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Socio-technical lock-in hinders crop diversification in France

Jean-Marc Meynard¹ · François Charrier^{2,3} · M'hand Fares³ · Marianne Le Bail¹ · Marie-Benoît Magrini³ · Aude Charlier^{1,4} · Antoine Messéan⁴

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Abstract

Crop diversification is considered as a major lever to increase the sustainability of arable farming systems, allowing reduced inputs (irrigation water, pesticides, fertilizers), increasing the heterogeneity of habitat mosaics, or reducing yield gap associated with too frequent returns of the same species. To free up paths of collective action, this article highlights obstacles to crop diversification, existing at various levels of the value chains. We used a threefold approach: (i) a cross-cutting analysis of impediments to the development of 11 diversifying crops (5 species of grain legumes, alfalfa, flax, hemp, linseed, mustard, sorghum), based on published documents and on 30 interviews of stakeholders in French value chains; (ii) a detailed study (55 semi-structured surveys, including 39 farmers) of three value chains: pea and linseed for animal feed, hemp for insulation and biomaterials; and (iii) a bibliometric analysis of the technical journals and websites (180 articles) to characterize the nature of information diffused to farmers. We highlight that the development of minor crops is hindered by a socio-technical lock-in in favor of the dominant species (wheat, rapeseed, maize, etc.). We show for the first time that this lock-in is characterized by strongly interconnected impediments, occurring at every link of the value chains, such as lack of availability of improved varieties and methods of plant protection, scarcity of quantified references on crop successions, complexity of the knowledge to be acquired by farmers, logistical constraints to harvest collection, and difficulties of coordination within the emerging value chains. On the basis of this lock-in analysis, that could concern other European countries, the article proposes levers aimed at encouraging actors to incorporate a greater diversity of crops into their productive systems: adaptation of standards and labelling, better coordination between stakeholders to fairly share added value within value chains, and combination of genetic, agronomic, technological, and organizational innovations.

Keywords Specialization · Value chain · Agroecological transition · Pea · Linseed · Hemp · Unlocking

1 Introduction

Throughout the past 50 years, French agriculture has been undergoing a major movement towards specialization: a constant reduction of mixed crop-livestock farms, specializing in either animal or plant productions, and a specialization of territories, separating crops and livestock areas (Schott et al. 2010). Permanent grasslands and alfalfa have decreased everywhere; cereals (wheat, barley and maize) today cover about 60% of arable lands. Short rotations (rapeseed-wheat-barley, rapeseed-wheat-wheat, rapeseed-wheat, maize-wheat) are increasingly frequent (Schott et al. 2010). Monocultures (mainly maize and wheat) today cover 8% of field crop areas. On 17% of wheat areas, wheat follows another wheat, and in some regions, this proportion can exceed 30% (Fuzeau et al. 2012). This trend of specialization has resulted from the modernization of agriculture setup in the 1960s, based on

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economies of scales, substitution of labor by external inputs and machinery, and huge increase of labor productivity (Schott et al. 2010, Magrini et al. 2016). It was consistent with the objectives of the European Agricultural Policy over the past 50 years, which aimed at increasing food and feed production as well as the productivity of agriculture. A similar trend of specialization was described at the world level by the international panel of experts IPES-food (2016).

The negative consequences of this increasing specialization of rotations, farms, and territories are well known: tensions on water in areas with extensive monocultures of irrigated maize (Amigues et al. 2006), increase in fossil energy consumption and greenhouse gas emissions related to the quasi-disappearance of legumes (Jeuffroy et al. 2013, Magrini et al. 2016), increase in pesticide use related to greater difficulty in controlling weeds and pests in short crop rotations and homogeneous landscape mosaics (Schott et al. 2010), reduction in biodiversity related to the homogenization of habitats, and the frequent use of pesticides (Liebman and Schulte 2015). Lastly, shortened rotations also contribute to yield stagnation of arable crops (Bennett et al. 2012).

