



Pulses for Sustainability: Breaking Agriculture and Food Sectors Out of Lock-In

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Crop diversification can improve the sustainability of Western agriculture. In particular, pulses are crops that can help both agriculture and the food industry become more ecological, as they reduce greenhouse gas emissions and help reduce animal-based consumption. Today, however, the development of these crops in Europe has been hindered due to lock-in, since major crops have been co-developed to a greater extent in farming and food systems. After briefly reviewing the major mechanisms that lead to this lock-in, this article adopts a co-evolution framework to address the interconnected transition of agriculture and food systems. We explore how current societal trends in the agrifood system offer new opportunities for pulses, and how simultaneous changes both in production and consumption can facilitate this dual transition. Drawing on insights from the literature and interviews with stakeholders in France—taken here as examples—we argue that to develop pulses, strong support is required from public institutions to coordinate and guide the multiple actors involved in the same direction.

Keywords: agrifood transition, lock-in, innovation, cropping system, consumer, food behavior, pulses

INTRODUCTION

Over the last several decades, Western agrifood systems have created externalities affecting the ecosystem and human health (IPES-Food, 2017). These externalities have been caused by the lack of crop diversity and by intensive livestock production systems (e.g., Lang and Barling, 2013; Tilman and Clark, 2014, 2015; Weiner, 2017). These systems were shaped by consumer preferences and path-dependency mechanisms that led to the lock-in of agricultural and food systems (Vanloqueren and Baret, 2009; Meynard et al., 2013). In particular, cereals' increasing returns to adoption marginalized minor crops such as pulses despite their environmental and nutritional benefits (Magrini et al., 2016).

First, for agricultural systems, cereals are the major crops in European farming systems (around 50% of EU-28 arable cropland), whereas pulses account for around 2% (Eurostat, 2016). Europe is the top producer of wheat in the world, with France and Germany accounting for almost 50%. Increasing competitiveness between major species, such as wheat, and minor crops, like pulses, has pushed farmers to exclude the latter from cropping systems (Magrini et al., 2016; Zander et al., 2016). This trend has been also reinforced by scientific research, in which pulses have received less funding than major crops. Sonnino (2017) found that only about 1% of agricultural research has

focused on pulses. This strong crop specialization has occurred at the expense of agro-ecological principles such as greater crop diversity and especially nitrogen fixing-plants, which enable a reduction in synthetic inputs (Altieri, 1999; Stoate et al., 2009; Therond et al., 2017; Watson et al., 2017). More broadly, this situation also affects worldwide land use: in 2012, pulse crops occupied <1 million square kilometers, whereas cereals, 7 million, and oil crops nearly 3 million (Jahn et al., 2015).

Second, cereals also largely dominate in the food and feed habits of Western countries: in Europe, wheat consumption continues to increase with 45% of wheat used for feed. In Europe (like in other western countries such as the US), the consumption of animal-protein food is greater than what nutritional guidelines recommend (Ranganathan et al., 2016). For healthier diets, nutritionists advise eating more plant-based proteins, and pulses have the most protein of any plants (Chardigny and Walrand, 2016; Henschion et al., 2017). Pulses also contribute to better health as they reduce diabetes and cholesterolemia (Dahl et al., 2012; Sirtori et al., 2012).

Therefore, pulses could significantly increase the sustainability of our diets (e.g., Ebert, 2014; Jallinoja et al., 2016) as put forward in the FAO's International Year of Pulses in 2016¹. But faced with lock-in, what changes are needed in agricultural and food systems for pulses to develop? To break out of socio-technical lock-in and move toward more diversified agriculture and consumption of pulse-based foods, radical innovations must occur both downstream and upstream of agrifood supply chains (Voisin et al., 2014; Kuokkanen et al., 2016; Meynard et al., 2016). Such a transition calls for “a dual process that comprises both an upstream and downstream transition. The challenge, therefore, is to understand how these two transitions can be triggered simultaneously in order to coevolve toward a new sustainable agrifood system. A major driver of this transition lies in the greater diversification of plant resources in upstream production systems, which challenges the capacity of the downstream supply chain to promote a greater diversity of plant species in agrofood goods” (Elzen and Barbier, 2012).

Thus, the purpose of this article is to examine whether current pulse innovations in cropping and food systems favor such an alignment between the downstream and the upstream of pulse supply chains. In so doing, we draw on sustainability transition theories that have been developed in the social sciences since the 2000s. These theories highlight the complexity of structural change or “transition” (e.g., Geels, 2004; Foxon, 2011) that result in a coevolution of multiple components of production-consumption system. This study therefore required adopting an interdisciplinary heuristic framework in order to explain how alignments between technologies, markets, and regulation occur.

The aim of this article is to empower the reader with insights and understanding of the underlying processes that influence pulse development. This collective reflection is based on a review of the scientific and gray literature and analyses of stakeholders' opinions gathered primarily through a set of interviews. These were performed as part of a larger, interdisciplinary research

project involving French experts who are studying the factors that promote and hinder the development of pulses. This article does not, therefore, report the results of this larger project, but uses them to construct an analysis of the current situation and to suggest some solutions that may help overcome the situation. We adopted a co-evolution framework to consider simultaneously pulses' primary production (here termed upstream) and their processing and consumption (downstream). This enabled us to select the main characteristics of innovation paths on pulses that we found to be fundamental for triggering new actions and breaking out of lock-in. In that sense, this paper is a comprehensive overview of the main challenges facing the future of pulses and as such, also calls for complementary research and actions.

Moreover, while most transition research is based on historical case studies and has thus been conducted *ex-post*, the originality of this article is in examining the “transition in the making” (Elzen et al., 2011, p. 263): “We call these ‘transitions in the making, not because we are able to foresee this will lead to a transition, but because new developments are started...which may (or may not) lead to a transition.’” Thus, this article enables practitioners to conceptualize the complex and systemic policies needed to escape lock-in.

The focus of this study is to analyze some of the “new developments” in pulses relative to the agrifood sustainability transition. By exploring several innovations both upstream in agricultural systems and downstream in food systems, we examine whether those changes are sufficient to start a transition and then we discuss how policies could reinforced the process. Both our reflections and the stakeholders draw primarily on the case in France. The situation that prevails in that country, which is the top European cereal producer and one of the lowest consumers of pulses, could be more largely applied for Europe.

The first section sets out the theoretical framework for examining the coevolution of agricultural and food systems, identifying current trends that may support the transition toward more pulses. Two areas of innovations are studied: (i) upstream, agronomic practices, primarily fertilization, and valuation of ecosystem services (section Transitions of the Agrifood System: Theoretical Insights and Context); and (ii) downstream, promoting pulses in diets mainly by improving the balance between animal and vegetable proteins through several innovation pathways (section Materials and Objectives). In conclusion, to induce sustainable change, we argue that it is crucial for public agencies to adopt a coevolution view in order to promote simultaneous changes both downstream and upstream of the agrifood system.

TRANSITIONS OF THE AGRIFOOD SYSTEM: THEORETICAL INSIGHTS AND CONTEXT

Drawing on evolutionary economics, several authors have noted that a coherent organization of agricultural production and food consumption has progressively been woven and locked-in around a technological paradigm based on agro-chemicals

¹Pulses are defined as the dry seeds of leguminous crops that are not used for oil extraction, such as dried beans, lentils and peas, excluding soy: www.fao.org/pulses-2016/en/ (Accessed October 30, 2017).

(Cowan and Gunby, 1996; Wolff and Recke, 2000; Wilson and Tisdell, 2001; Chhetri et al., 2010). This lock-in favors major crops such as wheat and soya (Vanloqueren and Baret, 2008, 2009), marginalizing pulses (Magrini et al., 2016). As a result, today the only way that the agrifood system can break out of this lock-in is if all the inter-connected sectors that shape the agrifood system (such as those which breed seeds, produce fertilizers and pesticides, crop advisory services and harvest collecting, food processing, and retail) change together to favor a more sustainable system such as one with more pulses. The remaining question is how can such a transition in the agrifood system start? To answer that question, we first need to understand the mechanisms that led to lock-in, that is, we need to understand how a technology (i.e., a production method) gradually “dominates” other alternatives by being increasingly adopted (section Lock-In and Increasing Returns to Adoption (IRA) Mechanisms in the Agrifood Sector). Then, we explain the process through which the subsystems shaping the agrifood system co-evolved (section A Co-evolution Approach to Understanding How Agrifood Change Can Occur); within this framework, we need to analyze how current changes in several parts of the system could affect this coevolution. Finally, we suggest how public policy could foster those changes (section Current Societal Trends in the Coevolution of Agricultural and Food Systems).

