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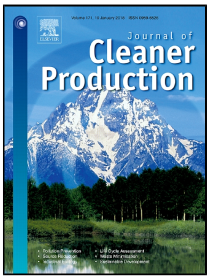

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Eco-innovation in Plant Breeding: Insights from the Sunflower Industry

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Abstract

Seeds are a major means for transforming farming systems and thus occupy a prominent place in the transition to more sustainable agriculture. This article analyses the conditions involved in creating and diffusing new plant breeds that have agroecological benefits, called eco-innovation varieties. By combining theories on eco-innovation processes with various scales of analysis, this study makes an original contribution to understanding innovation and transformation dynamics in the seed industry. Drawing on a case study of the sunflower industry in France and in Europe, the findings reveal which factors promote and hinder eco-innovation varieties. The results confirm the positive interactions between technology, regulation, and the market in eco-innovation processes. They also show that economic incentives for companies are insufficient to push them to develop more systemic eco-innovation varieties. Moreover, changes in the mainstream seed company regime, with the increasing internationalization of their strategies, call into question their ability to foster farming practices that promote the environmental benefits of these new varieties.

Keywords
Varietal innovation; sustainable agriculture; sunflower; agrochain; seed industry

1. Introduction

The productivist model of agriculture developed after the Second World War has enabled a rapid upsurge in global agricultural production (FAO, 2013). This increase has relied heavily on genetic progress combined with an intensive use of agrochemicals (fertilizers, pesticides), increasing yields for major crops. However, beyond these gains, this incumbent regime has been criticized because of the negative environmental externalities that it generates (Fresco, 2009). As environmental changes involve considerable externalities, regulations are fundamental in pushing the agricultural system in new directions (Elzen et al., 2014). Today, governments in Europe strongly encourage the seed industry to supply new seeds that favor sustainable crop systems. For instance, in 2011, the French government incorporated environmental criteria into its evaluation of new varieties as part of the tests for registering them in its official variety catalogue (Vialle, 2011). France is a leader in Europe for registering new varieties and this state-driven change may influence other European countries to follow suit. Moreover, the seed industry in France is composed of major firms who are based in France but operate on a European scale.

In order to transition to more sustainable agriculture, it is important to understand how the seed industry, in connection with other actors in the sociotechnical regime (cooperatives, technical and research institutes, etc.), is designing and improving varieties. The main aim of this study is to characterize which factors promote and hinder this sociotechnical seed regime in addressing environmental concerns. Although there are various models of ecological modernization of agriculture, here we analyze the conditions for producing and diffusing new varieties using Gliessman's agroecological paradigm (2015). We define new plant seeds that are more beneficial to agroecological crop systems as 'eco-innovation varieties' (EIV); with 'eco-innovation' referring to the environmental benefits derived from the functions or the properties of a new product (Carrillo-Hermosilla et al., 2010). The eco-innovative nature of a plant variety can be seen through various environmental benefits, both with crop systems and feed or food processing systems using those plants. Thus, we consider EIVs in light of the multiple environmental benefits they can provide throughout the entire agri-food industry.

This study builds on the literature on innovation processes and the transition to sustainable production models (Geels and Schott, 2007). Within innovation economics, the concept of 'eco-innovation' refers to how they can reduce negative environmental externalities (Rennings, 2000), while transition theories emphasize the importance of lock-in and breaking out of dominant regimes through innovation (Geels and Schot, 2004). However, few studies on eco-innovation have examined agriculture and, to our knowledge, there is no such study on the seed industry, even though genetics is a key means for transforming farming systems. The present study is thus original in combining theories on innovation process in order to understand the seed industry's ability to offer and distribute eco-innovation varietals.

The empirical findings in this study come from France, the main producer of seeds in Europe and home to major European and international seed companies. The species selected, sunflower, has eco-innovative potential due to its hardiness and low input requirements (nitrogen fertilizers, pesticides, water) and its usefulness in rotations (Christen and al., 1992). It thus offers an interesting case study for addressing these questions. Drawing on thirty interviews with leading European seed companies and other stakeholders in the sunflower industry conducted in France in 2015, this study reveals the main obstacles to greater sustainability as well as the factors that can encourage the industry's transformation.

The article is organized as follows. Section 2 presents the theoretical framework used to derive hypotheses about EIVs. Section 3 outlines the methodology for the interviews with actors in the sunflower seed sector. Section 4 details the organization involved in creating new plant varieties and discusses the results of the survey on the seed companies' capacity to propose EIVs for sunflower. The final section suggests ways to support the transition of the seed industry toward creating more EIVs.

2. Eco-innovation processes and varietal innovation

After reviewing the specificities of eco-innovation, we explain how to define eco-innovation varieties (2.1). We then present the main mechanisms of innovation processes identified in the literature that are particularly relevant to the present study. Among these, we focus first on firms' determinants (2.2) and then address the industry-wide dynamics involved in diffusing innovation (2.3).

2.1 Specificities of eco-innovation and the nature of EIVs

An eco-innovation is defined as a technical or organizational innovation that avoids or reduces negative environmental impacts (Horbach, 2008). These environmental benefits may arise during the production of a good or service as well as during use by the end customer. The main feature of an eco-innovation is that it generates a double externality: a diffusion of knowledge, which occurs with any innovation, and a positive externality for the environment (Rennings, 2000). Indeed, the economics of innovation hold that knowledge flows between organizations (knowledge spillovers), making knowledge a sort of public good that the innovating firm cannot appropriate exclusively. This knowledge externality is a major obstacle to innovation for companies, which can be overcome by incentives. The environmental externality of eco-innovations reinforces the need for public regulations in order to encourage companies to offer innovations with environmental benefits ("regulatory push/pull effect," Rennings, 2000); otherwise, such innovations would be underfunded (Bossle et al., 2016).