Crop diversification, at both field and territory levels, would therefore seem a major lever to increase the sustainability of arable farming systems, allowing reduced inputs (water, pesticides, nitrogen fertilizer), increasing the heterogeneity of habitat mosaics, or reducing yield gap associated with too frequent returns of the same species (Kremen and Miles 2012; Ponisio et al. 2015). However, diversification of arable farming systems will occur if not only farmers but also the numerous stakeholders acting along the whole value chains are involved. As shown by evolutionary theory (Kallis and Norgaard 2010), the relationships, within a socio-technical system, between values, knowledge, organizations, and technologies can create strong interdependencies and self-reinforcing mechanisms, which lead to a lock-in, and may discourage stakeholders from adopting alternative production systems. The concept of socio-technical (or technological) lock-in (David 1985; Arthur 1989) was developed on case studies outside agriculture (energy, transport sectors), but several lock-in situations have already been described in this sector, to understand the impediments to change towards more agroecological practices (Cowan and Gunby 1996; Wilson and Tisdell 2001; Vanloqueren and Baret 2008; Lamine 2011; Fares et al. 2012; Magrini et al. 2016). Most of these works showed, in various countries, a lock-in around pesticide use that hampers the development of Integrated Pest Management. Closer to our subject, Magrini et al. (2016) and Zander et al. (2016) analyzed the historical pathway that led in Europe to the decline of grain legumes, for the benefit of cereals. They pointed out the major role of the European Agricultural Policy, more favorable to cereals, and of the low price of nitrogen fertilizers, to explain the lock-in that results in the marginal area of grain legumes in the European

agrifood system. We assume that, beyond grain legumes, the development of minor crops (i.e., those grown on small areas) is hampered by a lock-in of the dominant socio-technical system of French agriculture around major crops.

However, the multilevel theory of socio-technical transitions (Rip and Kemp 1998; Geels 2002) highlights the coexistence of innovation niches, alongside with the dominant socio-technical system. Innovation niches are socio-technical systems that emerge and develop in a partial isolation from the dominant system, and so from the processes which select markets and technological innovations. Functioning with different standards and institutional rules, the niches allow for collective learning and the construction of economic networks able to deal with radical innovations (Schot 1998). If the socio-political context develops in their favor, these niches can become resources for an unlocking process, based on their hybridization with the dominant socio-technical regime (Geels 2002). We assume that the value chains of minor crops could act as innovation niches, liable to help diversification of farming systems and territories.

The purpose of this study is to better understand the agronomic and socio-economic processes underlying the simplification of rotations in arable farming, by identifying, both in the agricultural and agro-industrial sectors, the impediments to developing the minor crops (Fig. 1) and their value chains. Involving agronomists and economists, it is based on the analysis (i) of the strategies of farmers and of upstream and downstream stakeholders, (ii) of collective action and coordination, and (iii) of the agronomic, technological, or organizational innovations, which determine the development and use of these minor crops. Structuring the interdisciplinary approach with the framework of socio-technical systems, we performed a multiscale and systemic analysis of the problem of crop diversification, the only way to embrace its complexity. After presenting the perimeter of the study and the methods mobilized, we identify the various obstacles to the development of minor crops, and shed light on a socio-technical lock-in around the dominant species, which hinders the development of minor species. We then propose levers for unlocking this situation and paths for public action.

2 Materials and methods

The study, carried out in 2011 and 2012, brings together three approaches: (i) an analysis of the impediments to the development of 11 minor crops, based on published documents and interviews among public and private experts of these crops; (ii) for three contrasting crops/value chains, chosen among the 11 ones, an analysis of stakeholders' strategies and governance, based on interviews among the stakeholders at the different levels of the value chains; and (iii) a study of the