Lock-In and Increasing Returns to Adoption (IRA) Mechanisms in the Agrifood Sector

The founding assumption of the IRA theory is that technology is not necessarily chosen initially because it was the best, but it has become the best because it was initially chosen and that choice was reinforced over time. By being chosen first, investments are then concentrated on the first choice, increasing the performance of the dominant technology compared to alternatives that therefore receive less investment. Several contingent factors explain how a first choice occurs, and starting from this first choice, self-reinforcing mechanisms (Arthur, 1989, 1994) make alternatives increasingly difficult to adopt. In the French agrifood system, the historical choice of fertilized cereals and imports of soy from America after World War II resulted in a lock-in situation marginalizing pulses. These mechanisms are analyzed in depth in Magrini et al. (2016), highlighting the role of social interactions and markets. Here, we recall the main IRA mechanisms:

- i) Learning by using: a technology’s productive performance increases with users’ experience.

The learning by doing on cereals and mineral fertilization has led to favoring those practices, all the more so since cereals’ yield has greatly improved.

- ii) Network externalities: the more adopters there are, the better it is for other users to adopt that technology to take advantage of additional products and services that are developed to be compatible with the dominant technology.

Upstream, this meant the continuous genetic adaptation of wheat to increase the dose of nitrogen fertilization and the development of phytosanitary products for cereals. Downstream, this led to the development of agri-food products based on cereals. Whereas for minor crops, there is no development of phytosanitary products and few market opportunities in the food industry.

- iii) Scale economies and economies from learning by doing: the unit cost of production decreases over time as a result of volume and improved technology, making the technology even more attractive.

Upstream, since R&D both for breeding and phytosanitary products (registration, distribution) is generally plant-specific, investments have been made with the goal of producing substantial production volumes to make that investment profitable. On the farm side, the process of specialization is explained by the greater ease of acquiring technical control, the amortization of agricultural equipment, and the organization of work with some crops in which the farmer specializes. The adoption of major crops has thus been reinforced to the detriment of other species such as pulses, whose yields are lower and/or more variable, in particular because technical advice and varietal selection are less advanced. Downstream, organizations for storage, processing, and selling the crops follow the same rationale: specializing the business in a few dominant species led to economies of scale, thereby reducing the marginal cost of use for a given species.

- iv) Informational increasing returns: the more a technology is used, the more it is known and understood, thereby encouraging other users to adopt it.

Upstream, this means more advice favoring mineral fertilization and cereal cultivation (by public and private technical institutes, cooperatives, the trade press, etc.), with little advice focused on managing the nitrogen supply ecosystem service of legumes. Downstream, the increased consumption of cereal-based products has led to increased knowledge on the technical-functional properties of cereals within the agrifood industry.

- v) Technological interrelatedness: other technologies and production standards are established in line with the dominant technology.

The industrialization of agri-food chains has led to a growing number of production standards that contribute to locking practices. For example, requiring high level processing qualities (protein rates for both bakery and pasta) hinders the adoption of innovative farming systems that use less nitrogen fertilizers.

Thus, it is clear why IRA are termed “increasing”: the greater the number of users, the greater the value for these users at the expense of alternatives. Therefore, even though today it is widely recognized that greater crop diversity would provide a broader range of ecological services through their functional properties and would therefore enable a significant reduction in synthetic inputs (e.g., Therond et al., 2017), it is hard to break out of the path chosen previously, that led to crop specialization,

a considerable use of chemicals, and greater environmental problems.

A Co-evolution Approach to Understanding How Agrifood Change Can Occur

The sustainability transition literature starts with this finding: the systems fulfilling societal functions such as food supply are locked-in. To highlight how change could occur, this literature argues for the coevolution in several areas such as social, political, economic, and technical ones (Elzen et al., 2011). This body of work highlighting the complexity of transition provides a new analytical perspective “particularly relevant for addressing environmental and sustainability challenges” (Foxon et al., 2013, p. 190). While the energy and transportation sectors have been largely analyzed with this framework, little work has been done on agrifood systems (Markard et al., 2012; Touzard et al., 2015). Several authors stress the need to consider agriculture and food as closely linked, yet few studies explicitly tackle the joint transition of agriculture and food systems (Francis et al., 2003; Marsden, 2012; Kuokkanen et al., 2016; Meynard et al., 2016).

Indeed, analyzing the entire agrifood system and the interactions between its components is very complex. One way to tackle this transition is to consider it as a dual process comprising both an *upstream* and a *downstream* transition. Then, the “transition of the agrifood system” can be viewed as a dual transition implying simultaneous changes in both agriculture and food systems. For the present analysis, we drew on Foxon’s framework (2011) that identifies complex interactions between five main components (Figure 1):

- *Institutions (I)* denote the set of social rules (North, 2003). The institutional environment refers to all collective rules of action (political, social, legal), such as agricultural trade agreements, environmental protection policies, and standards such as food consumer standards (Allaire, 2010). These rules are conveyed through explicit as well as tacit norms. Institutional arrangements refer to that ways that agents organize economic transactions within these rules (Laperche, 2012).
- *Technologies (T)* refer to technological processes and practices of a given type of production used by firms, including scientific knowledge.
- *Business activity (B)* of firms means the economic strategy for producing goods and services that meet the expectations of *users (U)* in accordance with the other system components.
- All these choices interact with or affect *ecosystems (E)*, understood as the ensemble of all natural resources (water, air, soil, biodiversity, etc.), which themselves influence firms’ production capacity, particularly as regards food products.

The interactions among those sub-systems are too numerous to be explained in detail here. However, we should note that the environment influences technical choices as well as the choices of businesses and users, and is increasingly taken into account by institutions regulating stakeholders’ actions (Rennings, 2000). Aligning changes between these sub-systems is necessary to break out of lock-in.

As we consider these two systems in a dual transition, we expanded Foxon’s diagram (Figure 2) to include the upstream

and downstream of the agrifood system through the supply chain. Thus, our approach is similar to Kuokkanen et al. (2016), who divide the food system transition into three co-evolving dimensions: production, institution, and supply chains. Cropping systems are combinations of agricultural practices depending of several inputs processors (seeds, phytosanitary products), including crop rotation, variety, soil tillage, fertilization, crop protection, irrigation for arable crops; whereas the processing of harvested crops are defined by other technical processes. They are strongly connected: for example, grain qualities must be adapted to food processing requirements (Meynard et al., 2016). In another example, new consumer preferences may lead the upstream of the supply chain to change cropping systems that will have in turn affects on ecosystems, or more precisely here agroecosystems.

Thus, the challenge is to understand how changes can be triggered simultaneously in order to coevolve toward a new sustainable agrifood system. We detail below the main current trends paving the way for a transition to diversified cropping systems with pulses as well as food uses for those crops.

Current Societal Trends in the Coevolution of Agricultural and Food Systems

To increase interest for pulses both upstream and downstream, the agrifood transition could be linked with other major transitions (Figure 3):

- The *energy transition*: the long-term depletion of fossil-fuel resources affects the production of mineral fertilizers. The increase in prices of inputs may reduce the gap in profit margins between protein-rich pulses and cereals in the coming years, as high European yields for cereals depend strongly on the use of large amounts of fertilizer (Magrini et al., 2016). Yet up to now, the increasing price of cereals has limited this trade-off opportunity² (Loyce et al., 2012).
- The *ecological transition* is related to the *energy transition*. It refers to the challenge to develop natural-resource-based systems to reduce the negative externalities from synthetic-input-based ones (Garnett, 2013). For agriculture, this *agro-ecological transition* (Horlings and Marsden, 2011; Therond et al., 2017) aims at reducing the use of chemicals to preserve biodiversity and public health. One challenge is to reduce the use of mineral fertilizers whose production, transport, and use significantly contribute to greenhouse gas emissions (Lassaletta et al., 2014), which in turn drive climate change. This challenge calls for increased use of pulses in cropping systems, as they do not need nitrogen

²Loyce et al. (2012) have shown that with lower global wheat prices in 1990s and early 2000s, low-input crop management for lower N input systems were more profitable. But in the context of very high wheat prices (as at the end of the 2000s) “high-input systems making use of high-yielding cultivars are currently more profitable” (p. 174). The authors concluded that the tradeoff between profitability and environmental benefits is very sensitive to grain and oil prices. There is less dependence on oil prices, however, because, according to the authors’ calculations, the elasticity between the price of nitrogen fertilizer and oil is 0.55 (i.e., an increase of 55% in N fertilizer costs for a 100% increase in fuel costs, p. 170). Thus, although production with intensive synthetic inputs has clear energy and environmental disadvantages, the profitability of this high-input system depends mainly on a high wheat grain price.

