Implementing the agroecological transition: weak or strong modernization of agriculture? Focus on the mycorrhiza supply chain in France.

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Implementing the agroecological transition: weak or strong modernization of agriculture?

The example of the mycorrhiza supply chain in France

(Provisory draft)

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Abstract

The modernization of agriculture is under scrutiny. It is currently debated within the growing concept and practice of agroecology that applies ecological fundaments to the design and the management of sustainable agroecosystems. In matter of ecologization of agriculture, agroecological transition may be considered as a privileged pathway. It relies on two main forms: the weak (that intends to reduce the use of chemicals by alternative practices such as their substitution by biological inputs) versus strong modernization of agriculture (based on the valorization of biodiversity providing ecosystemic services). In this article, through an analysis of the technological innovations used for the enhancement of mycorrhiza (symbiotic interactions between plants and soil microorganisms) as an illustration of the implementation of the agroecological transition in France, we wonder in what extent a strong modernization of agriculture is likely to occur.

This paper shows how the conceptual framework of socio-technical regime is useful to analyze the dynamics of the agroecological transition. Our demonstration relies on an empirical material (survey of the main actors of the mycorrhiza supply chain) that permits to understand how is structured the dominant system and how it impedes the development of the alternative niche. We then give some prerequisites in terms of public action to define in what extent the niche can be supported and can compete the current system.

Key words: Agroecological transition, socio-technical regime, technological paradigm, evolutionary economics

JEL code : B52, O33, Q01, Q55.

Introduction

Ecological transition remains a core and strategic question to be raised and implemented in the ongoing context where the agricultural productionist paradigm is being overwhelmed. The green revolution and its technological package (simplification of agricultural production system (*i.e.* single-crop farming), intensive farming, mechanization, use of chemicals) show major limits (Altieri *et al.*, 2012). Industrial agriculture is no longer in position to ensure food security (sufficient and safe food production and distribution). The development of industrial agriculture was founded on three main assumptions (the availability of fossil energy (fuel), abundant water and a stable climate) that are completely revoked. Moreover the strong and negative externalities produced by this agricultural model are numerous: persistent pollution, irreversible risks on ecosystems (degradation, loss of biodiversity, depletion of natural resources, emerging diseases etc.) and human being (deterioration of health). Therefore, these damaging effects and the inability of the post green revolution agricultural system to improve its performance have become a starting point to think about alternative techniques and reverse farmers' practices. This fact historically constitutes the ecological footprint of modern agriculture. It relies on the implementation and the adoption of environmentally friendly agronomic practices (intercropping, organic fertilizers, agroforestry, biological control etc.) to reduce the use of chemical inputs and thus rehabilitates biological regulation and ecological interactions (Jackson *et al.* 2010; Brussaard *et al.* 2010; Chave *et al.* 2014). In this new era the utilization of beneficial microorganisms will take more and more importance (Ijdo *et al.* 2011).

In matter of ecologization of agriculture, agroecological transition may be considered as a privileged pathway. Nevertheless, two major evolutions of modern agriculture can be distinguished (Duru *et al.* 2014). (i) The weak ecologization of agriculture implies few changes. These changes are limited to the implementation of "good practices" that intend to improve the efficiency of chemicals and/or reduce their use by altenative practices such as their substitution by biological inputs. (ii) The strong ecologization is based on biodiversity providing ecosystem services. Therefore, it imposes a real change of paradigm and "requires to deeply revise farming system, resources management at territory/landscape level, and the agrifood chain" (Duru *et al.* 2014, p.85).

In this article, we focus on the enhancement of mycorrhiza (symbiosis between roots and soil fungi), key elements of soil biodiversity which becomes a momentum in matter of agroecological engineering. Mycorrhizal fungi, present in most of the soil worldwide, colonize more than 80 % of plant species and enhance crop health and productivity (Smith and Read, 2008). We discuss in what extent a strong modernization of agriculture is likely to occur. We show how the conceptual framework of socio-technical regime is useful to analyze the dynamics of the agroecological transition. We use this approach to study the complex interrelationship structure implying a diversity of actors (farmers, industrials, researchers, policy-makers etc.) that interact. The result of their coordination (market and non-market) and the networks formed by these actors shape what is called in the economic literature a "socio-technical regime" (Geels and Shot, 2007). As shown by Vanloqueren and Baret (2009) for agricultural research systems, this concept is compatible with the ones of *technological paradigm* and *trajectory* proposed by Dosi (1992) in his evolutionary approach of industrial processes, changes and innovation. This evolutionary approach explains that a socio-technical system evolves thanks to the actions of economic agents whose capacities of learning, innovation and adaptation are central. In that sense, socio-technical systems are driven by knowledge, and knowledge constantly changes.

We mobilize this approach to identify the set of actors who pilot the technological trajectory of the socio-technical regime grounded on the use of mycorrhiza. Using the stakeholder analysis (Mitchell *et al.,* 1997), we conduct around 30 interviews that permit (i) to characterize the nature of the relationships developed between the agents (share of information, subsidies, good and services) and (ii) to specify in what extent these interactions stabilize the existing technological paradigm. We then produce a heuristic map designing the main categories of actors implied in the mycorrhiza supply chain (industrials, scientists, public authorities, farmers) and their role, place and power in this regime. This empirical survey founds the raw material to appraisal the robustness of this agroecological pattern.

We show that the agroecological pattern based on the inoculation of industrial strains participates in the reinforcement of the prevailing socio-technical regime. It corresponds to a weak form of ecologization of agriculture and hinders the emergence of alternative innovative niches (*i.e.* mobilization of indigenous mycorrhizal networks) that could support a strong modernization of agriculture.

This article is organized as follows. Section 1 shows the consistency of the socio-technical approach for the comprehension of the drivers of changes that support the agroecological transition. Based on the example of the mycorrhiza supply chain in France, section 2 depicts a description of the diversity of actors that implement this agroecological pattern. Our empirical results help understand in what extent the dominant socio-technical regime supports a weak modernization of agriculture. We also give some highlights on the way this prevailing regime lock-in alternative niches that could allow a strong ecologization of agriculture. We then discuss in a public action perspective how to break out the lock-in processes.

1. The socio-technical regime framework as a consistent evolutionary approach of changes driving the agroecological transition

In this section, we attempt to define what is agroecological transition that we apprehend as a process of transformative change rooted in collective innovation systems (1.1). Doing so, we show the consistency of the socio-technical regime framework to conceptualize the drivers of change that occur in the agroecological transition (1.2). We then mobilize this approach to analyze the current agroecological socio-technical system (1.3).

1.1. The agroecological transition: a transformative and collective change driven by innovations

We seek to understand the drivers of the agroecological transition. First, we explain that it is a process of transformative change that occurs by innovations supported by paradigms and technologies. Secondly, we show that this process cannot be implemented by a single category of actors but fully necessitates the adhesion and the commitment of the diversity of stakeholders involved in agricultural concerns.