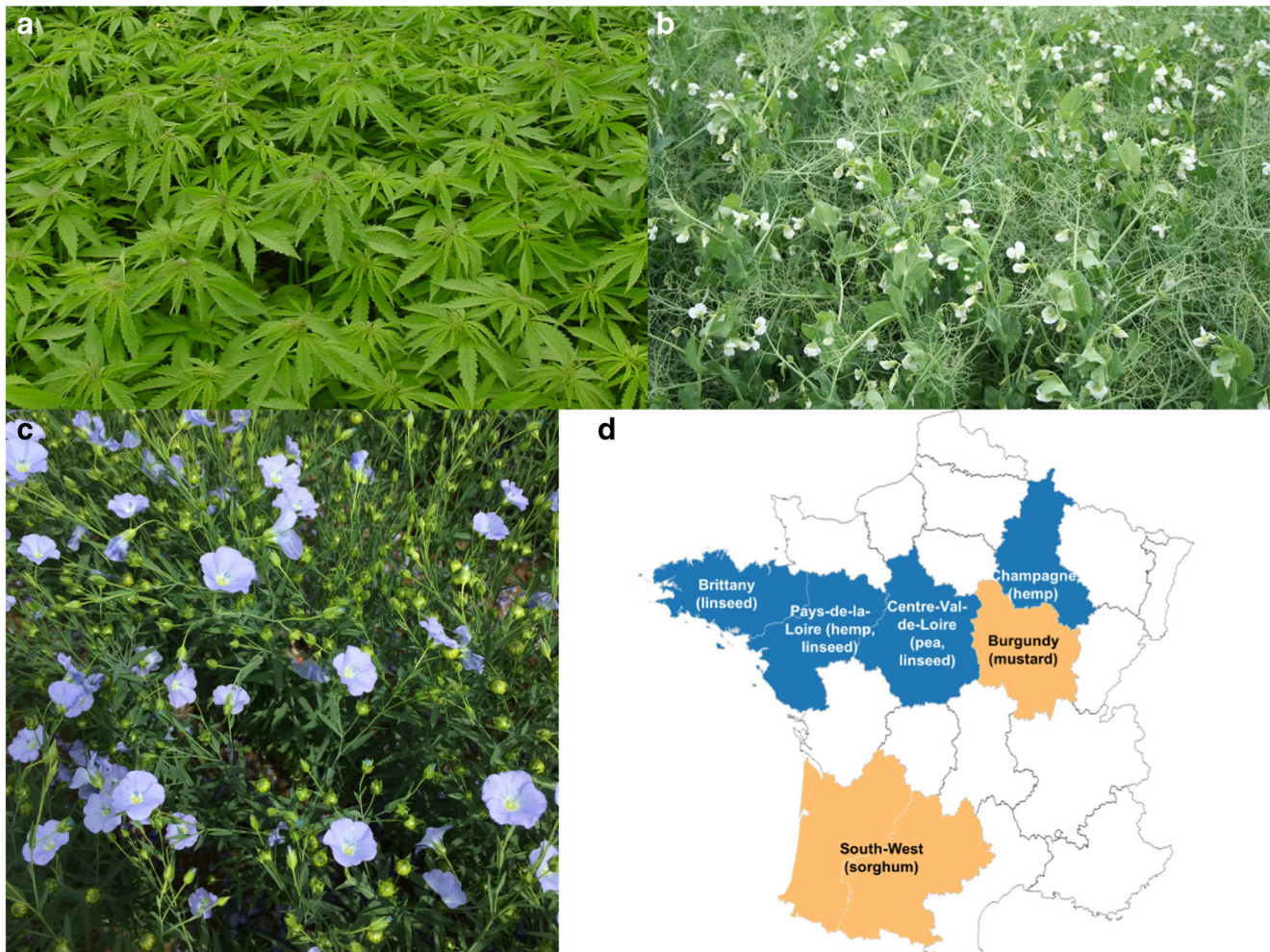


Fig. 1 Three minor crops: **a** hemp, **b** pea, and **c** linseed, and **d** a map of France indicating the regions in which surveys about these three crops were realized (in blue), and two other regions, quoted in the paper, concerning other minor crops (in orange)

content of information diffused to farmers, based on a bibliometric analysis of the national technical press.

2.1 Bibliography analysis and expert interviews about 11 minor crops

The 11 crops studied were chosen among species well known by agronomists and adapted to French conditions, and selected on the basis of three main criteria (Table 1): relatively small production areas (from 3000 to 180,000 ha in France, as against approximately 5 million ha for common wheat, and 1.5 million ha for rapeseed); existing outlets for their products, currently supplied by other crops or imports; and contrasted dynamics of production areas (increasing, decreasing, or fluctuating).