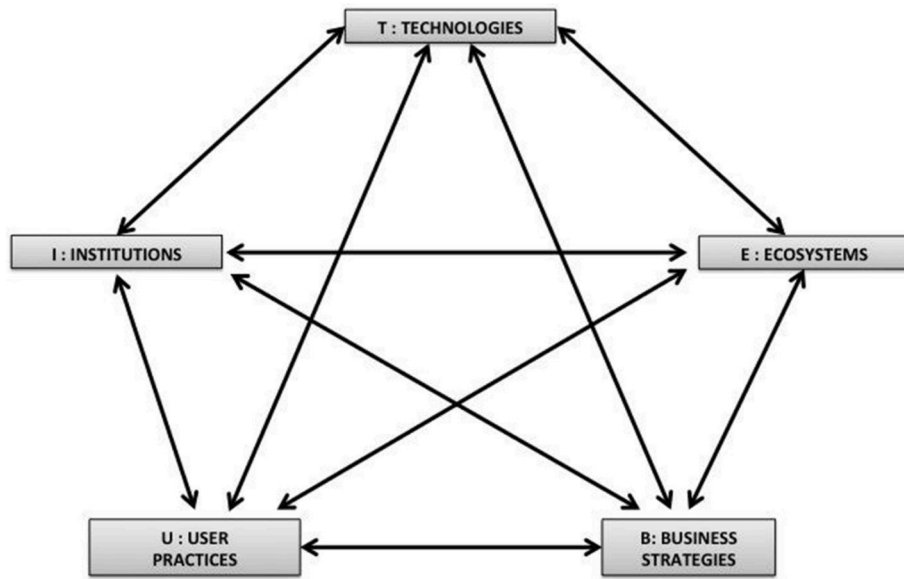


FIGURE 1 | Coevolutionary framework (Foxon, 2011).

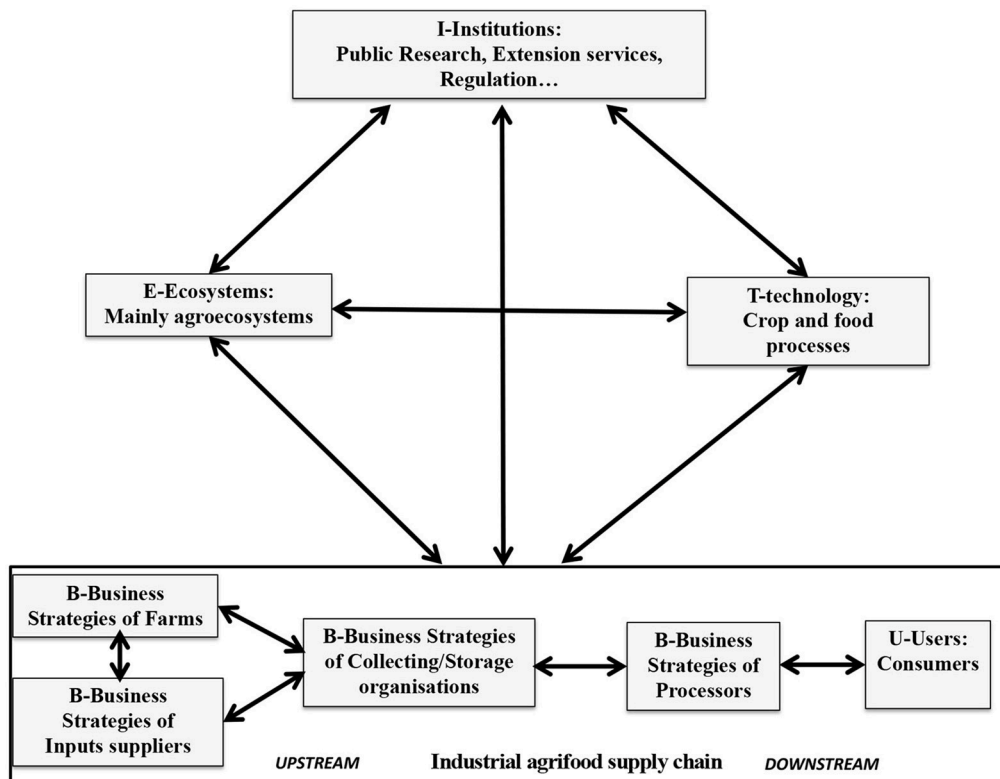


FIGURE 2 | A coevolutionary framework for conceptualizing the transition of the agrifood system.

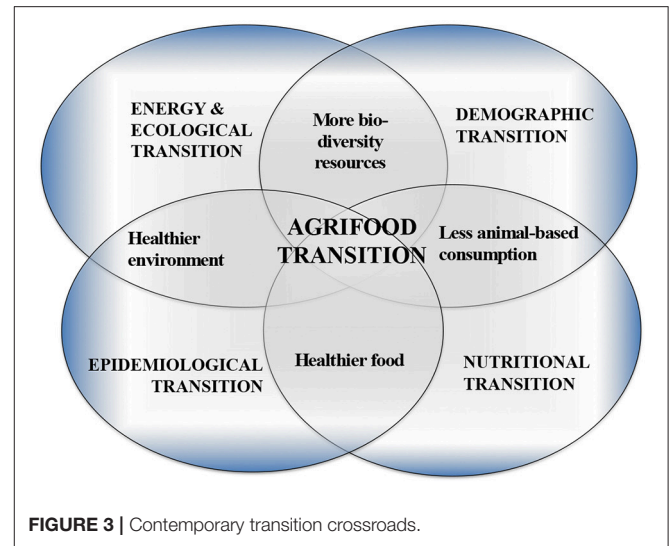
fertilizers and also reduce the fertilizer requirements of the following crop (Nemecek et al., 2015). Greater crop diversity in cereal-based cropping systems also helps reduce pesticide

use (Weiner, 2017). Crop diversity and legumes also affect soil fertility (Gogoi et al., 2018). Finally, as nearly half of cereal production is used for animal feed, less animal-based, and

more pulse-based diets have lower greenhouse gas emissions and land use (Friel et al., 2009; Scarborough et al., 2014; Hallström et al., 2015; de Boer and Aiking, 2018).

- The *demographic transition*: The world's growing population (from 7 billion today to over 9 billion people in 2050) will increase food demand (by 50% from 2013–2050, FAO estimates). The lack of additional arable land and increasing farming productivity and yields are needed to meet food security objectives. But this increase in yields must be done without expanding the agricultural frontier at the expenses of natural resources, and be tackled differently according to the yield gaps observed around the world. For the most intensive cropping systems, “upper yield plateaus” have been observed (Grassini et al., 2013; Tilman and Clark, 2015) for wheat in northwest Europe and maize in southern Europe. This is partly due to shorter crop rotations in agriculture, meaning major crops are more frequently cultivated on the same land thereby reducing some positive agronomic services that could otherwise be provided by crop diversification (Benett et al., 2012; Weiner, 2017). Crop diversification with legumes is thus advanced as a more comprehensive approach to lowering yield variability and improving the resilience of cropping systems, especially for lowering the inputs needed (Bedoussac et al., 2015; Cernay et al., 2018). While increasing yields remains essential in some parts in the world, and given that the global transition calls for fewer synthetic inputs, other solutions are needed to reach food security. One such solution would be greater direct consumption of plant-based foods, thereby reducing land needs for feed, which could be allocated to producing more plant-based food (Nijdam et al., 2012; Garnett, 2013; Westhoek et al., 2014; Henschon et al., 2017).
- The *epidemiological transition*: reducing infectious diseases has given way to an increase in non-communicable diseases (termed chronic or diseases of modern civilization) such as obesity and cardiovascular disease: “Research anticipates that global rates of diet-related diseases will continue to increase as diets shift toward increased calorie, empty calorie, and meat consumption” (Tilman and Clark, 2015, p. 16). This raises the question of changing eating habits (Auestad and Fulgoni, 2015) to favor healthier foods such as pulses (Curran, 2012; Dahl et al., 2012; Mudryj et al., 2014; Havemeier et al., 2017).
- The previous two transitions are related to the *nutritional transition*: Western diets over the past century have increased consumption of animal products. Yet plant-protein diets provide a cheaper protein supply and require less energy to produce. In addition, of all protein-rich plants, legumes are the ones whose nutrition profile best complements that of cereals (Chardigny and Walrand, 2016). Finally, as consumers are also increasingly concerned about ethics and animal well-being, these aspects may signal a major dietary change in the years to come (Clonan et al., 2015; de Boer and Aiking, 2018).