- *The agroecological transition: an innovative transformative change*

The agroecological transition is nowadays advanced on the political agenda as a common and central goal to achieve and aims at providing the development of doubly efficient agricultures stemming from their economical and ecological performances (Guillou *et al.*, 2013). It is engraved in legal frameworks that call for sustainability. Around the world, growing attention is being paid to the importance to sustain agricultural and food systems, particularly in the face of climate change. At the international level, significant effort can be noticed. For instance, the United Nations Environment Programme (2012) points out more than 500 international agreements for environmental matters since 1972 on diverse issues as hazardous wastes, climate change, biological diversity and desertification. For agriculture, international agreements cover issues as plant genetic resources, plant protection, pesticide residues.

In the context of global changes, innovation is recognized as a driving force of progress for sustainable and fair development. It is a priority that cannot be ignored by either industrial nations or developing countries, which have to address numerous economic, societal and environmental challenges. Indeed feeding a growing population and ensuring food security and safety whilst protecting ecosystems and natural resources are crucial priorities. To respond to these priorities the development of knowledge is central to apply ecological fundaments to design and manage sustainable agroecosystems. Therefore, the agroecological transition cannot be tackled without considering the crucial question of innovation.

Agroecological innovations can be incremental or radical. Incremental innovations contribute to improve the efficiency of chemicals and/or reduce their use by alternative single substitution practices such as biological inputs (weak ecologization of agriculture). They imply few changes as they are limited to the implementation of "good practices" and single technologies in agrosystems. These technologies are usually implemented in substitution for chemical inputs and are used and assessed separately. For instance, many agroecological practices such as organic soil amendments, solarization, plant-induced resistance stimulation, biological control agents or symbiotic microorganisms inoculation contribute partially to reduce the use of chemical inputs such as fertilizers and pesticides.

Radical innovations impose a real change of paradigm that necessitates a holistic comprehension of agrosystems in interaction with their environment. These innovations aim at a strong modernization of agriculture. They rely on alternative methods and technologies to regreen agriculture through the enhancement of ecosystem services based on biodiversity. This ecological technological package combines innovations based on the mobilization of multiple ecological interactions at nested multi-scaled levels to achieve tradeoffs and synergies. This technological package fits with the smart conception of agricultural systems (FAO, 2011) that relies on deep innovative changes based on ecological interactions. Therefore, activating ecological processes, revealing, mobilizing and promoting latent resources like biodiversity offer new lines of action to implement new technologies. For instance, the action of a chemical input can seldom be replaced by the stimulation of a single ecological process (Lopez-Escudero and Mercado-Blanco 2011) while the holistic approach has been proved to be the best strategy to effectively control soil-borne pathogens by integrating biological, physical, and crop-management approaches (Collange et al. 2011; Oka 2010).

This technical progress is intrinsically knowledge-intensive. It does not derive from turnkey technologies that can be applied and replicated in different environmental contexts. The smartness of agroecology is incremented by the fact that the available technologies have to be combined and adapted to the heterogeneity of the environment. Smart technologies result from cumulative experiences that are in rupture with the ones developed within the previous paradigm that supports conventional agriculture. The agroecological package has to build its own internal coherence, which appears as a promising prospect to place agrosystems on a new technological trajectory.

The weak and the strong modernization of agriculture respectively supported by incremental monotechnologies innovations or radical mixed technological packages are fully part of the agroecological transition pattern. Since they are both encouraged by public authorities whatever their scales of application (national, supra-national, international), they make unclear the political strategy and fuzzy up the delivered institutional message. This regulatory framework (or landscape) is ambivalent. It nevertheless constitutes the rules of the game within the actors take their decisions.

- *The agroecological transition: a collective process of change*

Though it has been engraved in regulatory frameworks, the agroecological transition cannot be established by decree. It results from a process which implies a diversity of actors. The implementation of the agroecological transition fully depends on the adhesion and the commitment of the majority of stakeholders that are and will be *de facto* involved in this process. Agro-ecological concerns encompass not only production, but also agro-transformation and food supply and commit a wide range of actors.

As underlined by De Schutter (2014), strong environmental arguments in favor of agroecology are well popularized nowadays but agroecology also provides other economic and social benefits. For instance, by reducing the cost of farming (minimization of the use of expensive inputs), it improves the livelihoods of farmers. Moreover, because it is knowledge-intensive and generally more laborintensive, it creates employment opportunities and then supports rural development. These observations allow to consider the interdependence and linkages between actors, sectors and systems. They show how the landscape is being shaped not only by farmers' decisions, but also by decisions made through the supply chain from producer to consumer. They highlight the importance of looking across multiple perspectives for options of synergies and trade-offs and policies for transforming agricultural and food systems.

On this basis, the effective implementation of the agroecological transition comes to crystallize into a complex network of actors (farmers, industrials, researchers, policy-makers etc.) whose interactions and coordination processes for technological innovations shape a "socio-technical regime" (Geels and Shot, 2007). The agroecological transition is not spontaneous. It goes through innovation stages, cumulative learning and collective processes. It that sense, it is not linear but matches by trial and error and evolves thanks to the actions of economic agents. Therefore, the setting up of the agroecological transition can be analyzed as an evolutionary process.

1.2. The agroecologial transition in the conceptual framework of socio-technical system

The notion of socio-technical regime is fully included in Nelson and Winter's (1977, 1982) and Dosi's (1982) economic evolutionary approaches. These authors defined the theoretical understanding of industrial process which is interpreted as a dynamic and competitive innovation process. They explained industrial dynamics asymmetries as the result of differentiated technological regimes. A regime is a combination of factors such as technological opportunities, the ease of access to these technological opportunities (high or low importance of barriers to entry) and learning patterns. This conceptual frame permits to identify common properties of innovative processes in distinct sets of production activities. It assumes that industrial structures and dynamics strongly depend on the properties of technological regimes.

Three concepts laid the groundwork for technological regimes: technology, paradigms and technological trajectory. "*Technology* cannot be reduced to the standard view of a set of well-defined blueprints. Rather, it primarily concerns problem-solving activities involving – to various degree – also tacit forms of knowledge embodied in individuals and organizational procedures. (…) *Paradigms* entail specific heuristic and visions on "how to do things" and how to improve them, often shared by the community of practitioners in each particular activity (…) i.e. they entail a collectively shared cognitive frames. (…) Paradigms generally also define basic models of artifacts and systems which over time are progressively modified and improved. These basic artifacts can also be described in terms of some fundamental technological and economic characteristics". (…) The concept of *technological trajectories* is associated to the progressive realization of the innovative opportunities associated with each paradigm, which can in principle be measured in terms of the changes in the fundamental techno-economic characteristics of artifacts and the production process" (Cimoli and Dosi, 1995, p. 246).

Whatever their levels of sophistication, artifacts are always produced, appropriated and used by agents operating in an economic, social, cultural and institutional structure. Technologies are thus described as contingent upon their context or contextualized. Their regular use augments their legitimacy and takes them as references. Technological concerns necessary deal both with technical and social considerations, what is summed-up by the expression "sociotechnical systems".

From the economic literature where it originally comes from, the concept of technological regime has been expanded to the one of sociotechnical regime. While a sociotechnical system is a set of artifacts, market and non-market rules, norms and practices, formal and informal organizations, networks that makes collective sense, a regime designs the governance of the system.