The corpus of the consulted scientific and technical articles included 63 references (quoted in Meynard et al. 2013). The scientific papers on this subject are far from numerous, and the articles of the agricultural or economic press are generally

centered on one species, and on one link in the value chain (plant breeding, agriculture or processing). To supplement this patchy documentation, we conducted semi-structured interviews with 30 experts from the French agrifood system, pertaining to a variety of private and public organizations (at least three experts per crop), to whom we asked the following questions: “Do you think that the development of the crop(s) you are expert in should be a good opportunity for French agriculture? What are the impediments to extending the area of this crop (these crops)? In your opinion, what levers could be used by public authorities or by actors of the value chain to enable this crop (these crops) to be developed?” Information coming from the interviewed experts and from the written documents was assessed by triangulation, i.e., we only used an item of information if it appeared in two independent sources at least. From all interviews and documents, we identified and hierarchized, for each of the 11 crops, the impediments to their development, which differ from one crop to another. These impediments were then spread over the

Table 1 Main characteristics of the 11 minor crops studied

Crop	Product outlet	Surface area 2011 (× 1000 ha)	Surface area 1990 (× 1000 ha) and trends of evolution between 1990 and 2012
Pea (<i>Pisum sativum</i> L.)	Mainly feed	180	687 (sharp decrease, brief rise in 2010 under the effect of a specific premium)
Faba bean (<i>Vicia faba</i> L.)	Feed and food	90	23 (trend to growth, with fluctuations)
Lupin (<i>Lupinus albus</i> L.)	Feed and food	3	3 (fluctuating)
Chickpea (<i>Cicer arietinum</i> L.)	Food	4.5	Close to 0 (trend to growth, with fluctuations)
Dried alfalfa (<i>Medicago sativa</i> L.)	Feed	65	84 (estimation) (declining)
Fiber flax (<i>Linum usitatissimum</i> L.)	Textile industry, insulation	54	59 (relatively stable)
Linseed (<i>Linum usitatissimum</i> L.)	Chemical industry and feed	14	2 (trend to growth, with fluctuations)
Condiment mustard (<i>Brassica juncea</i> (L.) Czern. & Coss.)	Food	5	Close to 0 (growth supported by the IGP “Moutarde de Bourgogne”)
Sorghum (<i>Sorghum bicolor</i> (L.) Moench)	Feed	44	67 (low declining)
Hemp (<i>Canabis sativa</i> L.)	Paper making industry, insulation, biomaterials	6	3 (increasing until 1997, then fluctuating)
Soybean (<i>Glycine max</i> L.)	Mainly food	42	135 (declining until 2009, then fluctuating)

different levels of the value chains (seed breeding, agro-chemical industry, farm, collection and storage, processing, distribution). For each impediment, we only mention the species for which the development has been identified as hampered by this impediment.

2.2 Surveys of stakeholders from each link of the productive process for three crops/value chains

For linseed, pea, and hemp, a thorough case study was carried out, based on 55 semi-directive interviews with stakeholders of the value chains, including 39 farmers, selected by random sampling among all farmers having setup a contract with the processor (Table 2 and Fig. 1). These three crops were selected among the 11, for contrast between the value chains' coordination. In the case of pea for animal feed, coordination was essentially spot-market-driven; for linseed (animal feed) and hemp (multiple outlets), a highly structured coordination was organized around multiannual contracts. The value chain analysis, carried out from downstream to upstream, investigated the actors' strategies, the governance of their transactions (contracts, specifications, market prices and structure, information exchanged), and their capacity to generate sufficient incentives for the crop and its products to be adopted by their partners. We questioned the farmers on the change in their rotations, the reasons why they adopted minor crops, then retained or abandoned them, the constraints and difficulties they encountered, and their relations with the other stakeholders of the value chains. The companies were questioned on the strategic, logistical, and economic dimensions of the organization of their activities relating to diversification products, and on their coordination with other stakeholders.