Pulses can help address some of the issues raised by these transitions. What are the current innovation paths of pulses? Have any changes already begun on the components of the system, and are they sufficient to promote the development of pulses both upstream and downstream of these systems?



MATERIALS AND OBJECTIVES

Our objective here is to map and to analyze several main innovation paths that are currently shaping the pulse sector. We draw on various sources in order to form a comprehensive and synthetic analysis of the main issues in pulse development, with particular focus on the French sector as an example. This analysis is based on:

- Research on pulses;
- Open-ended interviews among representative stakeholders of the French agrifood sector, such as agricultural cooperatives, food processing firms, and retailers. **Table 1** details the various types of organizations that were interviewed over the three last years as part of several other studies, amounting to around 50 interviews. Most of these interviews were conducted for specific research on one topic in the development of pulses. The objective here is not to present the detailed methodology and results from these interviews, but rather to sum-up their main insights (for more details, see the relevant publications. The generic open-ended guidelines for these interviews are given in the **Appendix**).
- Technical and economic reports from French research institutes such as INRA (the French National Institute of Agricultural Research), ANSES (French Agency for Food, Environmental and Occupational Health & Safety), agricultural extension services, industry organizations, and the Ministries of Agriculture and Food;
- Other discussions were also conducted during specific professional meetings (several authors of this paper also serve as experts for the institutions mentioned), and academic seminars and conferences. These formal and informal exchanges between researchers and stakeholders enabled us to better define the main issues. In particular, we also drew on information from several workshops organized at the end of 2016 on various pulse development topics. Those workshops

TABLE 1 | Main types of information provided by different stakeholders.

Category	Type of organization	Name	Open-ended interviews/discussions conducted between 2013 and 2016
Institution	Public Agency	ANSES (French Agency for Food, Environmental, and Occupational Health & Safety)	Regular discussions 3 to 4 per year
Institution	Agricultural extension services	Terres Inovia (Unip before 2015) Agence Bio (the French organic agriculture agency) CER (Accounting agency for farmers)	Regular discussions 3 to 4 per year
Institution	Government	Ministry of Agriculture and Food	Regular discussions 1 to 2 per year
Institution	Industry Organizations	Terres Univia ANIA (agrifood manufacturing), GEV (French Industrial Group on plant-based proteins), FNLS (French Pulse Producers and Retailers Organization)	Regular discussions 3 to 4 per year
Institution	Association	French Vegetarian Association	1 open-ended interview
Upstream firm	Farms	Open-ended interviews of 143 farms in France from three regions (north, west, and south)	A study on obstacles and drivers for cultivating pulses in 2015 (more details in Nguyen et al., 2016)
Upstream firm	Agricultural cooperatives	The 20 largest agricultural cooperatives in France (Top20) Small cooperatives (<500 Ktons harvested) such as Qualisol, Coopérative de Creully	A study among the Top20 was realized in 2015 (more details in Cholez et al., 2017)
Downstream Firm	Agrifood firms	Soufflet, Roquette, Sabarot, Panzani, Barilla, Tipiak, Nutrion and Santé, Nutrinat	1 to 2 open-ended interviews with each firm
Downstream Firm	Catering food suppliers	Sodexo (international company), Récapé (French small-sized company in southern France)	2 open-ended interviews
Seminar, Congress	Title	Organized by	Place, date, number of participants
French Seminar	Pulses in food ("Les légumineuses à graines en alimentation humaine")	INRA https://www6.inra.fr/groupe-filiere-filiere-vegetales/Filiere-Legumineuses/Actualites-Evenements-du-groupe/Evenements-passees/Rencontres-2014/Seminaire-Legumineuses-a-graine-en-alimentation-humaine	Paris, France, October 2014, 130
French Congress	The first French meeting on legumes RFL1 ("Rencontres francophones sur les légumineuses")	INRA, CIRAD (Research Institutes) Terres Univia, Terres Inovia (Professional Organizations) https://www.rfl-legumineuses.com	Dijon, France, May 2016, 250
International Congress	Second International Legumes Society Conference	ILS International Legumes Society, Instituto de Tecnologia Química e Biológica-Universidade Nova de Lisboa http://www.itqb.unl.pt/meetings-and-courses/pulses-for-a-sustainable-world	Troia, Portugal, October 2016, 380
French workshops	COSELAG Project	INRA (Research Institute), Terres Univia, Terres Inovia (Professional Organizations) http://www6.inra.fr/coselag/	Paris, France, November 2016, 120

were part of a French project, COSELAG³, designed to obtain collective expertise on legumes from stakeholders and scientists in different disciplines. The results of this project are available on COSELAG's website.

Hence, the objective of this paper is not to review in detail the information gathered, but to present our collective analysis of the issues based on the findings from these various sources. Drawing

on recent advances in the literature on legumes and feedback from stakeholders, in the following sections we identify some of main characteristics of innovation paths on pulses. We selected those that appeared most fundamental from breaking out of lock-in, that is, the ones liable to trigger IRA mechanisms in favor of pulses both downstream and upstream of the agrifood system.

UPSTREAM CHANGES TO DEVELOP PULSES IN CROPPING SYSTEMS

The emphasis on ecosystem services, especially nitrogen management, is the strongest trend currently driving the

³COSELAG is a French project that aims to identify the major changes that may influence the strategy of pulse breeding. Several workshops have been organized on various subjects such as: the evolution of cropping systems with pulses, the evolution of institutional frameworks on pulses, consumer preferences, and new technologies. A synthesis of each topic is available on the website: <http://www6.inra.fr/coselag/>

interest in pulses in cropping systems for most actors. Farmers, cooperatives, and breeders have shown little interest in legume crops up until now, and so dissemination of knowledge is the first step needed for un-locking the system (section New Knowledge from Research Institutions on Cropping Systems). However, firmly establishing these greener practices requires multiple changes: in farming practices (section Farming Practices and Technical Advice from Agricultural Institutions), in breeding and supply chains (section Breeding, Innovative Agronomic Practices, and Supply Chain Consequences), and through multiple interactions among all actors to consolidate and disseminate that knowledge, with institutions playing a key role (section Feedback Insights: The Main Role of Institutions).

New Knowledge From Research Institutions on Cropping Systems

As defined by the Millennium Ecosystem Assessment, three types of services are provided by the symbiotic fixation of atmospheric nitrogen, which is a specificity of pulses (Reckling et al., 2016): (1) provisioning (fixing atmospheric N₂ helps produce protein-rich foods); (2) supporting (fixed nitrogen helps to improve soil fertility for subsequent crops and fertilization of the following crops may be significantly reduced); and (3) regulating (symbiotic fixation reduces the use of chemical fertilizers and thereby reduces the negative impacts linked with their use such as greenhouse gas emissions and fossil fuel consumption). Legume-based crop diversification also reduces pesticide use (primarily herbicides, Wezel et al., 2014) and increases the diversity of landscape mosaics, promoting biological regulations that further reduce the need for pesticide use (Vasseur et al., 2013).