This double externality is particularly important in the case of EIVs and has broader ramifications than for the seed industry alone. First, issues of knowledge production and dissemination are particularly important in this sector due to intense R&D and the major role played by government policy in regulating intellectual property rights (Wright and Pardey, 2006). Europe offers a type of IP in which rights are protected through a Plant Breeder Rights Certificate (*Certificat d'Obtention Végétale (COV))*, which allows creation to be remunerated while leaving the resource freely accessible.[1] Second, EIVs refer to seeds whose characteristics help reduce the negative environmental externalities in agricultural production systems and, more broadly, in the crop's use by the downstream processing industry. Examining the environmental benefits throughout the entire chain thus reveals the mechanisms for diffusion and adoption by all actors, not only the seed companies but also farmers, farm advisory services, and downstream processing firms.

From an agroecological perspective, Gliessman (2015) shows that environmental benefits can be understood in terms of the level of transformation of the agricultural system sought. These levels of transition range from seeking greater efficiency in the conventional agricultural system (level 1), to practices of substitution (level 2), to redesigning the agroecosystem (level 3), up to the socio-economic transformation of the entire food system (levels 4 and 5). EIVs thus meet various environmental objectives at several levels of a system's transformation (see Table 1). For example, adapting the growth cycle of a variety to its environment will limit the

[1] This differs from patents in which the genetic resource becomes private property.

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inputs needed (level 1 efficiency), but also encourages including this variety in crop rotations as part of diversification (level 3 redesign). The goal is to better understand how the dominant seed regime helps transform the industry through investment, even up to the most radical innovations.[2]

Table 1. Examples of varietal eco-innovations for field crops

Environmental Improvement Characteristics	Goals for Varietal Selection
Reduce the use of synthetic insecticides, herbicides, and fungicides	Improve disease resistance Improve competitiveness with weeds
Reduce the use of mineral/artificial fertilizers (particularly nitrogen)	Improve the plant's capacity to absorb nitrogen Improve the efficiency of nitrogen use
Promote rotations and intercropping	Adapt the plant cycle to rotations Adapt the plants to intercrop them with pulses
Avoid erosion and loss of organic matter in soil	Improve the covering capacity of plants
Reduce plants need for water	Improve resistance to hydric stress Adapt the growth cycle (earliness)
Greening transformation processes Develop outlets for organic products	Improve the technical-functional properties of plants to make the processing industry eco-efficient

Source: Authors, following articles in Gasselin and Clément (2006)

Analyzing the production and diffusion of eco-innovations in the seed sector requires an analytical framework that examines the determinants of such innovation at both firm and industry levels.

2.2 Firms' determinants of eco-innovation varieties

The 'Regulatory/Technology/Market' Triptych

Early environmental economics research strongly oriented the study of firm behavior toward a model in which environmental innovation is triggered by regulation, often according to a 'stimuli-response' kind of thinking. Integrating regulation addresses the issue of eco-innovations' double externality. This complements the classical approach in innovation economics, which has primarily focused on: i) supply-side factors (technology push) mainly related to firms' R & D capacity and changes in technology; and ii) factors related to demand and competitive market pressures (market pull). Thus, Rennings' (2000, p. 326) 'Regulatory push-pull/Technology Push/Market Pull' triptych provides an analytical framework well-suited to understanding the determinants of environmental innovations.

In France, public-private collaboration has been the main driver of technological advances in seeds, as evidenced with sunflower (Vear, 2016). Beyond the technology push, consumer demands have also changed considerably since 1980 with a new demand for quality products (Esquinas-Alcázar, 2005). This demand-pull effect is increasingly oriented to environmental criteria with the growth in organic agriculture and, more generally, calls for reducing pesticides in farming and maintaining biodiversity. This orientation can be clearly seen in the French Ministry of Agriculture's projects on varietal innovation. In 2011, it added environmental characteristics to its eligibility criteria for registering new plant breeds in France's national seed catalog (VCUS test: Value for Cultivation and Use and Sustainability)

[2] Delonge et al. (2016) draws on Gliessman's categorisation (2015) to assess the USA's research efforts on the transition to sustainable agriculture. They found that the improved varieties contributed to levels 1 and 3 of agroecology, with a great majority of research funding granted to projects that reinforce the efficiency of conventional agriculture (level 1).

(Vialle, 2011), strengthening the regulatory push. Thus, like any innovation process, EIVs are subject to technological and demand factors whose influence is, in turn, strengthened by regulatory factors, since the double externalities of eco-innovations require strong public incentives.

This triptych is further reinforced by the Porter hypothesis, which postulates that eco-innovation can generate economic benefits by increasing the efficiency of processes such as reducing loss and waste (Ambec et al., 2013; Porter, 1991). The Porter hypothesis considers that environmental innovation is not only a cost for firms but also a source of economic profitability by generating innovative processes. Porter and van der Linde (1995) show that because of the imperfect information agents possess and their limited rationality, many profit opportunities are neglected, thereby preventing greater profitability. They found that pollution most often results from a waste of resources and that reducing waste - by adopting environmental innovations - can lead to lower production costs, increased efficiency in productivity, and new market opportunities. For the seed industry, these potential economic gains linked to eco-innovation are not only related to the seed production process but also to the use of seeds in crop systems and product transformation. Indeed, these stages are the ones most related to environmental externalities. Therefore, we must take into account the productivity gains associated with adopting EIVs *throughout* the agricultural and processing chains in order to motivate the seed sector to propose varietal eco-innovations. For example, reducing pesticides reduces operating costs for farmers, which may foster farmers' adoption of EIVs. Similarly, new seed properties that facilitate hulling can limit waste and reduce the energy needed for processing.

Hypothesis 1: The development of EIVs is influenced by regulation, advances in techniques for improving varieties, consumer demands for environmental protection, and the search for better economic performance.

Knowledge management and adopting environmental innovation

With environmental innovations, the existence of an 'environmental externality' increases the uncertainty of adoption and strengthens the role of innovation diffusion mechanisms (Carrillo-Hermosilla et al., 2010). Several authors highlight the role played by knowledge and learning processes in the mechanisms for diffusing and appropriating environmental innovations, such as Cowan and Gunby's (1996) work on farmers' practices in crop protection. The importance of organizational learning processes, and the related creation of new skills, shows that adopting new practices is complementary to adopting eco-innovations (Galliano and Nadel, 2015). This raises questions about the seed firms' capacity to establish an ensemble of mechanisms that provide information and support to actors for fostering the adoption of EIVs.