2.3 Bibliometric analysis of the technical journals and websites

A bibliometric study was carried out to characterize the nature of information diffused to farmers, concerning the pre-crop effects of the 11 selected minor crops on the following crops. One hundred eighty articles in the main national technical journals over the period 2009–2012 (*Cultivar*, *La France Agricole*, *Perspectives Agricoles* and *Réussir-Grandes Cultures*), and 40 files available on the websites of technical institutes (Arvalis-Institut-du-végétal, Cetiom, Institut technique du lin, Union Nationale Interprofessionnelle des Protéagineux, and Coop-de-France Déshydratation) were analyzed. For each article relating to one or several of the 11 crops, we noted the species concerned, and the editorial content related to their effects on the following crop, and to the economic impacts of including them in the crop sequence.

3 Results and discussion

3.1 Impediments to the development of minor crops

Impediments to diversification were analyzed according to a two-step approach. First, relying on the pool of the 11 minor crops, we identified the obstacles to their development from upstream to downstream of the value chains (Fig. 2): (i) seeds and pesticides supply, (ii) farming, (iii) harvest collection and storage, and (iv) processing and distribution. Second, mainly relying on the three more detailed case studies, we characterized (v) the coordination between stakeholders of the value chains.

Table 2 The surveys carried out in the framework of the three detailed case studies

	Hemp		Linseed		Pea	Surveys common to the 3 cases
Region of France	Pays de la Loire	Champagne	Bretagne and Pays de la Loire	Centre-Val-de-Loire	Centre-Val-de-Loire	
Advice and R&D organizations	CA (Chamber of Agriculture)	CA	CA	CA	CA	UNIP, CETIOM
Plant breeders	–	1	1	–	1	INRA
Farmers	11	7	8	7	6	–
Accounting organizations	1	1	1	1	–	–
Collecting firms	1	1	1	1	1	InVivo
Industry	1 (insulation)	1 (paper-making)	1 (feed)	–	1 (feed)	–

3.1.1 Seeds and pesticides supply

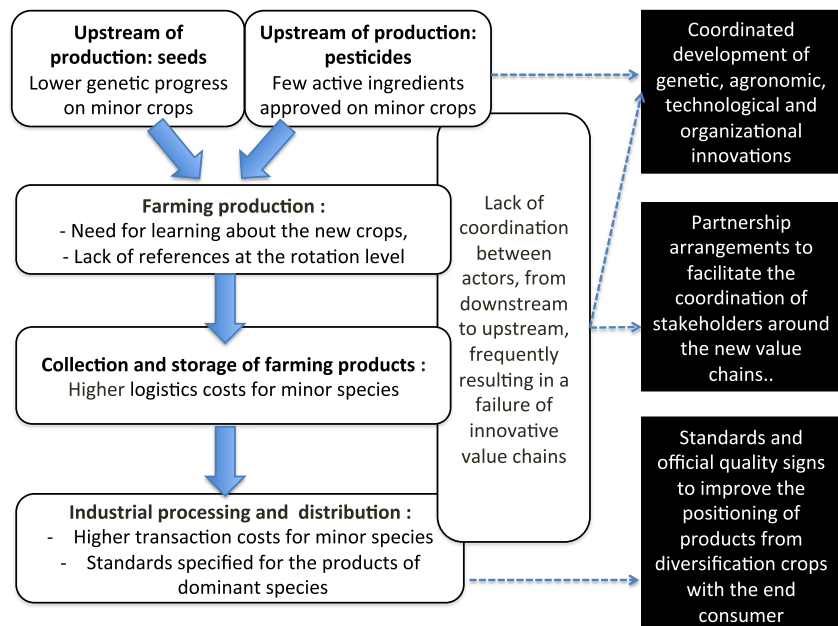
All experts interviewed for the 11 crops underlined that the crops covering small areas are characterized by a lower breeding investment than major species. Magrini et al. (2016) confirmed it comparing grain legumes and wheat. Over the period 2009–2012 (4 years), no new variety was registered in France for chickpea and hemp, only 1 for lupin and mustard, 6 for faba bean, and 10 to 22 for the other species, while 360 new varieties were registered for maize, 139 for wheat, and 69 for oilseed rape (Geves 2018).

