and political systems
Model of change	Regime as a dominant and coherent set of rules, social networks and organizations, and prevailing infrastructure Path dependence and technological lock-ins: previous state of the system determines its evolution Niche as key drivers for change (Schot and Geels 2007)	Resilience as the target: maintenance of system function and structure under shocks Adaptive cycles and panarchy More recently, deliberate transformation of SESs in unsustainable states Transformative, small-scale experiments and cross learning	Non-linear and cross-scale in time and space, institutional and evolutionary models of change (Ostrom, 2005, 2014), Multi-tiered institutional diagnostic of SES and of possible transformations Problem-solving oriented and Co-management of SES Transformative through changes in users' knowledge, beliefs and mental models
Governance	Rules and routines TM: Given a target, adaptation through the transformation path, niche management	Adaptive Co-management: Adaptation of institutions to circumstances thanks to continuous learning (alignment principle) Adaptive governance (Chaffin et al. 2016, Folke et al. 2005): individuals, organizations, agencies, and institutions at multiple organizational levels	Adaptive and Polycentric Governance (Ostrom 2010) Formal and informal norms and rules-in-use (operational, collective, constitutional) (Ostrom and Cox 2010) Missing institutions and institutional barriers Collective action, social norms and connectivity of self-organized network governance (McGinnis and

Spatial-temporal scales	No spatial anchorage and various time scale	Very local or global, space and time are fundamental	Polycentric approach beyond local vs. global, spatial anchorage linked to the action situations and issues to be solved
Social-economic system conception	Macro and meso actors with a focus on "social groups" defined according to their functions (consumers, etc.) Society is produced by the intersection of structures and agents (Giddens 1984) Little analysis of individual practices	Focus on micro and meso actors: individuals, institutions, communities, networks Functionalist epistemology	A dynamic view of policy processes, in which social, institutions and biophysical factors are inputs to the decisions made by individuals Methodological individualism Users' or actors' knowledge, institutions, collective action, and rules
Technology	Constitutive of the system studied, mainly energy macro-systems	Barely conceptualized	Balancing a specific resource use and system maintenance in the SES (McGinnis and Ostrom 2014)
Ecological system thinking	Ignored	Central and in interaction with social systems From resource conceptualization with no ecological system or process elicitation	Focusing on a specific natural resource, dynamic ecological processes being treated as exogenously given Not ecologically explicit
Dimension interactions considered	Social > Technological > (Ecological)	Ecological > Social > (Technological)	Social > Ecological > (Technological)
Gaps and criticisms	Power and politics underestimated Ecology and territory not considered	Unbalanced analysis of social-ecological interactions (Binder et al. 2013) Narrow conception of social dimensions Technology not theorized Management of changes not sufficiently addressed	A mis-perceived static conception of rules change Lack of normative clarity Upscaling models

(con'd)

Table 2. Comparison of agroecological transition studies

	Forest Management (Gascony hills)	Erosion Caux (Normandy)	Biovallee (Drôme)	Legume Crops (France)
Framework used	SES (Resilience)	SES (IAD)	STT (MLP)	STT (MLP)
Research question	How to improve forest management by implementing innovative forestry techniques?	How to reduce the negative impacts of soil run-offs at the watershed level in a mainstream cereal-growing agricultural area?	How has organic farming been developed in a territory where numerous alternative initiatives coexist with mainstream ones?	How can actors develop legume food-chains and revive pulse crops?
Scholar posture	Inductive and exploratory; Symmetry between ecological and social system	Companion modeling (Commod)	Analytical	Descriptive and analytical
Disciplinary background	Ecology and ethnology	Agronomy and ecology	Sociology, mainly Multilevel Perspective and Actor-Network Theory	(Socio)Economics, Agronomy, MLP as a heuristic device for interdisciplinarity
System delineation	Forest management practices in the studied area	Farm management issues at a watershed level	Territorial agrifood system	French legumes agrifood chain
Multilevel conception	Analysis at the landscape level, while accounting for different land-use interactions and social representations Sample areas chosen "in such way that they were superimposed as much as possible and nested."	A non-hierarchical multi-tier approach of the variables affecting the SES, as well as its multi-level/polycentric governance approach, by identifying the multiple key stakeholders involved	Analysis of diverse local niches and their influence on the regime	Standard conception of MLP framework. Focus on lock-in effects.