- *Regimes, landscape and innovation niches*

In the vein of the economic evolutionary approach of innovation systems, the multi-level perspective analysis grid of socio-technical system (Geels, 2002; Geels and Shot, 2007; Geels, 2011) describes three elementary components: the *regime* which is the main element of the socio-technical system, the *landscape* that shapes the regime and the *innovation niches* that may under certain circumstances contest the current regime. In this conceptual framework, the regime level is the first one to be considered because transitions occur by shifts from one regime to another regime. The niche and landscape levels are defined in relation to the regime. These 'derived concepts' (Geels, 2011) influence the evolution of the regime. The niches include practices and/or technologies that are not part of the current regime. The landscape is the external environment that pressures the regime and impacts its interactions with niches.

The *regime* is composed of different actors that regularly interact on the strength of routines. These actors are closely linked, share norms of action, values and fund the stability of the regime. One of the most important Nelson and Winter's (1982) contributions relies on the role of routines in stabilizing regimes. By the way, the two authors present routines as a key unit of analysis in their approach. In such a framework, the weight of routines is likely to explain: (i) how change occurs, (ii) how selection processes are implemented, and (iii) under what conditions what has been selected is maintained through time (that is to say transmitted from one period to another).

The regime is characterized by three elements: its technology, its paradigm and its trajectory. The trajectory of a regime is stable over time as the regime evolves on the basis of incremental innovations. The literature put emphasis on the notion of paradigm defined as a particular worldview (*i.e.* strong specific beliefs) trusted by stakeholders. Beliefs guide actions. In that sense, they pilot change. Paradigms are diverse: they coexist, and in some cases, stay fully opposite and competitive.

Paradigms constitute the solid fundaments on which niches emerge. Sociotechnical niches are privileged arena for innovations. Within niches, technologies are invented, tested and developed. "Niches are crucial (…), because they provide seeds for change." (Geels, 2002, p. 1261). They generate radical innovations, a fact which is possible because of the confidentiality of niches. New technologies are then protected from pure and perfect competition mechanisms which is a prerequisite for their development as they are low efficient and costly. Niches assume business risks (*i.e.* economic and technological) and act as "incubation rooms" (Geels, 2002) where social networks supporting learning processes for radical innovations arise and grow.

The innovation niches provide disruptive innovations that rely on a radical paradigmatic rupture from the one followed by the current system. Niches are numerous and are of varying duration. They are composed of more or less stabilized groups of actors whose norms of actions are not necessarily routinized. Although niche-innovations are central, they do not govern by themselves the success of a new technology.

The third level to be considered is given by the metaphor of the landscape. This macro-sphere designs external factors that constitute "a set of deep structural trends" (Geels, 2002, p. 1260) which is imposed to stakeholders. It describes the broad context in which sociotechnical regime are embedded. It defines all the structural rules that regulate the regime. "The sociotechnical-landscape contains a set of heterogeneous factors such as oil prices, economic growth, wars, emigration, broad political coalitions, cultural and normative values, environmental problems" (Geels, 2002, p. 1260).

- *The drivers of change and innovation*

The evolutionary approach of socio-technical system explains that a socio-technical system evolves thanks to the actions of economic agents whose capacities of learning, innovation and adaptation are central. In that sense, socio-technical systems are driven by knowledge, and knowledge constantly changes. In later works, Cimoli and Dosi (1995) conceptualized this mechanism. They analyzed patterns of learning and show the cumulativeness property of learning for innovation.

Technological transitions are prepared in niches that may impact the sociotechnical regime. As Geels and Schot (2007) underline, “radical innovations have developed in niches, but remain stuck because the regime is stable and entrenched (Geels and Schot, 2007, p. 409). Hence, “technological regimes create stability because they guide the innovative activities towards incremental improvements along trajectory” (Geels, 2002, p. 1259). On these bases, we admit that radical innovations are provided in niches and incremental ones in regimes as risks are better assumed in niches than in sociotechnical regimes. The major difference between niches and regimes is that regimes hold historical and social thicknesses contrary to niches. Therefore, niches emerge and disappear easier than regimes which appear to be more stable though they are not inert.

For a new technology to be adopted and disseminated in a smooth transition, the alignment of the three spheres (niches, regime and landscape) that influence stakeholders’ action is required (Geels and Schot, 2007). This opens a window of opportunity that modifies the sociotechnical system trajectory. This configuration is most of the time observed by current socio-technical systems. Nevertheless, other situations are also experienced.

From landscape, emerge slow but severe dynamics of change that shift the sociotechnical regime. In short, sociotechnical change derives from slow and rapid movements depending on strong interactions between the niches, regime and landscape. It is lead by profound mutations in certain parties of sub-societal systems and stresses a shift from a dynamic initial equilibrium to another one.

Sociotechnical systems are then not static, they continuously evolve: technology, rules, social representations, relations among actors, undergo substantial transformations. In the long run, these systems experience different successive states of equilibrium. We then talk about dynamic equilibrium. In the literature, a sociotechnical system in a state of dynamic equilibrium is usually called "regime". The succession of dynamic equilibria forms a trajectory. It appears then that change is not only technological but also social. Thus, the actors (and their systems of values, norms, beliefs etc.) must also evolve for change to occur in sociotechnical regimes.

The multi-level perspective framework takes into consideration the landscape and the niches as variables that impact the regime in different ways. These interaction mechanisms lead to different transition pathways depending on whether the landscape is more or less unstable and the niches developed or not (Geels and Shot, 2007). Four scenarios are identified.

Box 1 Transition pathways (Geels, 2011, p. 32)

“• *Transformation*: In this pathway, landscape developments exert pressure on the regime when niche innovations are not well-developed. Incumbent actors modify the direction of innovation activities and development paths, which leads to gradual adjustments of regimes to landscape pressures. Although niche-innovations do not break through in this path, experiences from niches can be translated and accommodated (often in a watered-down form) in the regime (Smith, 2007).

• *Reconfiguration*: In this pathway, niche-innovations are more developed when landscape developments exert pressure on regimes. If niches are symbiotic to the regime, incumbent actors can adopt them as ‘add-ons’ to solve local problems. This incorporation can trigger subsequent adjustments, which change the regime’s basic architecture.

• *Technological substitution*: In this pathway, competitive niche-innovations are well developed when landscape developments exert pressure on regimes. Tensions in the regime form a window of opportunity for the breakthrough of niche-innovations that replace the regime. An alternative route is that niche-innovations gain high internal momentum (because of resource investments, consumer demand, cultural enthusiasm, political support, etc.), in which case they can replace the regime without the help of landscape pressures.

• *De-alignment and re-alignment*: In this pathway, major landscape pressures first cause disintegration of regimes (de-alignment). Then, taking advantage of this ‘space’, multiple niche-innovations emerge, which co-exist for extended periods (creating uncertainty about which one will become the winner). Processes of re-alignment eventually occur around one innovation, leading to a new regime".