These significant environmental benefits of pulses are increasingly promoted by French public research institutions, the government, and technical institutes. A free handbook on pulses published by the French government, the French technical institute Terres Inovia, and the national research institute INRA is one main example (Schneider and Huyghe, 2015). This book for researchers and practitioners synthesizes the benefits of pulses at the scale of cropping systems and at the scale of national production systems, similar to other international syntheses such as Jensen et al. (2012) and Murphy-Bokern et al. (2017). This important push to disseminate knowledge was created to try to change the fact that, in practice, these services are currently poorly valued by farmers and agricultural advisers. Generally, they are unfamiliar with the benefits of crop diversification (Meynard et al., 2013; Reckling et al., 2016). In organic systems, pulses are more frequently grown, but far less so in conventional systems (Zimmer et al., 2016).

Farming Practices and Technical Advice From Agricultural Institutions

Conventional farmers (within the agro-chemical paradigm) rarely take into account the medium-term, biology-based effects of minor crops in their rotations (Magrini et al., 2016). Our open-ended interviews with technical advisers of storage organizations confirm indeed that the introduction of pulses into a crop sequence is rarely linked to adapting the nitrogen management of the following crops, although the nitrogen supply from pulses can result in decreasing N fertilizer from 20 to 80 kg N/ha

(more details reported in Anglade et al., 2015; Schneider and Huyghe, 2015). This variability hinders farmers when precisely adapting fertilizer doses, as current methods estimate the N supply needed from the preceding crop. New knowledge or indicators on this variability are required to more accurately value this legume-based service. Fertilizing based on regularly measuring the nitrogen nutrition status of the following crop should help us to better value the preceding effect of legume crops (Ravier et al., 2018). Yet up to now, farmers find it easier and more reliable to base the nitrogen nutrition of their crops on synthetic fertilizers than on biological soil processes because they lack such information. The decision tools available to them have also been designed within the synthetic-fertilizer paradigm.

Thus, improving the environmental and economic assessment of introducing pulses at the scale of the cropping system presupposes a deep understanding of that system: farmers must switch their practices from the agro-chemical input-based model to a more biological-regulated model that requires more local observation and local know-how (Toffolini et al., 2016). This is a great transformation that demands new skills among farmers and new information support from advisory services, such as accounting systems to calculate the multi-year effects of practices. In several case studies, multi-year assessment of introducing pulses in cropping systems showed no economic loss or gain, thanks to the cost reduction that pulses enabled on other crops (Schneider and Huyghe, 2015; Ravier et al., 2018). However, from interviews with accounting agencies, we found that few farmers use a multi-year evaluation of crop margins, as they are encouraged to use the year-based tools provided by the accounting agencies that are advising farmers. Annual crop-based margins do not reveal the economic advantages of pulses.

Taking into account the multi-year effect of pulses requires greater support from agronomic advisers from both public and private institutions. Agricultural extension services are currently not able to advise on choosing the legume species best adapted to local environmental factors and its place in the rotation. In fact, a wide variety of legume species can be grown in Europe (winter or spring peas, winter or spring fava beans, white or blue lupins, soybeans, lentils, dry beans, chickpeas, etc.) with several possible management patterns (pure crops or intercrops). Yet there is currently no management tool to help farmers choose the most suitable pulse crop to grow according to the targeted services it may provide and its local adaptation to soil and climate conditions. The majority of scientific and technical reference data available in Europe is limited to peas, the most cultivated pulse species. The potential for growing and using a wide range of legume species deserves to be better evaluated. In particular, all actors agree that research is urgently required for quantifying the yield performance and the preceding-crop effects of various legume species grown in diverse soil and climate conditions. This is needed in order to increase the reference data available and at the same time to foster crop biodiversity.

Breeding, Innovative Agronomic Practices, and Supply Chain Consequences

Creating new varieties is another major means advanced by stakeholders for securing yields. We need to increase their

adaptation to a given environment and select traits favoring resistance to biotic and abiotic stresses and their adaptation to a diversity of cropping systems. Even though large genetic resource collections are available throughout the world, and new genomic tools are making rapid progress in speeding up the selection process, the small size, and the low number of breeding programs in private and public European organizations still hinder genetic progress on these species. Indeed, in 2015, fewer than 400 new pea varieties were publically registered in Europe, and fewer than 150 for beans, while there were nearly 2,500 for wheat (Magrini et al., 2016).

To characterize and quantify the performance and ecosystem services of pulses, today public research institutes and agricultural cooperatives are experimenting with innovative cropping systems such as legumes-cereals intercrops (for instance wheat/pea, durum wheat/fava-bean, and triticale/lupin), primarily grown in organic systems. By growing species together in the same field, intercrops provide ecological functions that increase resource-use efficiency compared to species grown in pure stands. It also leads to greater yields than the average of both pure crops (Pelzer et al., 2012; Bedoussac et al., 2015). Legume-based intercropping enables higher nitrogen use efficiency and far lower fertilizer use compared to pure crops. In addition, intercropping reduces the risk of nitrogen leaching into the environment and is an effective way to reduce air-borne diseases, weeds and sometimes pests, and all of which enable a reduction in pesticide use (Ndzana et al., 2014). Finally, intercropping also improves product quality, such as the protein content in cereals, up to 2 points more in low-input systems (Bedoussac et al., 2015). This agronomic innovation opens up new outlets for wheat (both for pasta and bread), especially for organic markets. Considering the great diversity of intercrops possible, more research is still needed to design support tools that help farmers choose the best species to intercrop depending on the results desired and the pedo-climatic conditions (Anglade et al., 2015; Kuhlman et al., 2017).

Yet the practice of intercropping is also limited because logistics are not adapted for pulse sorting by harvesting/storage firms and market organizations (Magrini et al., 2013). However, several cooperatives in France, such as Terrena (one of the major French cooperatives) and Qualisol (a small-sized French cooperative), have recently adapted their logistics and organized their advisory services to promote intercropping. In addition, these cooperatives have created new value food chains for lentils (Qualisol) and lupins (Terrena) to reach higher value markets. Qualisol even created its own brand and adapted its packaging and market outlets. Qualisol sells lentils directly to consumers and to food ingredient suppliers in long supply chains. In order to sell “pure” lentils or “pure” wheat harvested from intercrops, they invested in a highly efficient optical sorter. They also set up an advisory organization to introduce farmers to intercropping. This example shows how several innovations were simultaneously designed (technical, organizational, and marketing) that enabled the increased use of pulses in cropping systems. More research should focus on designing this type of interconnected-innovation and specifically, its collective organization since it generally involves several actors (Meynard et al., 2016).

Feedback Insights: The Main Role of Institutions

Agricultural institutions, especially for research, advising, and education, have a key role to play in the collective education needed for transitioning to farming systems with more pulses. Education and disseminating knowledge are key factors for the transition (Kemp et al., 1998). This progress will be fostered if the agricultural system supports the development of knowledge and innovative practices: (i) it should include more programs on pulses during initial agricultural training for young farmers; and (ii) more advice and technical reference data for farmers. Hence, increasing legume crops requires mobilizing these organizations and thus requires new training for their employees.

According to our open-ended interviews, French ministries also acknowledge that European public subsidies are not enough. They recognize that the greening measures of the new Common Agricultural Policy (CAP), which began to be implemented in 2015 and introduced the green direct payment scheme, are not sufficient to significantly increase these crops. Other experts interviewed in Mahmood et al. (2017) had similar findings: as prices on pulses are not high enough compared with major crops like wheat, more price incentives are needed for French farmers to grow them.

Most of the stakeholders interviewed felt that new outlets with a higher added value are needed to create economic incentives for cultivating these species. Interviews with the top twenty French cooperatives (Cholez et al., 2017) reveal that they consider the market value of pulses too low to be included as a main part of their business strategy, except for a few market niches such as peas or lupins for food ingredients. This competitiveness problem also derives from the fact that the environmental services provided by those crops are not valued by the market. Yet smaller cooperatives' strategies (Qualisol, cited above) show that niche-markets may also be created for pulse consumption.