(con'd)

Model of change	Slow changes of individuals; inherited local socio-cultural representations	Changes from individual eco-socio-technical mental models to individual actions and required collective negotiations	Change relies on the progressive legitimation and coexistence of niche initiatives inspired by a radical ecologization paradigm and more conventional stakeholders' initiatives endorsing an ecological modernization paradigm	Rooted in evolutionary economics (path dependency). Change driven by technical innovations (as a system). Co-evolution between various dimensions/levels of the systems.
Spatial-temporal scales	From long-term, slow incremental ecological changes to faster cutting practices and social opportunities Current practices accounting for vernacular uses	Defined by the time needed to implement the technical solutions identified (here 12-18 months to change crop rotations), or as iterative periods of adjustments and replication	Territory as political-administrative boundaries that shape actors' interactions Study of ecologization processes requires analysis at 2 main temporal scales = 4 decades (socio-historical analysis), 5 years (direct observation through fieldwork)	National scale Long term (regime construction/lock-in; various temporalities across different levels of the social system)
Social-economic system conception	"The social system is traditionally organized in 'houses' that correspond to well-identified land domains, names, and social roles, which, in particular, determine the inheritance process...and cooperative relations between neighbors."	A simplified version of social and economic rules is integrated into the role-playing game, through pre-identifying key actors based on their function (farmer, watershed managers, extensionists), the rules-in-use, and power relations at play.	Focus on interactions between local actors and power relations that are transformed because alternative actors make alliances and gain influence.	Institutional set up progressively constructed over time. Institutions frame collective behaviors and promote (or discourage) particular modes of organization.

(con'd)

Technology (& technical practices)	Techniques are the main driver of change in land-use (from cutting trees to agriculture)	Techniques, and possible adjustments to the social-economic system, are the focus of a role-playing game to assess the collective effects of individual decisions of involved farmers and to identify the best collectively agreed-upon solutions.	Adoption of organic farming practices was key for some initiatives in the region, but social and organizational innovations were more central in the approach.	Technology, a fundamental dimension of lock-in, plays an important part in aligning niches and regimes.
Ecological system thinking	The forest is conceived of as an ecosystem and as a managed habitat supplying services to adjacent agricultural activities.	The initial conceptual model addresses only specific natural resources (here water and soil erosion), identified as problematic, while keeping a mainstream approach to the design of farming systems.	No ecological system thinking applied to the agrifood system as a whole within this approach.	The ecological system is not considered as such: environmental benefits are taken for granted, and nitrogen fixation is considered as an exogenous variable of the problem.
Dimension interactions considered	Ecological - Technological - Social	Technological - Social-economic > (Ecological)	Social > (Technological) > (Ecological)	Social - Technological > (Ecological)
Gaps & criticism	Does not account for the different ways organizational levels interact. Does not account for some social dimensions (related to ethnology). Cannot be used to test hypothesis.	Limitations of modeling: - complex conception and use which limits replication - lack of analysis of rules change and upscaling processes, and follow up of the effective implementation of solutions found.	Limitations of the MLP framework: power relations, change mechanisms (how rules and practices are driven to change), ecological dimensions.	MLP is insufficient for understanding: - how regimes are locked-in - how niches integrate regimes - the means by which actors from niches and regimes can cooperate - the links between "niche" and "landscape"

(con'd)

Fig. 1. Resilience Thinking representation of SES dynamics: a) ball and cup heuristic of the stability landscape and b) panarchy model of adaptive and resilient change (adapted from Gunderson and Holling 2002)