1.3. Framing the current agroecological system through the socio-technical regime approach

In accordance with the socio-technical system approach, we attempt to operationalise the multi-level perspective in order to understand what is at stake in the context of the agroecological transition. In what extent the current agroecological system constitutes a regime? Do niches and landscape reinforce or break the existing regime? We base our analysis on the identification of the actors that interplay in the agroecological pattern. We wonder whether they constitute a regime and act for its stabilization. Following Duru et al. (2014) who distinguish the *weak* versus *strong* ecological modernization of agriculture, we assume that agroecological concerns do not constitute a unique and unified set of practices. In other words, the paradigms, the technologies and the trajectories deriving from these two conceptions of agroecology differ.

In the case of the strong modernization of agriculture, a radical and definitive rupture is made with the productionist paradigm whereas the weak modernization scheme appears for some scholars as a slight rupture and is considered as the extension of the previous paradigm (Amilien 2005). Adopting the analytical approach developed by Amilien (2005) which deals with food system, we identify three views of agricultural and food concerns: the productionist paradigm (that support the conventional agricultural and food systems), the life science integrated paradigm and the ecologically integrated paradigm.

For the author, the well known and popularized paradigm has been well established for more than 50 years, while the two others are more recent and turned toward the future. This "life science integrated paradigm" stands on market stances (Amilien, 2005, p. 3). Within this socio-technical system, multinational enterprises try to get patents on the living entities (Orsini, 2010) and are very turned toward genetically modified organisms, biotechnology and support growth bolstered by globalization. It lines up well with business perspectives and well established productionism (Amilien, 2005). This paradigm is fully orthogonal to the "ecologically integrated paradigm" which promotes a "fair distribution of nature and goods" (Amilien, 2005, p.3) with territorial embeddedness as strong modernization processes require. Thus, the weak ecologization of agriculture stems from the life science integrated paradigm" while the strong modernization is rooted in the "ecologically integrated paradigm".

If we conceive that the setting up of the agroecological transition relies on two distinctive socio-technical systems, we must analyze each of them. We start the reflection by an historical review of the evolution of agriculture discussing the three paradigmatic movements depicted before. To flesh our view, we will answer the following questions: How does landscape transformation impact the dominant regime and give alternative niches the opportunity to expand? How do the niches-actors organize to augment their visibility and seize the chance to become real engine of change?

The three paradigms correspond to three distinctive moments in the history of agriculture. They have fully left their mark on the landscape. These different paradigms cohabitate and are still ratify by the wide range of actors involved in agriculture and food concerns. In that way, they make the message (macro-rules, deep cultural patterns etc.) given by the landscape fuzzy and ambivalent.

The more well-established paradigm is the productionist one. It has emerged during the post-war reconstruction where total production and yields should strongly increase to ensure food security in the countries that had suffered from the destruction of their infrastructure. This paradigm was economically coherent and emphasized the productive function of agriculture. It relies on technologies related to the manipulation of the environment by various means: mechanization, synthetic chemical inputs, genetic engineering, and monoculture. The socio-technical system put in place on this basis was deeply established thanks to the strong interrelationship structure that joined together scientists, industrials, public authorities, farmers, consumers. Scientific knowledge deeply dominated the organization of the system with the belief that science does not face any limits and can best control natural processes. Vertical relationships occur between these categories of actors. Innovations are provided by scientists and are produced by industrials. When scientists and industrials disseminate new technologies, public authorities give strong incentives to farmers to ensure the purchase of these chemical or mechanical inputs. Consumers committed in this globalized scheme buy the goods and services produced in this context. This interrelationship structure governs the socio-technical regime.

As expected, this simplification of cropping systems increased productivity and yield, but it had undesirable side effects. One of the most important side effects is the degradation of the environment that still suffers from the consequences of dramatic pollution episodes (alteration of natural resources, loss of biodiversity, risk to human health, vulnerability of people depending on polluted resources etc.). Moreover the recognition of the inability of the current productionist socio-technical system in providing increasing yield anymore comes to the conclusion that this paradigm is obsolete.

In the 1990s, the institutionalization of sustainable development created a window of opportunity for a growing recognition of the other functions of agriculture: social and environmental. This legitimated the rise of the “life science integrated paradigm” and modifies the landscape. This paradigm is compatible with the development of technologies that support a weak modernization of agriculture. We also observe strong collusion of interests among the set of actors that constitute this socio-technical system. Scientists, industrials, public authorities, farmers and consumers are still involved in the governance of the system thus forming a regime. Scientists and industrials are deeply committed in the developed of new technologies (mainly biotechnologies, GMO) (Vanloqueren and Baret, 2009). Public authorities still continue to distribute incentives to farmers for the use of these technologies. The coherence of this regime relies on economical stances. But since its emergence, the regime is severely internally criticized on the basis of its scientific fragility. A growing recognition of uncertainties surrounding the soundness of scientific knowledge gained more and more currency. This context of incertitude opened up new opportunities for epistemic communities (Callon et al., 2001) that contest the solidity of the regime. These epistemic communities are composed of different kind of actors providing from the civil society framing new consumption references (basically more attached to ecological fundaments).

The “ecologically integrated paradigm” has gained in importance for the 2010s and generates disruptive innovations. The technologies it supports mobilize solely natural elements. They combine vernacular and scientific knowledge that surge in collaborative processes. In that way, the nexus of actors is not hierarchically organized. It deeply stands on horizontal relationships (Schut et al. 2014). These actors constitute an arena where joint visions of the future are being built. They elaborate scenario, they define programs of actions and shape the future of the system. They design transition paths that should lead on the basis of collaborative and proactive processes to more sustainable food systems. Such networks act as "innovation thought collectives" and can facilitate the paradigm shifts which are important for disruptive technologies.

From this historical review of agriculture and food system, we point out that the agroecological transition is implemented in a specific landscape context. Agroecology does not rely on a single paradigm and associated technologies. The strong versus weak ecologization of agriculture are rooted in a confusing and ambivalent message delivered by the landscape. As explained by Geels and Schot (2007), the best configuration for change to occur without triggering strong disturbance of the existing regime is when the alternative niches, the regime and the landscape are linked to each other and aligned, creating thus a dynamic stability. This articulation assures positive outcomes as it permits long-term structural transformations. When the alignment is not realized, change occurs erratically (it can be blocked) due to strong confrontations and tensions among the niches, the regime and the landscape.

More often, crises or shocks occurring in the landscape destabilize a regime, whose practices and technologies are then challenged by the alternative innovations developed in niches. In response, to face increasing competition from alternatives, actors marginally refine existing solutions. At the end, it may be possible that the actors of the ongoing regime progressively abandon their old practices and techniques and adopt or investigate for more radical solutions. This *de-alignment and re-alignment* pathway is observed in the modernization process of agriculture where the confusing message of the landscape exerts pressures on the current regime. In front of global changes that imply deep mutations in the landscape, dominant industrial groups invest nowadays in ecological innovations. By doing so, they prove the inefficiency of the prevailing sociotechnical regime in feeding the world and achieve long term sustainability using technologies stand in the productionist paradigm (Altieri *et al.*, 2012). Hence, these actors rehabilitate the niches they had actively resisted to and that they deliberately confined in narrow position thus impeding they became a new regime.