This led us to examine how seed companies and other actors in the sociotechnical regime support farmers' learning when adopting EIVs. Indeed, the benefits of an EIV are expressed when the cropping system, in which the new seed is used, increases positive environmental externalities such as greater crop biodiversity. An EIV's environmental benefit, therefore, is highly dependent on farming practices and, more broadly, the advisory services and knowledge disseminated to farmers (Labarthe, 2009). For example, releasing certain genetic materials can render an EIV ineffective if not done properly. Thus, we hypothesize that the diffusion of EIVs requires a support process for diffusing knowledge and for changing practices.

Hypothesis 2: The diffusion of EIVs requires a support process to promote the diffusion of knowledge and learning processes.

2.3 Industry-wide processes for designing and diffusing eco-innovation

The literature on innovation economics has largely shown the importance of the external environment in firms' innovation behaviors (Malerba, 2002; Geels 2004). Evolutionary approaches focus on the industry dynamics that shape innovation pathways. The innovation pathway of a business sector is characterized by an accumulation of incremental innovations that help reinforce an initially selected technology paradigm (e.g. Dosi and Nelson, 2010). This path dependency gradually contributes to the lock-in of a given "sociotechnical regime" due to the growing interdependence among actors (Geels and Schot 2007; Malerba, 2002). In agriculture, the socio-technical regime based on intensifying production using agrochemicals and genetic plant selection has gradually become locked-in, while its negative environmental externalities raise questions about its ability to evolve (Vanloqueren and Baret, 2009; Magrini et al., 2016). A paradigm shift such as agroecology is needed to develop more environmentally friendly agriculture and biodiversity (Levidow, 2015), in which new plant varieties are a means for fostering the development of greener pathways.

However, which seed industry actors are sufficiently attentive to regulatory developments, consumer demand, and technological advances to be able to offer EIVs? The MLP (Multi-Level Perspective) approach posits that the most radical innovations are created by small networks of actors outside the dominant regime and that the spread of radical innovations from niches is likely to cause the dominant regime to change more through a hybridization process (Geels, 2004). Other studies argue the contrary, that niches develop in isolation as a strategy of insularization (Vankeerberghen and Stassart, 2016), that is to say, in independence from the dominant regime in order to preserve the initial radical nature of their innovation. This dichotomy of industry innovations thus raises the question of whether the dominant regime, evolving through incremental adaptations, can coexist with more radical innovation niches, with both incorporating changes into the regulatory landscape. In fact, the radical niches seek an agroecological redesign of farming and food systems (Gliessman 2015).

These observations lead us to question the sources of innovation in the dominant seed industry as well as in innovation niches and to examine the relationships between them.

Hypothesis 3: As the seed industry system and innovation niches strongly differ in their sources of innovation, the dominant regime will have greater difficulty integrating the most radical EIVs.

3. Methods

After presenting the context of the French sunflower industry (2.1), we explain the methodology of the empirical study (2.2) and then the lifecycle for creating new varieties as seen from the results (2.3).

3.1 The Sunflower Industry in France

Although originally from America, today the bulk of sunflower production is concentrated around the Black Sea (Terres OléoPro, 2014). Russia and Ukraine alone produce 50% of the world's sunflower and the European Union, 20%. France's industry is known to be highly organized and has considerable private and public funding for research. Despite this international recognition, the French sunflower industry needs to remain competitive while the most profitable markets are in Eastern Europe and while taking into account new environmental issues involved with the agroecological transition (Vear, 2016).

Despite its genetic potential, sunflower has a productivity deficit compared with other crops, due to the fact that technical pathways were often not optimized resulting in poor health management of crops. To improve productivity, great hopes have been placed in genetics, notably on disease resistance (Vincourt, 2014). Genetic resistance has now been found for phoma, phomopsis, mildew, and broomrape, but the rapid evolution of pathogens requires continuous research. For broomrape, a highly invasive parasite, research has also focused on Herbicide Tolerant Varieties (HTVs) to enable the use of a post-emergent herbicide. However, while the genetic method of creating these varieties is under debate, their diffusion also raises the issue of the increased use of chemical intrants that would promote resistance to these products (Beckert et al., 2011).

3.2 The Survey

To better understand how new sunflower varieties are created and diffused, we conducted thirty semi-structured interviews in 2015 with a representative sample of actors from the dominant socio-technical regime seed industry in France (see Figure 1). With seed companies, we interviewed the heads of R&D at six global sunflower seed companies who work on seed selection in France.[3] In addition, sixteen interviews were conducted with people in professional, technical, and research organizations involved in selecting and diffusing sunflower varieties.[4] Finally, four cooperatives and four companies working in the first and second transformation of crops were interviewed, which are representative of the French sunflower sector.

The interviews were based on a common line of questioning to better understand the ways in which criteria were chosen for a new sunflower variety. After addressing the issues related to sunflower with the participants, the discussions focused on the choice of criteria related to productivity, disease resistance, adaptation to soil and climate conditions, and technical qualities such as oleic acid content. Genotype, environment, and crop management interactions (GEM) were also questioned (Andrianasolo et al., 2014). Finally, aspects related to the diffusion of new varieties and the impact of the regulation on plant breeding were discussed.

[3] All the large sunflower seed companies were interviewed with the exception of Pioneer (second in the industry).
[4] One of the heads of the *Réseau Semences Paysannes* [Farmers' seed Network] was interviewed. This group calls for an alternative pathway for genetic progress based on a 'population' selection approach adapted to local conditions.