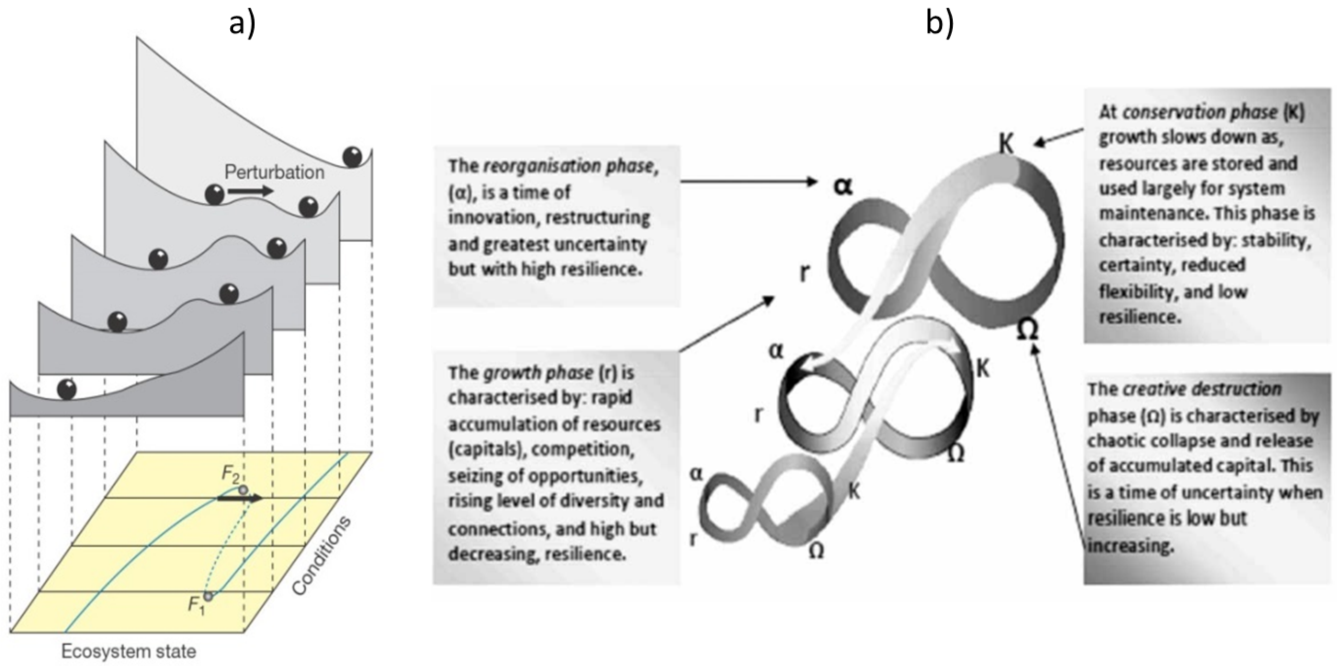

Fig. 2. IAD representation of SES (source: Ostrom and Cox 2010)

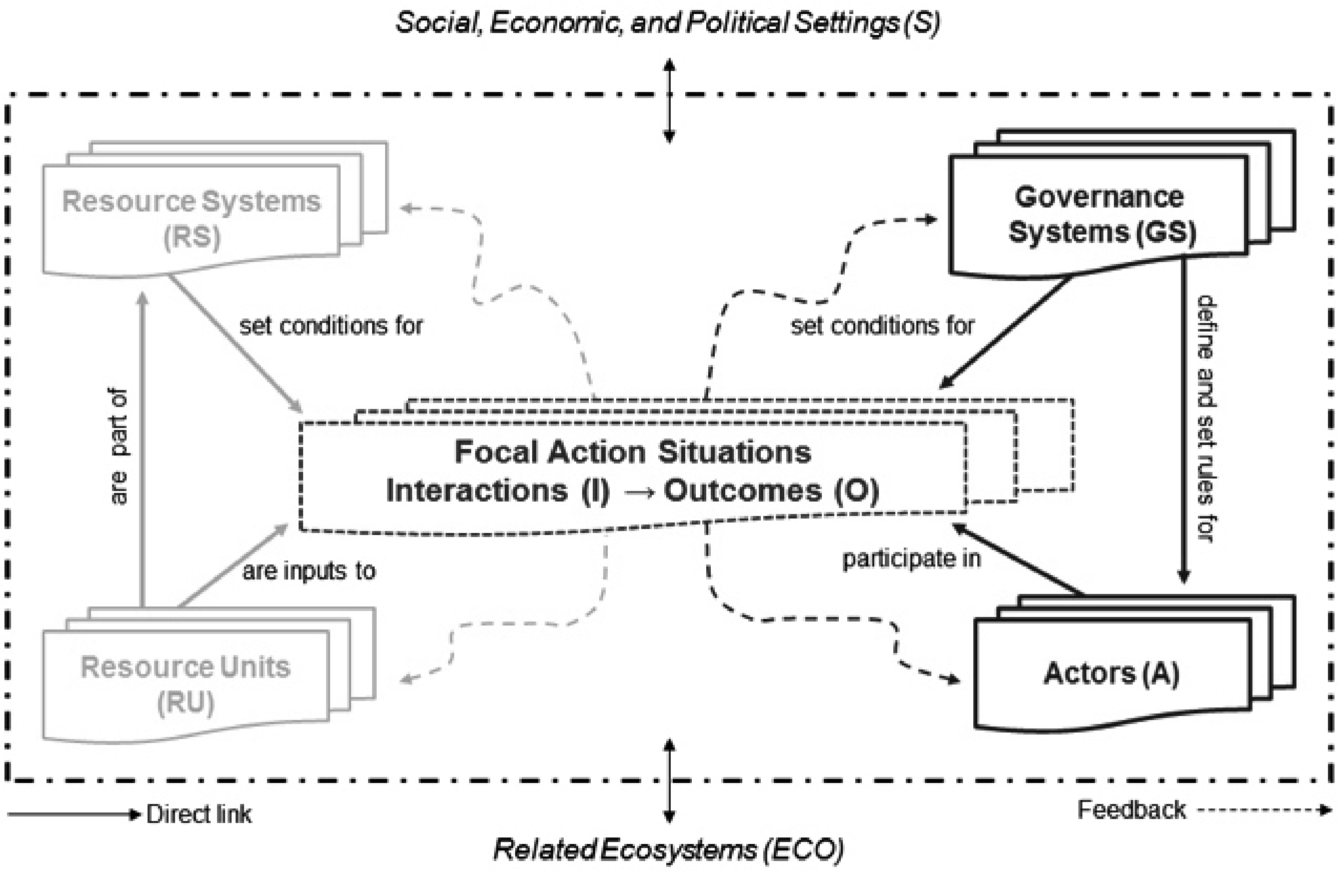

Fig. 3. The Multi-level View of Transitions (source: Geels 2011)