The current agriculture and food systems show a misalignment between the landscape (which indifferently supports weak and strong agroecological concerns), the productionist and the life science integrated regimes and the diverse niches fit in the ecologically integrated paradigm. We can observe that most of the new technological innovations adopted in the current socio-technological regime fit in the weak modernization of agriculture. The life science integrated paradigm that funds this regime resolutely stays economic although it integrates ecological concerns. In that sense, the ongoing productionist regime runs under incremental changes and thus corresponds to the transformation transition pathway identified by Geels and Schot (2007). The stakeholders change the direction of innovation activities, which allows progressive adjustments of the regime to the landscape's ambivalence. The previous niches resulted from the life science integrated paradigm has progressively formed an alternative regime.

However, niches based on strong agroecology principles (ecologically integrated paradigmatic) still stay niches. In the high competition between the two first regimes (productionist and life science integrated paradigms), the ecological niches are under pressure and literally crushed by the dominant regimes. In the following part, we illustrate the robustness of the life science integrated regime, taking as an example a growing technology centered of the enhancement of soil microorganisms (mycorrhiza).

2. The robustness of the current life science integrated paradigm regime. Focus on agroecological innovations based on mycorrhiza in France

Among the criticisms addressed to the multi-level perspective issues, the question of its operationalization and its empirical assessment is currently raised (Geels, 2011). This section aims at discussing the implementation of the agroecological transition by analyzing the example of myccorrhiza which is of growing interest in matter of modern technologies in agriculture, horticulture, and forestry programs, to enhance crop health and productivity and to reduce the use of chemicals (Ijdo et al. 2011). The use of mycorrhiza can be interpreted as a weak or a strong way of ecologization of agriculture depending on practices. Inoculation of industrial strains in substitution to chemicals corresponds to the weak ecologisation of agriculture while a systemic analysis of the agrosystem to benefit from the ecosystem services provided by natural mycorrhizal networks (enhancement of soil structure, increased resistance to plant abiotic and biotic stress: salinity, drough, pathogens, etc. (Gianinazzi et al. 2010)) corresponds to a strong ecologisation. Taking this example, this section analyzes in what extent the spread strategy of inoculation is fully part of the existing "life science integrated" regime and discuss its robustness.

Aiming at identifying the actors involved in the sociotechnical system, we describe the characteristics of the network they constitute. We then provide an explanatory grid to measure the nature and the importance of the flows that circulate within this network (2.1). This helps understand the functioning of the network, its power structure, the internal rules ratified by the agents which are consistent analysis categories to understand how innovative learning processes are put in place and establish and reinforce the current life integrated sociotechnical regime (2.2). We point out how this complex network structure lock-in the embryonic but competitive innovation niche illustrated by the local strategy of mycorrhization. We discuss the potential evolution of the niche anchored in the 'ecologically integrated' paradigm. We then highlight some guidelines for it to be reinforced and penetrate the existing regime (2.3).

2.1. Appraisal the robustness of the life science integrated regime: methodological issues

The operationalization of the multi-level perspective has been illustrated with different case studies of transitions. Among others, we can list: land transport (Geels, 2005), shipping (Geels, 2002), cargo handling (Van Driel and Schot, 2005), sanitation (Geels, 2006), waste management (Geels and Kemp, 2007). This approach has also been applied in contemporary studies to shed light on transition pathways to sustainability (*i.e.* electricity systems (Verbong and Geels, 2007, 2010; Hofman and Elzen, 2010), mobility and 'green' cars (Nykvist and Whitmarsh, 2008; Van Bree et al., 2010; Geels *et al.*, 2011), biogas and co-combustion (Raven, 2004), organic food and sustainable housing (Smith, 2007), animal welfare (Elzen et al., 2011) and crop diversification (Meynard *et al.*, 2013)). These studies explain the dynamic of changes occurring in these systems by analyzing their learning processes, network dynamics, and the way existing regimes are impacted. The case of mycorrhiza is a supplementary example that gives empirical evidence on the implementation of the agroecological transition.

Our methodological investment relies on three main raw materials.

The first one consists of an analysis of the mycorrhiza supply chain based on rare available data and a multidisciplinary literature review (biology, agronomy and ecology sciences) to describe challenges faced by the two mycorrhiza enhancement strategies (inoculation of exogenous industrial strains and the mobilization of indigenous natural mycorrhizal networks). Literature was sourced in an iterative manner. We identify the scientific community working on mycorrhiza (International Mycorrhiza Society), their supports of publication and the articles considered noteworthy and relevant (effects of reputation). Our methodological approach combined thus literature review with expert judgment by researchers working on mycorrhiza. An identification of the scientific landscape on mycorrhiza shows a great enthusiasm for this topic which is at the cutting edges of research in Europe (Belgium, France, Italy, Spain, Switzerland, Czech Republic etc.), North America (United States, Canada), Asia (India) etc. By an online literature review using a variety of academic search engines, we considered the highlights on mycorrhiza issues. From these two approaches, two evidences emerged.

(i) The mycorrhiza market is dominated by a few number of producers around the world (around 35 producers were registered in 2004 (Gianinazzi and Votsaka 2004) but the number is certainly higher today). It is an oligopolistic market.
(ii) These producers popularize and diffuse the strategy of inoculation of exogenous mycorrhiza though inoculations are not universally beneficial and can generate invasive species problems (Schwartz *et al.* 2006, Verbruggen *et al.* 2012).

Focusing on the development of the mycorrhiza supply chain in France, an analysis of key policy documents produced by public authorities (European Commission, the French Ministry of agriculture) on the regulation of the use of mycorrhiza has been made. There is now in France a large consultation to favor the marketing approval of biological agents (Herth, 2011). From this work (articles L.255-1 to L.255-11 of the French rural and fishery code) we learnt that mycorrhiza are legally commercialized as fertilizers. The regulation does not then cover the other properties of mycorrhiza like their ability to compete with elements of natural biodiversity. The recognition of this propriety should imply restrictive approval processes to ensure the safety of inoculation. Under the current state of the art, the regulation does not promote the existence of control mechanisms to ensure this quality. For example, in existing commercialized products, the presence of pathogens is not always detected (Schwartz *et al.* 2006).

The second methodological material provides from an analysis grid developed in previous works and conceived to apprehend the nature of the links developed among agents in agricultural innovation systems (researchers, farmers' associations, industrials, regional authorities, public or private funders) (Chave et al., 2012). This grid was designed to by-pass the rigidity of a top down approach by a systemic analysis of innovation trajectories. It aims to identify financial, material and information flows circulating from a category of agent to another over time. We applied this grid on the case study of the mycorrhiza supply chain.