Figure 1: Interviews for the Sunflower Case-Study

PROFESSIONNAL, TECHNICAL AND RESEARCH ORGANIZATIONS
GNIS/CTPS/GEVES/Terres Inovia/INRA/RSP — *16 interviews*

SEED COMPANIES — *6 interviews*

COOPERATIVES — *4 interviews*

DOWNSTREAM INDUSTRIES — *4 interviews*

GNIS: Groupement National Interprofessionnel des Semences et plants (French Association for Seeds and Seedling)

CTPS: Comité Technique Permanent de la Sélection (Technical Committee for Plant Breeding)

GEVES: Groupe d'Etude et de contrôle des Variétés Et des Semences (Variety and Seed Study and Control Group)

Terres Inovia (Technical Center for oilseed crops, grain legumes and industrial hemp)

INRA: Institut National de la Recherche Agronomique (French National Institute for Agricultural Research)

RSP : *Réseau Semences Paysannes* (Farmers' seed Network)

This group of questions was supplemented by specific questions depending on the type of actor. The seed company participants were asked about their motivations for prioritizing selection criteria and their international strategies. With actors in the French regulatory system (professional, technical, and research organizations), issues related to the registration process for the national catalog were explored, including the addition of a sustainability component to the VCU(S) trials. Finally, cooperatives and processing companies were asked about their role in diffusing new varieties.

4. Results and Discussion

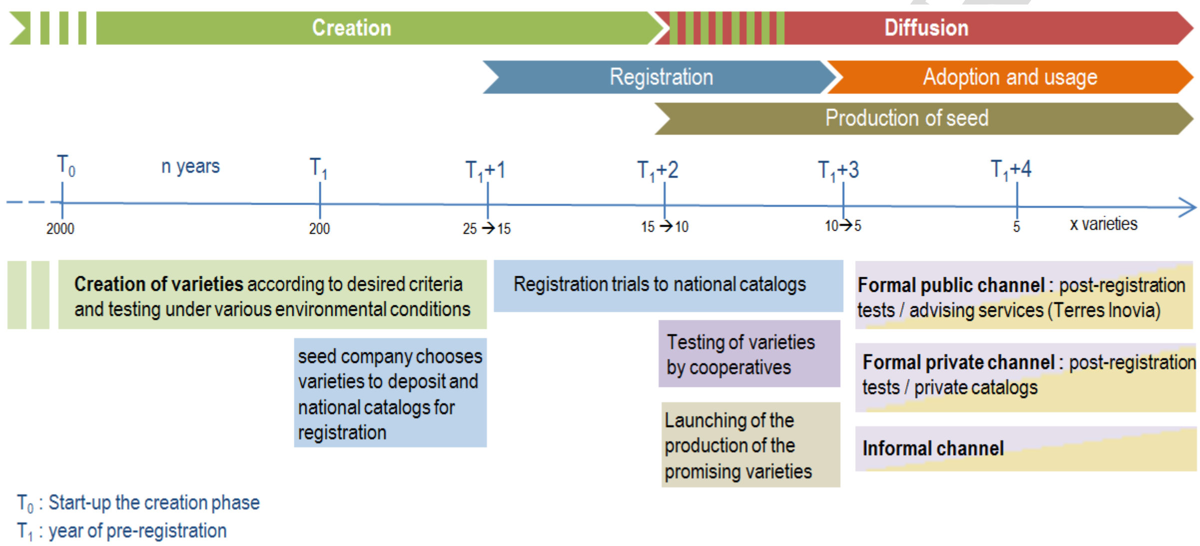
The findings highlight the key role of public regulations in creating new plant breeds. They also show that as seed companies look to improve economic performance, they implement international strategies to adapt to different national regulations. They concentrate their efforts on broad-spectrum EIVs with little attention to the more radical redesign of agri-food systems.

4.1 The Multiple Phases of Varietal Innovation

The results enabled us to compile a diagram of the process for creating and diffusing EIVs (see Figure 2). Understanding the issues involved at each step is essential for a better comprehension of the ways in which EIVs are diffused throughout the various industries. In fact, this process takes more than 10 years from the creation of varieties to their availability on the market (and only a few varieties ever reach the market). The key step in this process is registering the variety in at least one European national catalog as a prerequisite for being sold on the European market.

The length of the phase for creating a new varietal depends on the novelty of the desired criteria and the genetic resources of the seed company. During the creation phase, the performance of varieties needs to be tested under various environmental conditions, which gradually leads to reducing the number of selected varieties. This first stage can last from about four to seven years before the T1 year of pre-registration for the national catalog. During that T1 year, the seed company must decide which varieties it will submit for approval. Those varieties are then subjected to two years of registration trials. They must first pass the DUS (Distinct, Uniform and Stable) tests common to all catalogs, which establish intellectual property in the form of a *COV*, and then pass the VCU(S) tests (with sustainability added for the French catalog).

Figure 2: Developing a New Variety



Source: Authors based on the interviews conducted

The proposed varietal is evaluated on a group of experimental plots based on the list of reference criteria defined by the experts of the *Comité Technique Permanent de la Sélection* [Permanent Technical Plant Breeding Committee], made of up industry professionals and people from technical and research organizations. Thus, the VCU(S) criteria vary from one country to another. For sunflower in France, grain yield, oil content, and tolerance to major diseases are evaluated. The diffusion phase starts from the second year of the registration tests (T1 + 2). If the results from the first registration year are encouraging, cooperatives will ask to test these varieties in their own networks in order to be able to offer them to their members from the moment they are accepted in the catalog (year T1 + 3). At the same time, while taking the risk that the variety is refused registration, seed companies start producing seeds of promising varieties in year T1 + 2 in order to be able to sell them to distributors in T1 + 3. Post-registration tests are also done to refine the advising services for farmers and tailor that information to the varieties according to the planting zones and the health status of the various regions.

Being included in the national catalog of one European member state is required for selling a variety throughout Europe. The question thus arises as to the selection criteria for being registered in a given country's catalog. While France's catalog is recognized for its high standards on breed quality and the inclusion of environmental criteria, seed companies need to balance the cost of registration in a given country's catalog with the marketing prospects throughout Europe.