DOWNSTREAM CHANGES TO PROMOTE PULSES IN HUMAN DIETS

As the agro-ecological benefits of pulses are increasingly promoted, information about their contribution to more sustainable diets is also increasing (section Advances in Plant-Based Protein Research for Food). But while new scientific knowledge and breakthrough innovations in the agrifood industry provide new market opportunities, the future of these innovations is also strongly linked to institutional changes in nutritional classifications and consumer preferences (section Institutions: Pulses for Human Diets), knowing that consumer preferences are highly dependent on nutritional and culinary education (section Nutritional and Culinary Education of Consumers About Pulses). In addition, we observed recent technological progress enabling more innovative food products (section Food Processing Innovations: New Pulse-Based Products) especially concerning proteins (section Food Processing: The Development of Protein Ingredients), but currently this still needs stronger connections with the upstream

of the supply chain (Coupling Upstream and Downstream Innovations).

Advances in Plant-Based Protein Research for Food

Human diets in most developed countries have too many calories from animal sources (Combris et al., 2011; Garnett, 2013; Whitmee et al., 2015). Currently, developing countries (China, Brasil, India, etc.) are following the same path with a large increase in animal-based food consumption. As a result, micronutrients, fiber, and polyunsaturated fatty acid intake are unbalanced and more attention needs to be paid to assessing the nutritional balance between animal and plant foods. Moreover, as mentioned in Section Transitions of the Agrifood System: Theoretical Insights and Context, the environmental considerations of dietary choices are a growing concern (IPES-Food, 2017). Most of the people interviewed stated that protein delivery in terms of energy use and GHGs (including production and transport) is more efficient for pulses than animal proteins or other plant proteins, which has also been demonstrated in the literature (e.g., González et al., 2011). The environmental footprint of pulses is thus far lower than animal protein sources (Nijdam et al., 2012; Marlow et al., 2015). Therefore, promoting the nutritional properties of pulses can lead to higher consumption of pulse proteins as partial substitution for animal proteins. In addition, with the predicted increase in meat prices and global population growth (OECD-FAO, 2013), households seeking to reduce their food costs may begin to include more pulses in their diets.

However, animal proteins are known to offer the best nutritional quality protein and are better assimilated by the human body, which is essential when meeting infant developmental needs and for maintaining body protein mass in the elderly (Tome, 2012). Strong progress has been made in understanding the nutritional efficiency of pulses by specific combinations of plant protein sources to ensure the complementarity of essential amino acids needed for protein metabolism and repair. Recent studies show that the simultaneous consumption of proteins from pulses and cereals reproduces the pattern of essential amino acids contained in animal products (Petitot et al., 2009, 2010; Chardigny and Walrand, 2016; Laleg et al., 2016, 2017).

Institutions: Pulses for Human Diets

Although there has been considerable progress in research, new food applications are scarce. In France, firms state that they do not promote the nutritional benefits of pulses to consumers because public institutions do not classify pulses as an animal protein alternative. Indeed, French agencies, such as National Advisory on Food (*Conseil National de l'Alimentation*) do not publicly promote balancing the intake of proteins from animal and plant sources, despite the fact that the scientific public recommendation is a 50/50 balance. Pulses are classified as starches alongside cereals in the French food pyramid, but more consumers increasingly cite pulses as a protein source: in 2016, 31% of French consumers considered legumes as rich-protein sources compared with 11%

in 2011 based on a representative consumer survey (GEPV, 2016).

Yet French national standards from the GEM-RCN (national group of company representatives that promote nutritional recommendations for the restaurant/catering industry) limit the frequency of consumption of vegetable protein dishes from four to twenty successive meals. However, in other Western countries, food pyramids classify pulses as a source of protein and a meat alternative⁴ for example, the top of the USDA's dietary recommendations reads, "With protein foods, variety is key. Protein foods include both animal (meat, poultry, seafood, and eggs) and plant (beans, peas, soy products, nuts, and seeds) sources." Since the first food guidelines were introduced in Canada in the 1940s, pulses have been presented there as alternatives to animal proteins. This policy, combined with issues of crop diversification, means that for several decades Canada has had a strong policy promoting pulses as food. Today, pulse consumption in Canada is the highest among Western countries at around 10 kilos/person/year, whereas the average in other Western countries is around 4 kilos and <2 in France (FAOStats). Several European countries classify pulses as a protein source, such as the United Kingdom, Spain, Italy and more recently Belgium, which adopted this classification in 2017. Many firms interviewed believe that a strong public awareness campaign on the nutritional properties of pulses is one of the main programs needed to change consumer behavior. In France, there have been discussions on this subject between the research institutes INRA and ANSES (French Agency for Food, Environmental and Occupational Health & Safety), which led to a significant change in the institutional position: in January 2017, ANSES updated its food consumption guidelines with a specific recommendation to increase pulse consumption and reduce meat consumption. Yet French institutions continue to classify pulses as carbohydrates.

Advances in scientific knowledge on these species have also revealed other nutritional benefits. In a recent survey, Champ et al. (2015) reported that pulse consumption had preventive effects in some non-communicable diseases (type 2 diabetes, mellitus, dyslipidemia such as hypercholesterolemia, colon cancer, etc.). However, for European authorities to approve specific nutritional claims, additional research for "evidence-based" statements are required, while in non-European countries (like Canada) such claims have already been accepted. For example, in Canada, pulses are recognized as being rich in fiber (Curran, 2012), while this claim is rarely on French product packaging. Several ongoing studies are also trying to better assess the effects of pulses in terms of fiber intake and micronutrients such as potassium, in order to correct nutritional deficiencies of certain age groups. For example, the diets of elderly people are often characterized by a sharp reduction in meat consumption, partly due to problems chewing as well as

⁴<http://www.choosemyplate.gov>, the official site of the USDA, Center for Nutrition Policy and Promotion, is the equivalent of the French PNNS. See also the food pyramid recommended by the Harvard School of Medicine in the US: <https://www.hsph.harvard.edu/nutritionsource/healthy-eating-plate>. For the Canadian government's food guide, in which "cooked pulses" are listed as an alternative to meat products, see http://www.hc-sc.gc.ca/fn-an/alt_formats/hpfb-dgpsa/pdf/food-guide-aliment/view_eatwell_vue_bienmang-eng.pdf.

budget considerations. This results in a deficiency for people who in fact have increased protein requirements as they age. Several firms interviewed are developing research on new foods, such as bread or pasta enriched with pulse flour, to counteract this low meat intake. Another specific advantage of pulses is that they provide starch with a lower glycemic index than cereal starch. The resistant starch in pulses helps improve glucose tolerance as well as insulin sensitivity, making them a healthy food for people with diabetes or helping prevent the risk of Type 2 diabetes (Mudryj et al., 2014; Laleg et al., 2016).

While pulses' protein supply is strongly promoted, their other nutritional benefits with starch and fiber seem less valued by firms. Business models based on co-product development, such as soy and rapeseed used for both oil and protein, are less advanced for pulses, which can be used for both starch and protein. There is still less scientific knowledge available on the composition, structures, properties, and uses of pulse starches compared to cereals (Hoover et al., 2010). Progress in scientific knowledge is thus required. In addition, some compounds of pulses, include protease inhibitors, phytic acid, and α -galactosides, are able to reduce protein digestibility and nutrient absorption and may be responsible for intestinal discomfort. Yet despite these disadvantages, some of these antinutritional factors are now recognized to have beneficial effects on human health (Laleg et al., 2016). For instance, phytic acid has a preventive action against cancer by chelating the metals involved in DNA damage, and α -galactosides have some prebiotic activity. Moreover, the amount of bioactive compounds in legumes can be significantly reduced by food processing (soaking, fermentation and germination) and cooking. Hence, we can understand why processing firms recognize that there are many future avenues for the development of pulses in our diets.

Finally, the environmental benefits of pulses are rarely promoted by agrifood firms (for instance, they do not mention environmental benefits on the pulse-based food packaging). However, agrifood firms are beginning to take into account the role pulses can play in fostering sustainable agriculture. Our interviews (Table 1) revealed that firms' first goal is to make pulse products tasty and easier to cook for consumers. Once those objectives are reached, then other arguments to increase pulse consumption may be highlighted depending on consumer trends and public policy discourse about the challenges facing society. Agrifood firms are aware that there are growing numbers of flexitarian and vegetarian consumers (estimated at 30% flexitarians and 3% vegetarians among the French population), so most of them are conducting research on plant-protein combinations and assimilation to have more products on the market in the near future.