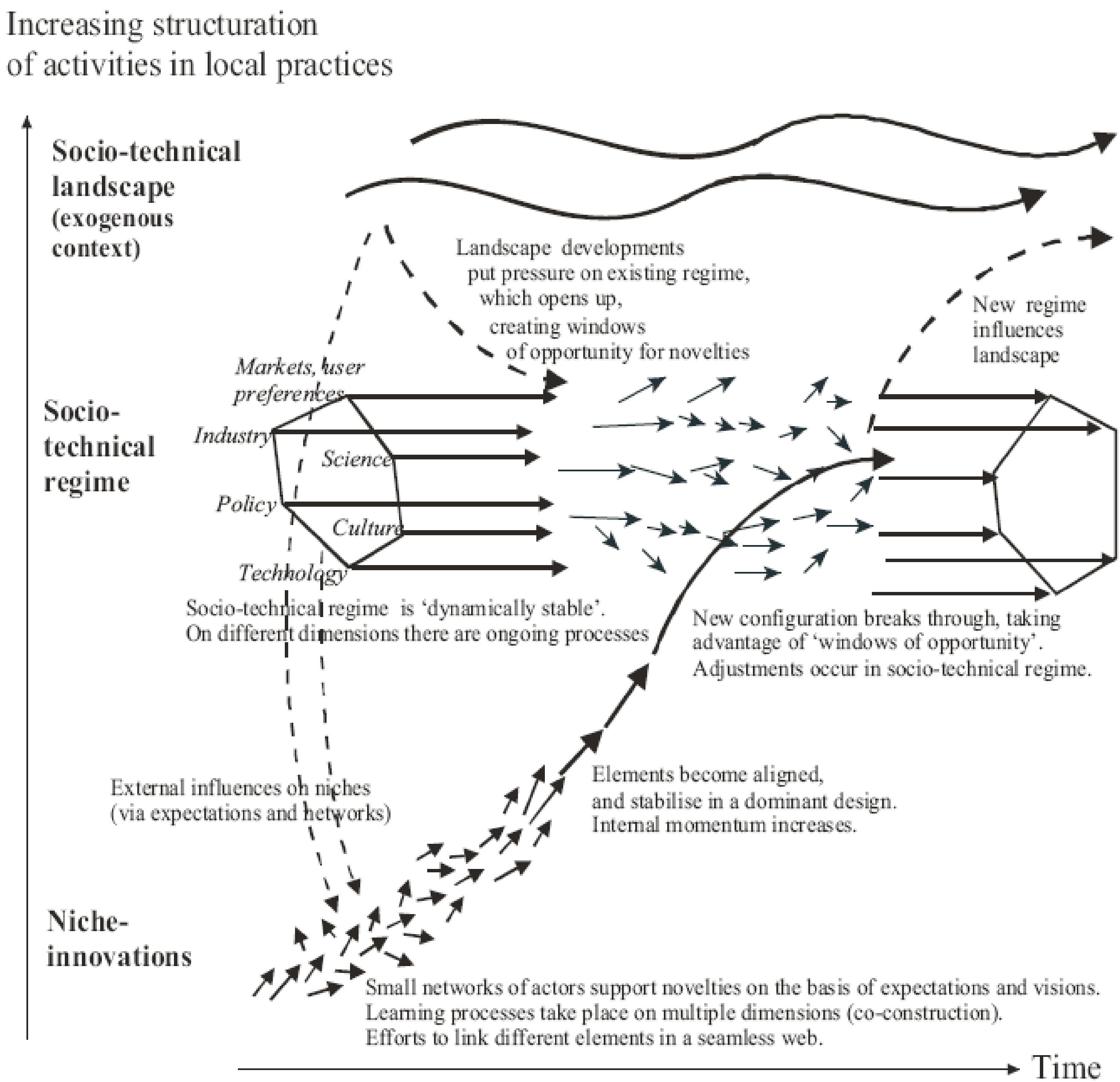

Fig. 4. Position of the selected studies according to the social-economic, ecological, and technological dimensions studied