4.2 The 'Regulatory/Technology/Market' Triptych

Regulation: a Pivotal Moment in the Creation of an EIV

The results confirmed the strong influence of regulations on the creation of new varietals as well as the difficulties in integrating environmental criteria into regulation. Registering varieties in a catalog as a pre-condition for sale is a key element of the regulatory framework. While the rules for evaluating varieties are decided by the experts, the Ministry of Agriculture decides on the main orientations for breed creation and the final acceptance for registering a variety. The national catalog is, therefore, a major public policy tool for guiding the development of the French seed industry. However, while the choice of selection criteria orients genetic research, many actors interviewed both in organizations as well as seed companies pointed out a number of limitations to using the catalog to drive progress.

First, the unification of the European seed market enables various actors to circumvent French law, which is more stringent than its neighbors on selection criteria. Thus, which European national catalog to choose for a new breed is a strategic choice for seed companies. The interviews clearly illustrated that the French catalog was chosen after a cost/benefit analysis about whether to prefer stricter registration criteria with a more prestigious image (France) or in other countries whose registration is easier but with more difficulty marketing those varieties.

Secondly, interviews on the environmental component of EIVs revealed different views. Many participants feared that if France's catalog had too many restrictions, more seed companies would register in other countries and turn the French market into a niche market, which would discourage the seed industry in France. In addition, intensive crop management during evaluation tests has been debated. For some scientists and technical experts, such intensive farming does not promote the expression of hardy behavior by certain varieties, which would be better adapted to the extensive conditions in which sunflowers are often grown. This concurs with the position of distributors and seed companies, who have argued for developing varieties that would certainly have lower yields in intensive and favorable conditions (deep soils, etc.), but ultimately turn out to be better for farmers' less favorable plots. Almost all kinds of actors interviewed argued that production costs, including the use of intrants to achieve productivity, must also be taken into account by basing variety evaluation not on gross yield but on its economic and environmental efficiency. Yet adding this sustainability criterion (the S in VCUS) for sunflower would seem to pose a few problems. According to the interview data, current thinking is moving toward a wider range of experimental conditions for the registration tests so as to better promote the most hardy varieties and better test the stability of elite varieties. Thus, industry actors argue that sunflower, which has a low treatment frequency index (TFI) and needs little irrigation, is already adapted to sustainability demands. The limiting factor is the rather low productivity that farmers have to address without using additional chemical intrants.

Finally, the idea of more systemic regulation using selection criteria that take into account all a variety's effects on the cropping system (soil cover, nitrogen soil enrichment, pesticide use, etc.) also emerged from the interviews. However, participants wondered how regulatory authorities would be able to promote the development of EIVs. For example, adopting more systemic evaluation trials (assessing biotechnological, economic, and environmental aspects of new breeds) would be costly, and current budgets do not allow for multiplying test criteria and territories. Moreover, participants questioned the quality (including statistical) of the information that can be drawn from such systemic tests. However, according to the interview data, various solutions are currently being explored (such as registering populations of varieties, testing in low-intrant conditions, and including the GEM).

The Relationship between Economic and Environmental Performance

All seed companies agreed that both economic and environmental performance are essential to developing an EIV. This implies that the environmental criterion provides added-value for the seed company (Porter and van der Linde, 1995). However, the seed companies interviewed think about environment-economy interactions in terms of large European production areas. Pre-positioning in market strategies shows that a seed company constantly maintains a pool of varieties from which it can draw according to changes in production requirements and market demand. However, the high costs associated with plant breeding and seed production push seed companies to choose varieties with a broad-spectrum of characteristics (resistance to water stress, disease resistance to broomrape, etc.), which can then be sold throughout large growing areas. This way, they work on a continental scale, dividing sunflower cultivation areas into large soil and climate belts (from three to around ten for the companies surveyed). Thus, the plasticity of varieties is favored because companies are seeking economies of scale. Yet this kind of broad-spectrum EIV does not allow for a more systemic approach at the scale of the cropping system.

Thus, only one of the seed companies indicated that more systemic EIVs were a good idea for the future of genetic selection and a way to diversify the company's product range. This seed company, in fact, offers new plant varieties that offer both economic and environmental benefits at the crop system level, through improved interaction between the different crops in the rotation. Tests on this type of sunflower variety are underway and would allow for better soil cover and reduced disease pressure while promoting crop diversification. However, there have been few financial incentives supporting these more systemic EIVs. This result explains why the most radical changes in production systems (levels 2-5 in Gliessman, 2015) have hardly been taken into account by the dominant seed companies, who are mainly interested in increasing the efficiency of existing agricultural systems and downstream sectors (level 1).

The participants involved in diffusing EIVs (as well as the literature on sunflower) report an increasingly difficult agronomic context: greater disease pressure, more frequent summer droughts, and restrictions on irrigation and applying fertilizer, which genetics alone struggles to solve. Thus, the hardiness of varieties and their adaptation to the crop zone are marketing arguments for farmers' cooperatives, which encourage seed companies to integrate these aspects in their selection strategy. However, the search for economies of scale in seed distribution and crop monitoring means that cooperatives choose a limited number of broad-spectrum varieties. Finally, while food processing and transformation companies downstream are sensitive to sustainability issues, they do not prefer EIVs as they are more interested in new varieties that improve nutrition, for example oleic sunflower. While greater added-value for downstream industries may well motivate eco-innovation upstream, seed companies, as well as food processing companies, point to the difficulties of developing EIVs, as the selection work requires an investment of several years while downstream demands change over a much shorter time frame.

In conclusion, the results confirmed the importance of regulation in EIV dynamics, with particular emphasis on the dual nature of regulation with incentives and restrictions (DiMaggio and Powell, 1983). The interviews clearly showed that excessive regimentation at the French level would prove counter-productive due to the lack of regulatory harmonization at the European level. At the same time, the investment costs needed to create EIVs mean that seed companies look for economic performance by developing broad-spectrum varieties. Yet for the time being, the economic incentives are insufficient for them to offer more systemic EIVs that would truly take into account the GEM, although some criteria such as earliness have been widely researched. At this stage, therefore, it is difficult to validate the hypothesis that economic performance drives the development of EIVs and the expression of positive environmental externalities. This depends on the level of transformation of the agricultural system (in the sense of Gliessman, 2015) targeted with the EIV, which requires more detailed analysis of the expression of environmental benefits during the plant's use by all actors in the value chain.