Thus, advances in nutritional knowledge about pulses may help promote their use, which in turn would support several of the transitions that society is currently facing. However, strong changes in public policy and regulations are still lacking. As regards technology, scientific advances are also needed to encourage the food industry to innovate.

Nutritional and Culinary Education of Consumers About Pulses

Just as farmers need more knowledge about how to efficiently grow pulses, consumers need to increase their knowledge on the health benefits of eating pulses and how to cook and consume them. "Confidence in cooking, health outcomes, an increase in time devoted to cooking, an enhanced approach toward cooking, and consumption of healthy foods have all been attributed to culinary education" (Havemeier et al., 2017, p. 63). Nutrition education must therefore focus on developing culinary skills, such as food storage, preparation, grocery shopping, and meal planning, rather than only on nutrients. Better knowledge of cooking techniques may help consumers become familiarized with skills that promote the preparation of pulses (Jallinoja et al., 2016; de Boer and Aiking, 2018). As observed in the literature on food nutrition, several researchers included practical advice on how to increase pulse consumption in addition to their results on nutritional effects (see for instance Polak et al., 2015).

Nutrition education on pulses must also include environmental aspects, particularly regarding the challenge of increasing plant-based proteins in diets, as underlined by Hartmann and Siegrist (2017, p. 22): "in order to move toward more sustainable food behavior, consumers and citizens need to have better knowledge about the environmental consequences of their food behavior. Otherwise, it will be unlikely that consumers will be motivated to change their food behavior."

Food Processing Innovations: New Pulse-Based Products

Agrofood firms in France are currently working to facilitate the consumption of pulses and have already developed new products such as pre-cooked foods combining cereals and pulses. During the last decade, these innovative products have entered the large retail market in most European countries. For instance, we can mention companies such as Tipiak, Sabarot, and Panzani in France, Mopur, Fior di Loto, and Delverde in Italy, and Go Green in Sweden, which have been studied (Lascialfari and Magrini, 2016). Combination products have also been developed by retail brands. For the last several years in the USA, the top global pasta producer, Barilla, has offered pasta made from a mix of pulse and cereal flours on the market. The interviews conducted with these firms confirmed that the main goal behind these new products was to facilitate pulse consumption since pulses suffer from an outdated image. Moreover, the cooking time for lentils⁵, which is the fastest pulse to prepare, is still two to three times longer than that of wheat or rice. While major species such as wheat and rice have benefitted from innovations in varieties and in food processing to reduce their cooking time and to offer new products, such as pre-cooked wheat (Ebly[®] brand), little research has been done for pulses.

In France, pasta combining durum wheat flour and large amounts of legume flour has been subject to two studies (PASTALEG and VEGAGE) that showed both the technological feasibility and the specific nutritional qualities of these products.

⁵Except for red lentils.

Researchers demonstrated that it is possible to make pasta dough with a high percentage (35%) of pulse flour while using conventional manufacturing processes (Petitot et al., 2010). Another study found that even greater amounts of pulse flour could be used (from 35 to 100%) with conventional extrusion techniques under adapted conditions, described in an INRA patent⁶ (Laleg et al., 2016, 2017). The resulting pasta is high in protein (and balanced in essential amino acids) for the mixed legume-cereal product, gluten-free for the 100% legume pasta, and high in fiber, vitamin B1, Mg, and P. The pasta is also low in fat and in the alpha-galactosides responsible for flatulence. For the moment, none of these new mixed pastas is available in significant quantities on the French market. Current French regulations define pasta as made exclusively from durum wheat, meaning that these products cannot be labeled as “pasta” (only sold as a health-food product but not as common food product). This example thus shows one of the ways in which institutions condition firms’ market strategy.

Food Processing: The Development of Protein Ingredients

Pulse processing technologies have particularly evolved in recent years, even though the applications are still mainly oriented toward animal feed. Today, the market for pulses as ingredients in the French food industry (high-processing technologies) is increasing and estimated at 120,000 metric tons/year⁷, mostly for protein-rich peas (over 80,000 metric tons/year). In comparison, the market for direct consumption of pulses (mainly lentils, beans, and chickpeas) is estimated at 100,000 metric tons/year (more half of which is imported in France). Over half is processed with simple technologies (flours or canned products), while the remainder is sold as whole pulses for cooking. Thus, the market for food ingredients (high-processing technologies) has surpassed traditional consumption. This development is largely due to the progress of nutritional knowledge (see above) and the recognition of other functional properties, all of which contribute to transitioning the practices of food-processing industries. Many experts recognize there is still great potential for innovation due to technology transfers among sub-sectors of the food industry.

Ingredients derived from protein-rich plants are currently driving a dynamic worldwide market (Guéguen et al., 2016). Several technological processes provide these ingredients in various forms (flours, concentrates, isolates, etc.), which are characterized by different protein contents in dry matter (from 45% to over 90%). These ingredients are then incorporated into food products for their technological and nutritional properties. In France, two food product categories account for two-thirds of the foods containing vegetable proteins: bread/pastry and meat products (protein from pulses is added into meat preparations). In addition to their economic advantages, these plant proteins have features that optimize the texture and/or physical stability of the products by controlling rheological, emulsifying, foaming, and water retention properties. Some of their texturing properties (emulsions, foams, gels) mean they can substitute for other

materials (in particular for milk products). For instance, in the pastry sector, some manufacturers have replaced eggs with lupine flour, which have emulsifying properties, in addition to a yellow color and a high protein content. In another example, fava bean flour in bread enables a lighter color of the bread crumb. Today, most of these uses are limited to niche markets, but their use is expanding and these innovations should increase the demand for pulses.

However, some uses of these plant protein extracts are still hampered by lower functional performance compared with certain animal proteins (milk protein, egg products, gelatin) and by limited consumer acceptability because of an often-pronounced “plant” taste (or “green” taste). Progress must be made to overcome these sensory bottlenecks and to increase protein solubility (Chardigny and Walrand, 2016). Considering the achievements in recent decades, several avenues are worth exploring: (i) better managing the diversity of legume proteins’ functional potential; (ii) reducing undesirable tastes; and (iii) improving functional synergies between plant and animal proteins and other biopolymers (starch or other polysaccharides).

Highly innovative approaches, such as combining different plant proteins (pulses/cereals) or animal/vegetable proteins for better functionality, are currently being developed in many laboratories in both the public and private sectors. However, according to those researchers, to consolidate these new outlets for pulses, more research and development are required to (i) improve the extraction and recovery of co-products; (ii) screen functional assemblies for their innovative properties and the ease of obtaining them compared to purified molecules; (iii) develop animal/plant protein mixes for common products (incorporate plant proteins with animal proteins in formulated products that usually only contain animal protein such as cheese, yogurt) to spread the use of plant proteins and promote learning about their industrial uses; and (iv) update processes to incorporate eco-design, as the specificities of plant proteins (ability to aggregate, low solubility, interactions with metals, etc.) should lead us to rethink manufacturing processes. Firms also state that research on the latter should focus on methods that are environmentally beneficial, through greater production efficiency in transformation processes. In the same spirit, hydrolysis treatments improving solubility or fermentation, as well as innovative physical treatments (high pressure, microwaves, etc.) for texturing, are other technological advantages to consider. These various avenues to be explored create new market opportunities with high added value because they are based on specific technological advances for which few countries in the world have the required know-how. However, this should not deter us from making direct consumption of whole pulses more attractive to consumers; products should also be developed for diversifying the consumption of whole or minimally processed pulses.

All these types of outlets based on various processing pathways (for proteins, carbohydrates, fibers, starch, etc.) should be considered as innovation niches that can become dynamic markets in the future (Chéreau et al., 2016). But for the moment, this development calls for strong public investment in research to overcome lock-in. Indeed public research on pulses

⁶Patent FR 14 62811 - WO2016097328A1.

⁷Data from industry organizations.

is under-financed compared to major crops and soy, especially in food sciences (Sonnino, 2017). If we look at the position of grain-legume species in current food sciences, soy is currently the most researched crop (Figure 4) and strongly linked to protein research, whereas pea, fava bean and lupin are studied much less.