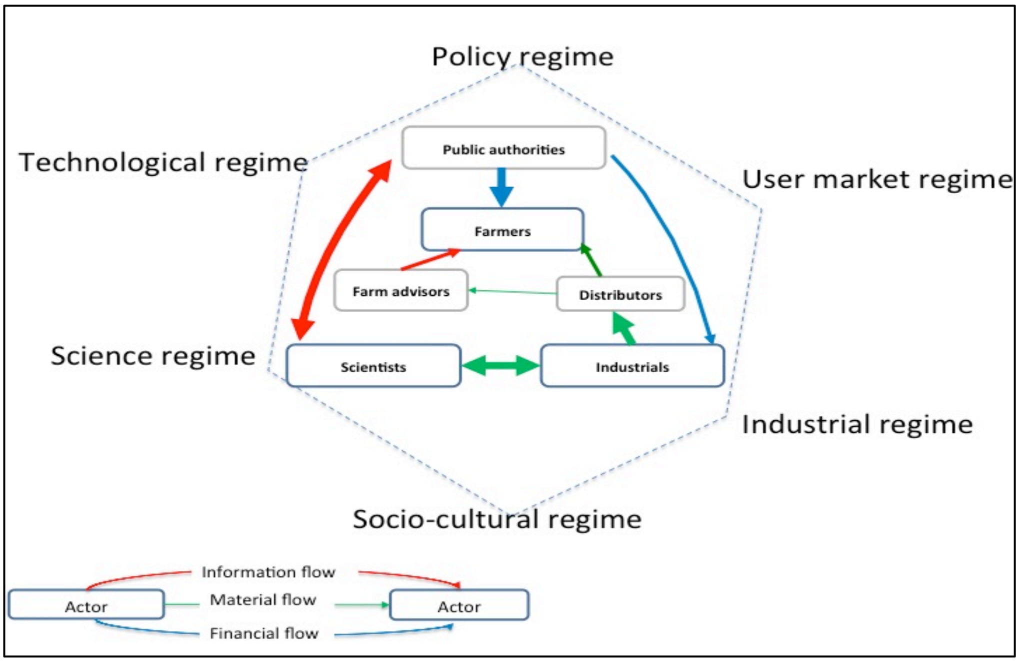

Figure 1: Representation of the flows exchanged among the main actors of a sociotechnical regime
(adapted from Geels, 2007 and Chave et al. 2012)

The third raw material relies on qualitative interviews with the main stakeholders on the mycorrhiza supply chain. Using the stakeholder analysis (Mitchell *et al.,* 1997), around 30 interviews have been made with producers and distributors of mycorrhiza (France, Canada, Austria, Germany, Italy, Czech Republic, Belgium, United States) and the researchers that develop the technologies which are commercialized (propagules producted *in vivo* or on transformed roots, distributed as single inocula or associated in organic fertilizers or by seed coating (Ijdo *et al.*, 2011, Adoleya 2013)). The classical approach of stakeholder analysis is a power / interest grid that permits to identify stakeholders, differentiate between them and categorize them, investigate relationships among them. It helps examine what are the main stakeholders of a network and how they pilot it given their influence and interests. We combine the stakeholder analysis with the snowball non-probability sampling method that allows existing stakeholders to identify others depending on the importance they recognize to them. Thus, at the end of the questionnaire, all the stakeholders were asked to cite other agents. The stakeholders mostly cited are then considered as those who are the most influent and therefore cannot be ignored.

Our analysis results in a comprehensive monograph of the international mycorrhiza supply chain with a specific focus on the French case study. We provide evidence on agroecological innovations from our surveys among stakeholders and scientific publications. Our results confirm the importance of the strategy of inoculation as an agroecological practice and the core role played by scientists and industrials.

2.2. The salient features of the dominant technological regime

To describe the sociotechnical system and to determine whether it constitutes or not a regime, we examine the interactions (nature and density) that are developed among identified key-actors. On this basis, we seek to build a heuristic map that represents the different flows exchanged among the actors of the system.

Three types of flows are considered (Chave *et al.*, 2012):

- Flows of information: orientation of public policies concerning research, partnership between private and public actors of research, knowledge transfer towards farmers etc.
- Financial flows: public authorities' subsidies towards private actors, funding offered to research units by industrials, farmers' or consumers' purchases and sales etc.
- Material flows: sales of inocula to farmers, exchanges of strains and inocula samples.

The flows of information are central as they can influence the shift of technology to another.

The identified stakeholders are the firms that produce mycorrhiza, the public research laboratories, the public policies responsible for directing research, the public policies for registration and certification processes of fertilizing materials and crop supports, the farmers, the organizations tin charge of agricultural council and the distributors. All these actors use **media** to diffuse information and communicate on their self representations. These media can take the form of published documents or participation to events.

All the firms whose products are registered and approved for the French market have been contacted. We also contacted the most important firms present on the international market as a result of the snowball sampling method to expand the set of surveyed firms. Using the same method, researchers have also been interviewed, starting from the French ones.

A first hypothetic map of the main categories of stakeholders has been built before starting the interviews. On this map, we materialized all the potential links that can exist between the stakeholders. The interviews aimed at verifying if the exchanges really exist and at assessing them for the most diffused strategies of mycorrhization.

The interviews were mainly conducted by phone or mail. From this raw material we learnt about the stakeholders' representations (the advantages and drawbacks of the technologies of inoculation identified by the actors, their level of knowledge about the existence of ecological alternative niches) and their strategic interactions. We then grasp the factors that determine the stakeholders' choice within the mycorrhiza innovation system. The influence of each determinant is systematically described (funding priorities, scientists' cognitive and cultural routines etc.).

- *Some highlights on the stakeholders' representations and strategies*

All the scientists that were interviewed work on the more spread strategy. Half of them also study practices that favor local mycorrhizal networks or are even able to cite this strategy as a possibility of enhancing mycorrhiza.

The industrials feel concerned only by the strategy of inoculation although one of them specify that the stains are local even if they are not able to explicit in what extent they are local. One of these firms pretended to be also positioned on the enhancement on local mycorrhiza by giving the farmers some advices. We must precise that one of the international leaders producing mycorrhiza does not recommend reducing the use of chemical fertilizers in parallel with the use of mycorrhiza (a fact that can be prejudicial to the efficiency of the microorganisms). In this case, the environmental argument thus disappears in favor of the economical argument (*i.e.* augmenting yield).

Half of the scientists mention the ecological risks deriving from the importation of inocula on local biodiversity but they minimize it. Only one of them indicates the risk of contamination by pathogens that can be integrated in the inocula.

One industrial revealed that he is perfectly aware of the potential negative risk of the exogenous mycorrhiza inocula and that he takes specific measures of protection using local strains. The other industrials only identify the potential economical risk resulting from the eventual inefficiency of the inocula.

The analysis also reveals that farmers have been educated in a particular way and have developed specific routines that enable them to stay in the productionist paradigm. The cost of moving from practices using mainly chemicals to more agroecological practices is high (knowledge, reputation, networks, access to research grants).

- *Assessing the flows among the actors*

From the interviews we learnt that farmers do not have access to sufficient knowledge on mycorrhiza. Information flows do not reach them. In these conditions there is no way that the farmers fully take advantage of these agroecological technologies.

Strong ties exist between researchers and industrials for the technology of inoculation. These proximity ties can be formal or informal and concern the three types of flows. All the scientists that we interviewed confirmed that they developed contacts with industrials whatever the medium used (research projects, exchange of information, and profit sharing of firms producing mycorriza). Most of the managers of firms producing mycorrhiza come from research laboratories. The three types of flows can be examined.