4.3 The Need for Support to Diffuse Knowledge and Foster Learning

The literature highlights the need for eco-innovations to co-evolve with organizational practices (Milgrom and Roberts, 1995). According to the study participants, this was all the more true as an EIV seeks an environmental benefit whose expression will depend on adoption and usage conditions. Therefore, to diffuse the EIV and to provide information about their environmental benefits, it is important to identify the actors that influence farmers' adoption and use of varieties and what information and advice they give them. In this diffusion process, the seed companies first work with advisory organizations (cooperatives, Terres Inovia, etc.), which play an important role in supporting the diffusion of EIVs (see Figure 2). It was clear from the interviews that advice from the cooperative most strongly influenced farmers' adoption of varietals. Cooperatives create their seed catalogs based on agronomic data from their experimental networks on EIVs, as well as on economic criteria related to commercial agreements with seed companies. According to the cooperatives and seed companies interviewed, the need for economic profitability can lessen the desire to search for an agroecological optimum. The Terres Inovia participants strongly insisted on the need to educate all stakeholders about the importance of mastering the diffusion of EIVs; otherwise, their environmental and economic benefits would be compromised.

Several examples were cited in the interviews indicating that agricultural practices are a key factor for diffusing EIVs and that improper diffusion can end up canceling out the environmental benefits. Although the cooperatives and Terres Inovia offer crop guides, participants from these groups were dissatisfied because the farmers did not heed the advice offered. The farmers' lack of interest[5] for sunflower explains the problems using this varietal (particularly planting at dates that do not follow the recommendations, or using fungicides that do not take into account varietal resistance) and was mentioned by all the actors interviewed as a major obstacle to developing EIVs in the sunflower industry. The agricultural institutes and the cooperatives stated that the farmers' choice of sunflower varieties was not always fully thought out: farmers chose some varieties based on disease resistance or precocity, but which were not adapted to their crop zones.

Moreover, the actors interviewed noted that improperly managed and massive diffusion causes pressure on parasite species, which may then speed up parasites' attempts to circumvent that resistance. For sunflower, this has been observed with mildew resistance for twenty years (Ahmed et al., 2012). The risk of circumvention for broomrape resistance in Eastern Europe was also mentioned by an expert interviewed. This may have resulted from the seed companies' preference for the macro-regional scale, whereas local approaches are needed for a more finely tuned diffusion of the proposed varieties. As certain respondents indicated, focusing on a few broad-spectrum varieties enables them to extend the agronomic (in surface area) and economic (in market outlets) potential of EIVs; yet this causes a loss in genetic diversity which is conducive to the rapid diffusion of disease resistance. However, all actors interviewed pointed out that the process of registering in the French catalog was an important moment for

[5] Participants explained this lack of interest by various factors, such as the difficulties of sowing, the considerable harm caused by birds, and the poor revenue of this crop compared to cereals.

exchanging knowledge among actors about the needs for EIVs and for advising in order to promote practices that foster the expression of environmental benefits.

Complementarity between farmers' practices and organizational innovations in advising is therefore necessary for expressing the environmental externality of EIVs. The interviews confirmed the importance of diffusing knowledge that is adapted to the expression of the environmental benefit. However, this diffusion is currently insufficient because it has not been accompanied by a strong commitment by the seed firms to support practices that promote expressing the EIVs' environmental benefit. These results are convergent with those in the literature which find that the success of an EIV requires organizing at the system level to ensure appropriate conditions for maintaining environmental externalities from creation to dissemination (Costantini et al., 2016). This questions the ability of the current system to rethink its organization to promote EIVs.

4.4 Seed Industry Lock-in Hampers EIVs

The interviews confirm the literature on the interweaving of economic, technological and regulatory aspects that have contributed to the lock-in of a dominant socio-technical regime (Geels and Schot, 2007). While innovation niches do disrupt the dominant regime here, the latter does not seem able to integrate these innovations due to the antagonism of the paradigms used. For Bonneuil and Thomas (2009), niches result more from the actors rejecting "what [Bonneuil] calls a 'fixist (or static) paradigm of variety,' which considers a genetically homogeneous and stable plant variety as the most perfect form of variety."

The concentration of the seed sector supports the progressive locking-in of the dominant regime, fostered by the arrival of biotechnology (Bonneuil and Thomas, 2009). Indeed, because of the production and intellectual property costs they require, these technologies encourage the concentration of actors as well as sectors, and the integration of seed and agrochemical companies (Lemarié, 2013). In the sunflower seed sector, 70% of the European sunflower seed market is supplied by three seed companies: Syngenta, Pioneer, and Soltis, a subsidiary of Limagrain and Euralis. The seed companies interviewed said that the sunflower seed industry, like other field crops, is a highly competitive industry in an already fairly segmented market (disease resistance, linoleic / oleic, HTVs, precocity, etc.). Faced with the need for economies of scale, they are becoming more internationalized and their EIV strategies focus on macro-areas, which do not take into account local environmental issues. Research on broad-spectrum EIVs also results from the substantial R&D required for creating new breeds. Similarly, some actors interviewed involved in the CTPS recognize that regulatory criteria for catalog registration, based on stringent VCU(s) trials, do not support the creation of varieties that are adapted to specific use conditions, as noted by Vanloqueren and Baret (2008). Thus, seeking to develop a few broad-spectrum varietals goes against both the need to increase crop biodiversity and the management of disease resistance through crop diversification or allele selection.