Coupling Upstream and Downstream Innovations

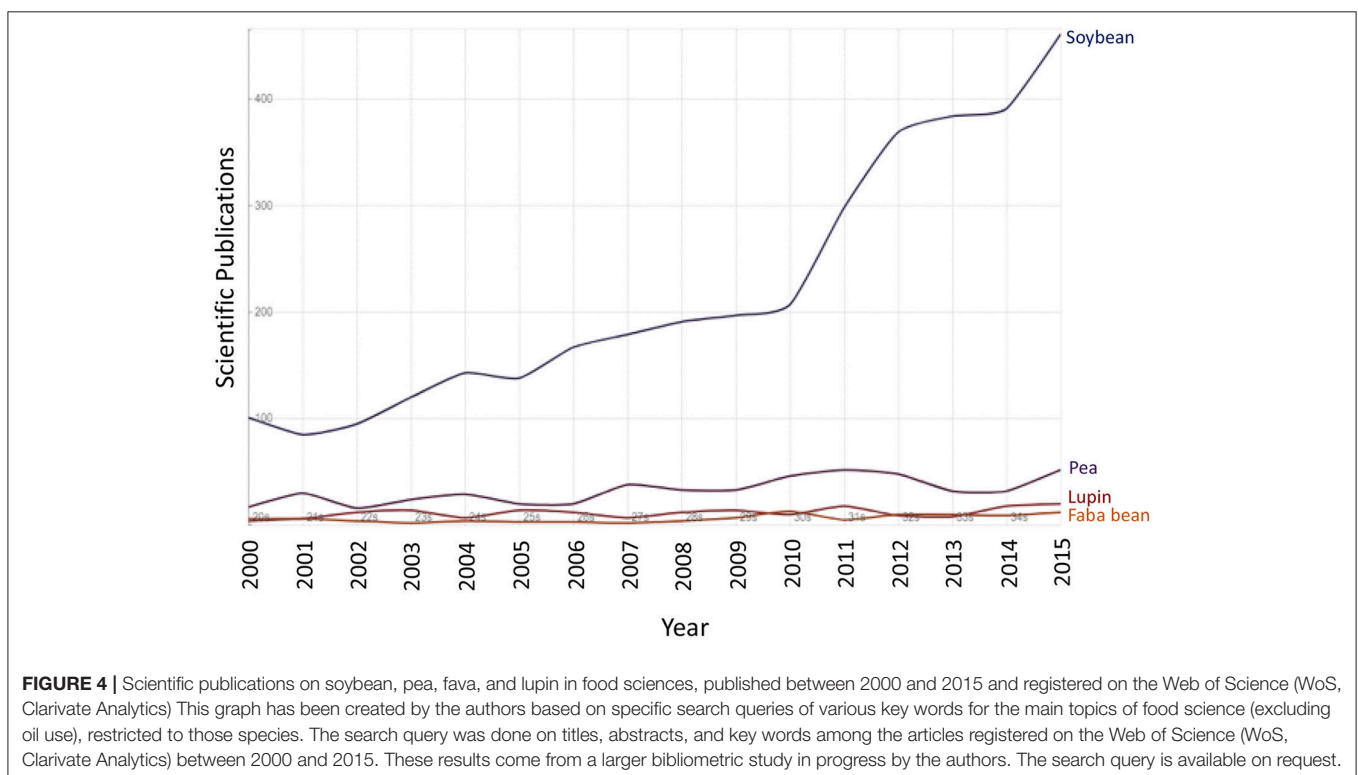
Whatever the technological process chosen to develop pulses, these innovations alone will not be sufficient to un-lock the entire agrifood system if upstream production is not simultaneously improved and developed. For example, new product innovations could trigger the breeding of new varieties adapted to food processing needs. Then, crop production must also increase to supply these new markets. As the processing firm Roquette (a major European food processor of pea protein) explained, they decided to focus their investment on pea protein in Canada rather than Europe, since Canadian pea production is greatly increasing. Barilla faces the same dilemma, as they are waiting for a greater institutional commitment from Europe to supply pulses. Other food processing firms such as Cosucra have tried to sign crop contracts with farmers to increase pulse production. It is clear that organizational innovations are also required to foster upstream and downstream changes. However, contractual arrangements in the pulse sector are still in the emerging phase, attempting to strengthen coordination among the supply chain stakeholders (Cholez et al., 2017). All stakeholders need to be involved in designing interconnected innovations, which opens up many avenues for future research as suggested by Meynard et al. (2016). Forums that bring together multiple types of

stakeholders working toward an agro ecological transition, as suggested by Le Masson et al. (2012), would also be useful, especially in order to share a common diagnosis of food system perspectives (Meynard et al., 2016).

CONCLUSION

Breaking agricultural and food systems (i.e., the agrifood system) out of lock-in requires new increasing returns to adoption that foster crop and food alternatives such as pulses. This article has explored various innovation paths regarding pulses, both upstream and downstream of supply chains, to get insights on the alignments that are possible. We have considered this alignment as the condition needed to trigger a sustainable agrifood transition in favor of pulses. In this article, we have stressed the importance of a co-evolution involving technologies, ecosystem, institutions, private actors, and research, in order to understand how innovations in one area can trigger changes in another.

The main conclusion is that public institutions have a major role in supporting this transition because the simultaneous evolution of the downstream and the upstream of the system is complex. In particular, public institutions need to: support investment in new storage facilities upstream and new processing technologies downstream; foster the sharing of information and knowledge on innovative cropping systems that include pulses (especially in agricultural advising) upstream, and the benefits of consuming pulses downstream. That is, to successfully accomplish the agrifood transition on pulses, policy makers need to view agricultural, and food policies as strongly interconnected.



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M-BM contributed conception and design of the paper, and wrote the first draft of the manuscript. All the other authors wrote several contributions in different sections of the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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APPENDIX

Summary of the Interview Guide With Agrofood Companies That Have Launched a new Pulse-Based Food Product

Starting Question:

Could you tell us how and why your enterprise decided to launch this new product based on pulses?

Concerning Your Business Strategy on Consumers, Could you Give us More Details:

- What are the determinants of consumers' purchase and acceptance?
- Is it a "pure" novelty for the market? Did you get inspiration from a niche product or a small firm?
- What is the influence of food trends? Who is the targeted consumer?
- Do you promote specific nutritional aspects?
- Do you promote specific environmental benefits?
- Is it a meat-substitute?
- Is it sold at a premium price? Comparing to which other products?
- What were the sales after the launch? Have they been growing or decreasing?
- Did competitors imitate your product?
- What obstacles did you encounter when launching your product into the market?
- Did you develop other similar foodstuffs? Have you had any failures with other food product innovations?

Concerning the Food Processing Technologies Used:

- Did you file a patent for your product?
- How did you design the pulse processing?
- Do you directly process your product? Did you need to adapt your production chain? If not, which processed pulses do you buy? With a specific partnership?
- Which kind of texture, color and tasting properties did you work on? What is the importance of cooking time?

Concerning the Knowledge Required to Develop Your Innovation, Could you Explain:

- The nutritional aims in product development? Did you work on the amino-acid balance and limitations? Or on other

nutritional factors? Did you take into account anti-nutritional factors or allergies related to pulses?

- Did you work with an external organization (R&S firm, academic, etc.) to develop your product?

Concerning Your Links With Agricultural Production:

- What is the geographical origin of the raw materials used, especially pulses?
- Do you use production contracts?
- What kind of pulses did you use? Were there specific quality specifications? If so, why?
- Is the increase of pulse cultivation in Europe part of your strategy?
- Do you have direct relations with farmers? Do you establish agreements to adopt pulses for crop rotations in order to obtain more sustainable wheat?
- What would you ask for from scientific research, in order to promote pulse development?

Concerning the Downstream of the Supply Chain:

- Were supply and marketing chains determinant for the choice of markets?
- Did you encounter differences between marketing chains in different countries?
- In which supermarkets did you place your products?
- In which main product lines are your products positioned? For instance, as a product for vegetarians or those with specific dietary requirements? Or among "standard" pasta and rice products?

Regarding the Institutional and Political Environment:

- Did you get support from public institutions in the development and launch of your product? Which institutions did you work with? Did you lobby them? How do you judge cooperation with public agencies, comparatively between European and North American ones?
- Is current legislation an obstacle for your product? Would you like to see a change in European legislation on pulses?
- How do you judge the implementation of nutritional objectives across various countries?
- What are the main policy challenges for developing pulses in your country and/or Europe?