(i) The **informations** are disseminated through research results that are shared among the stakeholders. For instance, a research laboratory and an industrial indicated that manage together a project on the development of genomic markers to identify and measure the arbuscular mycorrhizal fungi inocula in agriculcural soils. Moreover, in France, several firms were created with the support of public research laboratories as a result of collaborations.

(ii) Research culture collections provide selected material to companies (according to material transfer agreement) or act as repository for inoculum deposited by companies (Ijdo *et al.,* 2011). Some scientists also participated in the creation of firms. For instance the collections of the commercialized mycorrhiza are promoted by their laboratories. In our sample, a public laboratory directly commercializes mycorrhiza of its collection and suggests soils analysis. The exchanged flow is then **material**, with sharing of collections and products that the public laboratories use. These flows are also informal, with exchange of strains among scientist and firms for the development of the products and their evaluation.

(iii) The financial means are shared between research laboratories and industries with the support of the public authorities.

We show that the rules of decisions of scientists and industrials are predominant in the choice of technological paradigms and the development of technological trajectories. The results of our analysis sum up the key actors' strategies that structure the current technological regime.

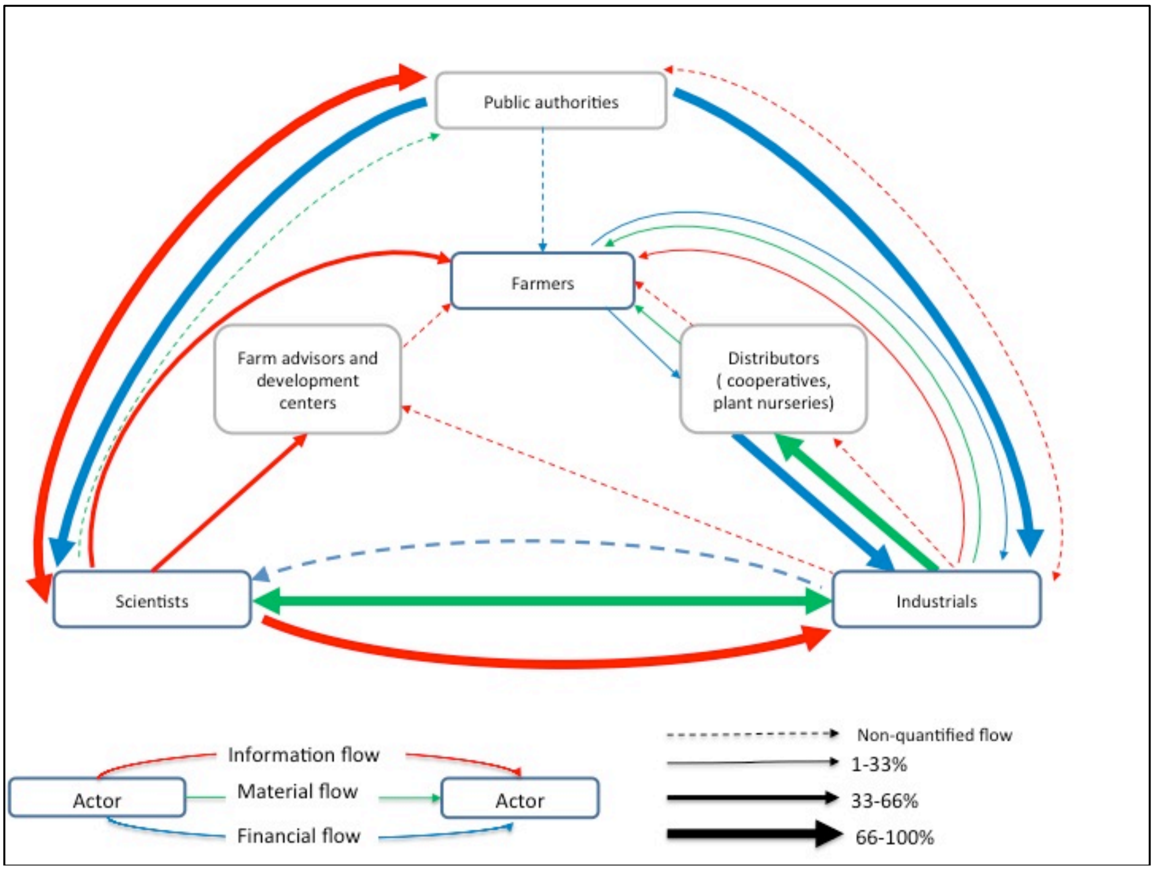

Figure 2: Representation of the flows exchanged among the main actors of the regime
The size of the arrows corresponds to the importance of the flux (frequency)

As a result of their interactions, these actors participate in the reinforcement of the current socio-technological regime. Special attention is then paid to research and industry as they seem to influence the current agroecological pattern. The rules of decisions laid down by scientists and industrials are predominant in the choice of technological paradigms and the development of technological trajectories. They thus determine a lock-in situation that impedes the development of the alternative niches (mobilization of indigenous mycorrhiza networks) that could engineer a strong modernization of agriculture. Issues on the breaking out of this lock-in situation are discussed in the following section.

2.3 Implementing the strong modernization of agriculture: some prerequisites

The socio-technical approach and our methodological contribution to appraise the factors that influence the technological choices and innovation processes mobilized for the use of mycorrhiza are fruitful to demonstrate how this pattern structures the current regime. We show how the cultural and cognitive routines, the market prices and the public policies orientations shape the decision rules of the whole stakeholders and generate lock-in situations and path-dependence.

The concept of path dependence has been imported in the multi-level perspective approach to explain the stability of sociotechnical systems. "Among several technologies that perform similar functions and compete for adoption by economic agents, one technology may become dominant, even though it may have an inferior long-run potential (David and Arthur, 1985; Arthur, 1989). This process is 'path dependant' as the initial conditions may greatly influence the success of the dominant technology, particularly when increasing returns occur. This process is self reinforcing and may lead to a technological lock-in situation in which the dominant technology excludes competing and possibly superior technologies (Liebowitz and Margolis, 1995)" (VanLoqueren and Baret, 2009, p. 980).

In a pragmatic approach, we must admit that lock-in situations have consequences for public action. The main question raised is to understand how to break out of lock-in because, as we pointed out before, incremental innovations are not enough to ensure the strong form of agroecological transition. Agroecological innovations supported the strong modernization of agriculture are of first interest as they are crucial for our contemporary societies, especially in the quest for sustainable agriculture context of climate change. In this section, we discuss three essential aspects that we consider as keys to manage the necessary shift requested for a transition path based on a strong modernization of agriculture. Considering the analysis grid of Geels (2011) that identifies a typology of pathways, we consider the two main levels that influence the regime suggesting then actions on the niches and the landscapes.

- Accompany the niches

The multi-level perspective approach emphasizes the niches level. Niches play a core role in the stimulation of radical innovations and counterbalance path dependence and lock-in situations. They are the locus where learning processes are improved, where technological developments are made, where market risks are assumed. Niches imperatively require strong supports for their development to occur in which case they do not survive.