This gap between the objectives of the dominant regime and society's environmental expectations has led to the opening of "windows of opportunity" for niches that are more responsive to local issues (Vanloqueren and Baret, 2008). It is expected that local actors are better able to manage diffusion and proper use of the varieties in a way that will maintain their environmental externalities. In the seed sector, these niches may seek to set themselves apart (especially regarding technology and intellectual property protection). Potential innovation niches are based on a variety of local innovations, grouped together in France in the *Réseau Semences Paysannes (RSP)*, for whom environmental criteria are intrinsic to a "population" approach to selection. This view is opposed to that of the dominant regime, both technologically and in terms of varietal diffusion, particularly for hybrid seeds that have to be purchased every year. Instead, these niches, as confirmed by the interview with RSP, propose a participatory and decentralized selection based on the evolving nature of plants. For the RSP network, a local systemic approach based on population varieties would enable better adaptation to climate change, in particular by mobilizing farmers' knowledge. This concurs with Bocci and Chable (2008)'s findings that selecting population varietals seeks to address the problems of the local adaptation of agricultural systems by drawing on local and often traditional knowledge. These differing views make it hard to combine the dominant regime with these innovation niches, as confirmed in the interviews. Instead, participants preferred a model of coexistence, which would require regulatory recognition of niches. This recognition is growing, as shown with the new *Semences et plants pour une agriculture durable* [Seeds and plants for sustainable agriculture] plan (MAAF, 2016).

Thus, despite the lock-in of the system and the lack of inclusive niches, the influence of the institutional landscape seems to push for a real change in the dominant seed industry regime.

We summarize the main results obtained and position them in relation to the agroecological perspective in Table 2, showing that the dominant regime is mainly focused on level 1 of efficiency.

Table 2. Synthesis of the main results

Hypotheses	Main results	Agroecological perspective
Influence of the Regulatory/ Technology/ Market triptych on EIVs	Registration of varieties is a key tool to develop EIVs but a need for regulatory harmonization at the European level. High investment in R & D orients EIV to broad spectrum. Economic incentives are insufficient to offer more systemic EIVs.	EIVs in the dominant regime concentrated mainly on level 1 of efficiency
Importance of support for diffusing knowledge and fostering learning	Broad-spectrum EIVs increase the risk of inappropriate use of the variety and question the organization and dissemination of advice associated with an EIV. Seed companies play a weak role in disseminating knowledge /practices for EIV benefits. The process of registering in the French catalogue is an important means for exchanging knowledge and advice on good practices.	Even for level 1 efficiency, knowledge diffusion with the relevant associated advice is needed to avoid improper farming practices.
Strong divergence in source innovation between niches and the dominant regime	Coexistence of a highly concentrated sector with lock-in and niches which have very different conceptions of varietal innovation. An institutional landscape that pushes for real change in the dominant seed industry regime.	The dominant regime focuses on level 1, while the niches emphasize a more systemic transformation of agriculture.

5. Conclusion

This paper analyses the conditions for creating and diffusing eco-innovation varietals in the sunflower industry. It also examines the processes that encourage or hamper the propensity of the seed sector to offer EIVs, that is, new varietals with agro-ecological properties. Drawing on the literature of the innovation economics, we defined a set of hypotheses about EIV determinants taking into account actors' behavior and diffusion dynamics within the industry. The empirical evidence comes from interviews with major seed companies and other actors in the sunflower industry in France, which enabled us to characterize the sociotechnical seed regime.

The results first show the importance of regulating EIV processes: the binding nature of regulation as well as the concertation between multiple scientific, technological, and economic actors. The study found that integrating environmental criteria in regulations was facilitated when those criteria also responded to basic market needs. More broadly, the results confirm that technological, regulatory, and market aspects interact, as highlighted in the literature on eco-innovations. However, the findings were more nuanced regarding the impact of economic performance on environmental performance. While economic performance improves by developing stable varieties for large crop zones, it is difficult to validate the hypothesis of a positive return on investment for a more localized and systemic approach to variety creation. Finally, farmers' practices and organizational innovations were found to be complementary in the EIV diffusion process. This finding raises questions about the ability of seed firms to invest in knowledge diffusion and in strengthening the learning needed for EIVs' potential to be expressed. In the case of sunflower, according to the participants interviewed, this is particularly important because a great deal of progress needs to be made on farmers' practices (longer rotations, disease management, etc.) to promote the environmental performance of new varietals.

At the industry level, two main findings emerged. First, the dominant socio-technical regime is influenced by the internationalization of the seed companies' strategies, which may make national regulations ineffective. Second, the dominant regime is generally locked-in and not very receptive to integrating the more local selection practices promoted by actors such as the *Réseau Semences Paysannes*. However, despite the lock-in of the system and the lack of niche integration, the change in the institutional landscape driven by society's new environmental expectations has opened the way for more sustainable regulations and practices. In addition to regulation, this evolution means that actors need to be supported through public policies to favor the diffusion process of EIVs and to ensure the expression of their environmental benefits.

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References

Ahmed S., Tourvieille de Labrouhe D., Delmotte F., 2012. Emerging virulence arising from hybridisation facilitated by multiple introductions of the sunflower downy mildew pathogen Plasmopara halstedii, *Fungal genetics and biology*. 49(10), 847-855.

Ambec S., Cohen M.A., Elgie S., Lanoie P., 2013. The Porter Hypothesis at 20: Can environmental regulation enhance innovation and competitiveness?. *Review of Environmental Economics and Policy*. 7(1), 2-22.

Andrianasolo F.N., Casadebaig P., Maza E., Champolivier L., Maury P., Debaeke P, 2014. Prediction of sunflower grain oil concentration as a function of variety, crop management and environment using statistical models, *European Journal of Agronomy*. 54, 84-96.

Beckert M., Dessaux Y., Charlier C., Darmency H., Richard C., Savini I., Tibi A. (eds), 2011. *Les variétés végétales tolérantes aux herbicides. Effets agronomiques, environnementaux, socio-économiques*. Expertise scientifique collective, rapport, CNRS-INRA (France).

Bocci R, Chable V., 2009. Peasant seeds in Europe: stakes and prospects, *Journal of Agriculture and Environment for International Development*. 103(1/2), 81-93.

Bonneuil C., Thomas F., 2009. *Gènes pouvoir profit : recherche publique et régimes de production des savoirs de Mendel aux OGM*. Versailles, Edition Quae.

Bossle M.B., Dutra de Barcellos M., Vieira L.M., Sauvée L., 2016. The drivers for adoption of eco-innovation. *Journal of Cleaner Production*. 113, 861–872.

Calderini D.F., Flaver A.A., 1998. Changes in yield stability in wheat during the 20th century, *Field crop research*. 57, 335-347.

Carrillo-Hermosilla J., del Río P., Könnölä T., 2010. Diversity of eco-innovations: Reflections from selected case studies. *Journal of Cleaner Production*. 18(10), 1073–1083.

Christen O., Sieling K., Hanus H., 1992. The effect of different preceding crops on the development, growth and yield of winter wheat, *European Journal of Agronomy*. 1(1), 21-28.

Costantini V., Crespi F., Marin G., Paglialunga E., 2016. Eco-innovation, sustainable supply chains and environmental performance in European industries. *Journal of Cleaner Production*. doi.org/10.1016/j.jclepro.2016.09.038

Cowan R., Gunby P., 1996. Sprayed to death: path dependence, lock-in and pest control strategies. The Economic Journal. 106, 521–542.

Delonge M.S., Miles A., Carlisle L., 2016. Investing in the transition to sustainable agriculture, *Environmental Science and Policy*. 55, 266-273.

DiMaggio, P., Powell, W., 1983. The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *American Sociological Review*. 380*48*(2), 147–160.

Dosi G., Nelson R.R., 2010. Technical change and industrial dynamics as evolutionary processes. In: B.H. Hall and N. Rosenberg (eds). *Handbook of the economics of innovation*, 1, Burlington: Academic Press, 51-128.

Elzen B., Barbier M., Cerf M., Grin J., 2012. Stimulating transitions towards sustainable farming systems. In *Farming Systems Research into the 21st century: The new dynamic*. Springer Netherlands, pp. 431-455.

Esquinas-Alcázar J., 2005. Protection crop genetic diversity for food security: political, ethical and technical challenges, *Nature*. 6, 946-953.

FAO, 2013. *Statistical yearbook, World food and agriculture*, Rome.

Fresco L.O., 2009. Challenges for food system adaptation today and tomorrow, *Environmental Science & Policy*. 12, 378-385.

Galliano D., Nadel S., 2015. Firm's eco-innovation performance and sectoral system of innovation: the case of the French industry. *Industry and Innovation*. 22, 467–495.

Gasselin P., Clément O. (coords.), 2006. *Quelles variétés et semences pour des agricultures paysannes durables?* Dossier de l'environnement de l'INRA. n°30, Paris.

Geels F.W., 2004. From sectoral systems of innovation to socio-technical systems - Insights about dynamics and change from sociology and institutional theory, *Research Policy*. 33, 897-920.

Geels F.W., Schot J., 2007. Typology of sociotechnical transition pathways. *Research Policy*. 36, 399-417.

Gliessman S.R., 2015. *Agroecology: The ecology of sustainable food systems*, Third edition, CRC Press

Horbach J., 2008. Determinants of Environmental Innovations, New Evidence From German Panel Data Sources. *Research Policy*. 37, 163-173.

Kastler G., 2006. Les semences paysannes : situation actuelle, difficultés techniques, besoin d'un cadre juridique. *Dossier de l'environnement de l'INRA*. 30, 53-56.

Labarthe P., 2009. Extension services and multifunctional agriculture, Lessons learnt from the French and Dutch contexts and approaches. *Journal of Environmental Management*. 90(2), 193-202.

Lemarié S., 2003. Evolution des structures industrielles et de la concurrence dans le secteur des semences et des pesticides. *Economie rurale*. 277-278, 167-182.

Levidow L., 2015. European transitions towards a corporate-environmental food regime: Agroecological incorporation or contestation? *Journal of Rural Studies*. 40, 76-89.

MAAF, 2016. *Semences et plants pour une agriculture durable*, Paris.

Magrini M.-B., Anton M., Cholez C., Corre-Hellou G., Duc G., Jeuffroy M.-H., Meynard J.M., Pelzer E., Voisin A.-S., Walrand S., 2016. Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system, *Ecological Economics*. 126, 152-162.

Malerba F., 2002. Sectoral systems of innovation and production. *Research Policy*. 31, 247–264.

Milgrom P., Roberts J., 1995. Complementarities and fit strategy, structure, and organizational change in manufacturing. *Journal of Accounting and Economics*. 19(2-3), 179–208.

Porter M., 1991. America's green strategy. *Scientific American*. *264*(4).

Porter M., van der Linde C., 1995. Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives*. 9, 97–118.

Rennings K., 2000. Redefining innovation - eco-innovation and the contribution from ecological economics. *Ecological Economics*. 32, 319–332.

Terres OléoPro, 2014. *Statistiques des oléagineux huiles et protéines végétales 2013-2014*.[online] (accessed 15 october 2016)

Vankeerberghen A., Stassart P.M., 2016. The transition to conservation agriculture: an insularization process towards sustainability. *International Journal of Agricultural Sustainability*. 14(4), 392-407.

Vanloqueren G., Baret P.V, 2008. Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural "lock-in"case study. *Ecological Economics*. 66(2), 436–446.

Vanloqueren G., Baret P.V., 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. *Research Policy*. 38(6), 971-983.

Vear F., 2016. Changes in sunflower breeding over the last fifty years, *OCL*. 23(2), D202

Vialle P., 2011. *Semence et Agriculture Durable*, rapport pour le MAAPRAT, Paris.

Vincourt P., 2014. Research fields, challenges and opportunities in European oilseed crops breeding, *OCL*. 21(6), D602

Wright B.D., Pardey P.G., 2006. The evolving rights to intellectual property protection in the agricultural biosciences, *International Journal of Technology and Globalisation*. 2(1/2), 12-29.