Agroecological innovations to enhance natural mycorrhizal networks such as mixed farming, agroforestry, or on-farm mycorrhiza production systems are precisely radical innovations as they necessitate redesigning the agroecosystems. In some respects, they can be considered as laboratories that prepare for the wider changes that are occurring or will occur. To make them reinforced, we assume that supportive action should be developed in priority in two directions.

(i) Accompany the niches in financial terms

If we consider the results of niches as public goods, whose benefits are not exclusively appropriated by a unique category of agents but create larger externalities, market incentives for their production are not efficient. Public intervention is required to support their high productive costs. Public support will then help networks become larger and enroll powerful actors that may convey legitimacy and resources to niche-innovations. In that way, learning processes could evolve on various dimensions (market demand and consumer preferences, techniques, organizational configurations, cultural and symbolic meanings etc.) and the niches could be more and more developed and compete with the innovations supported by the current regime.

(ii) Accompany the niches through public–private partnerships

The promotion of public–private partnerships (PPP) is henceforth acknowledged as an explicit mission hold by the public-sector research establishments because it is considered as a mean to transfer technology and knowledge (Tait *et al.*, 2001). The regime fitted in the productionist paradigm has strongly benefited from this partnership for the development of its main innovations. This is less the case for agroecological innovations (Vanloqueren and Baret, 2009).

We assume that agroecological innovations for the strong modernization of agriculture should be addressed more scientific attentions. Most of the time these innovations result from intensive vernacular knowledge processes and are not considered as decisive center of interest for research. More widely, studies on innovation show that the ability to innovate is often linked i) to collective action and sharing of knowledge between actors, ii) to incentives and available resources that were invested in collaboration actions and iii) to the creation of an enabling environment for the production of ideas and innovations by different actors (World Bank 2006). This militates in favor of creating the conditions of a horizontal partnership that helps increase and circulate information flows. Among the wide range of actors, advisory organizations (public or private) could be of fruitful collaboration provided that they share the right information flows and participate in the production of knowledge and innovation.

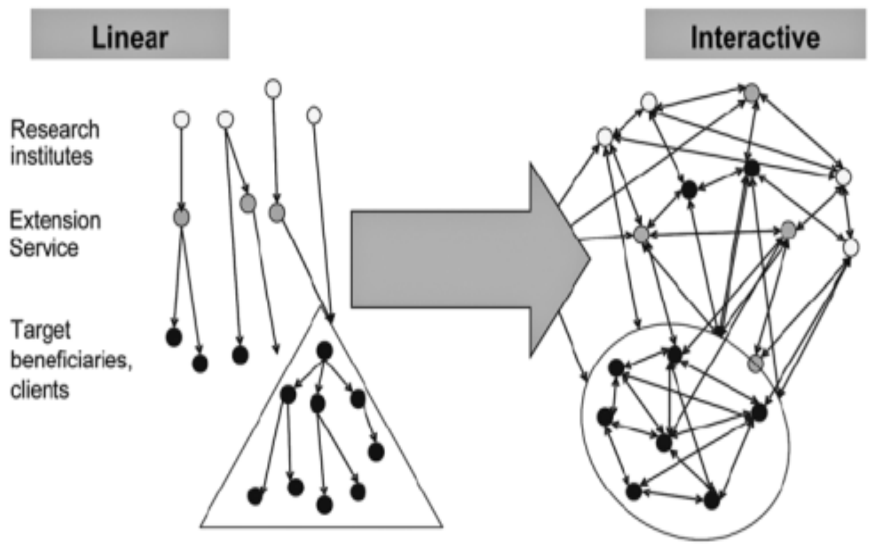

Figure 3 From a linear to an interactive conception of agroecological innovations (Daane, 2010)

Different studies on agroecological innovations show the importance of participatory methods in supporting new technological processes (Angeon et al., 2014, Duru et al., 2014). This is one of the means for building social networks and enrolling more actors to expand the resource base niche of innovation. More widely, this implementation process of collective actions pilots the creation and the evolution of the niches and its interactions with the current regime.

- Clarify the message delivered by the landscape

Up to this point, we mainly put emphasis on niches without considering the role of landscape. But, for niches to become thicker, external expectations must become more precise and broadly accepted. We indicated in the previous section that the institutional message delivered by the landscape is ambiguous. We then focus on the landscape to analyze the consistency of clarifying its macro-rules.

In the case of the agroecological transition the landscape is divergent (it both supports the weak and the strong modernization of agriculture). As pointed out by Geels and Schot (2007) increasing problems can be caused to the current regime. The stakeholders are lost and wonder about the technologies that are to be used. “The destabilisation of regime rules creates uncertainty about dimensions on which to optimise innovation efforts (guiding principles, user preferences, selection criteria, regulations, etc.)” (Geels and Schot (2007) p. 408). This context of incertitude can lead to the de-alignment of the current regime. As niche-innovations are not well developed, there is no clear substitute likely to redesign the regime. In this transition pathway the regime comes rapidly under landscape pressure. The regime experiencing troubles may collapse, erode and de-align.

If the niche-innovations are developed then one of them may become dominant and form a new regime. Public action has to create space for the emergence of multiple niche innovations issued from different types of knowledge (scientific and local) necessary for the implementation of the strong modernization of agriculture. These multiple embryonic niches are carried by outsiders. They diversify the set of actors governing the regime. This configuration corresponds to the reconfiguration pathway.

From our empirical results, we learnt that knowledge is not thoroughly shared except among scientists and industrials and does not favor the emergence of niche-innovations based on local mycorrhizal networks.

From the multi-level perspective, we show that an ambivalent landscape does not create windows of opportunity to produce scientific knowledge and to co-design and disseminate innovative technologies fit in the ecologically integrated paradigm. The trajectory of the forthcoming regime will confront a more challenging and uncertain context, a fact that hinders the strong modernization of agriculture.

Conclusion

In this article, we mobilize the evolutionary sociotechnical system approach to understand what is at stake in the agroecological transition. We analyze the mycorrhiza example to illustrate in what extent a weak versus strong modernization of agriculture supported by parallel paradigmatic movements can occur. We depict the bright and downsides of 'green' regimes and niche-innovations that are operating in the current agroecological transition. From an empirical work that seeks to assess the nature and the density of ties developed by the stakeholders, we found that the lack of shared-knowledge is a major innovation-inhibiting factor for regreening agriculture. We explain that the flow of information is relatively inaccessible to farmers. This makes difficult the implementation of agroecological innovations and even farmers' involvement in adopting and designing niche-innovations.

We put emphasis on the core and destabilizing role of the landscape resulting from its ambiguous message. The landscape supports both weak versus strong agroecological paradigms. It then provides contradictory injunctions and does not specify how to implement the regreening of agriculture. In this fuzzy context, where radical innovations-niches struggle to emerge, the current socio-technical regime stays on the same trajectory.

The need to create conditions of innovations and learning is required for the implementation of the strong modernization of agriculture. This can be achieved through the development of public-private partnerships

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