Genetic progress is therefore slower on minor species than on the dominant crops of the rotations. Magrini et al. (2016) considered that this phenomenon contributed to the increasing yield gap between pea and wheat, which partly explains the drop in pea areas. The surveyed experts also attributed to low

genetic improvement the difficulties lupin or chickpea areas had in taking off, in spite of domestic demand: for this last crop, the varieties available in France were not resistant enough to ascochyta blight, a major disease of chickpea in French conditions. Public research no longer counterbalanced the concentration on major crops by private breeders, because of its disinvestment in breeding of minor species (more than 100 species bred in 1975 by INRA, less than 10 in 2005, according to Bonneuil and Thomas 2009).

However, some regional stakeholders already included diversification in their development strategy, and supported local breeding activities. This was the case of the cooperatives Arterris on chickpea, or Terrena (via its breeding subsidiary Jouffray-Drillaud) on lupin. To reactivate the breeding of orphan species, consortia between public and private partners have also been created. For example, varieties of condiment

Fig. 2 The impediments to the development of diversification crops, from upstream to downstream of the supply chain (left) and the levers for unlocking (right, black boxes)



mustard for a niche value chain in Burgundy were bred by AgroSup Dijon (public engineering university) with the support of a Technical Institute (Cetiom) and the mustard manufacturer Maille. It was enhanced by the recent development of catch crops, as a growing outlet for mustard seeds, because of regulations prohibiting bare soils in winter. However, for crops contributing to not yet stabilized value chains, defining breeding objectives can be complex. This was the case for hemp, whose diversity of outlets for fibers and grains multiplied the breeding criteria (fiber and grain yields, quality of fiber, grain oil content), among which the stakeholders seemed to have difficulty in defining priorities.

Minor crops also need specific solutions to control their pests and diseases. However, for these crops, few pesticide products are registered. The approval procedure is quite complicated and expensive, which dissuades the agrochemical companies from investing in minor crops, where returns are limited. For example, only one herbicide was authorized for chickpea, and no fungicide was available against *ascochyta* blight. No herbicide has been approved on lupin, but the interviewed experts emphasized that effective products did exist that were only approved for cereals. Thus, paradoxically, whereas diversification would be useful to reduce the use of pesticides, one obstacle to this is the lack of pesticides that can be used on minor crops!

3.1.2 Farming

At farm level, diversification comes up against diverse constraints: inappropriate soil or climatic conditions, competition for labor, machinery not available on the farm, or no agricultural contractor nearby. Most interviewed farmers confirmed what the experts said: these impediments differ from one farm to another as regards a specific crop. Yet, if farmers want to diversify their rotation, they will always find one crop that is compatible with their soils, their climate, their work schedule, and the equipment they can use. So, the surveys with farmers identified two more general reasons for making diversification difficult: the need for learning about the new crops and the lack of technical and economic references at the rotation level.

Whenever farmers introduce a new crop, they first have to get familiar with its management and its harvest. Pea is difficult to harvest when lodging occurs, which is still common in spite of varietal improvements in stem resistance. In the same way, harvesting both seeds and straw for linseed or hemp is a complex procedure. Both experts and farmers argued that such specificities are sources of apprehension for farmers, which can hinder the adoption of these crops. Yet, solutions may be found during a learning phase. But this learning phase requires time, often several seasons (Chantre and Cardona 2014), during which there are high risks that the new crop will be abandoned (Conley and Udry 2010). When, in the first years, this crop produces a yield that is much lower than expected by

farmers, they are inclined to abandon it, unless they can identify the cause and solve it. But, as minor crops are not well known by the advisors themselves, the low performance often remains unexplained. Several farmers confirmed that a recently introduced crop is abandoned if it undergoes one or two unexplained failures. This lack of clarity as to the origin of yield fluctuations certainly does constitute an impediment to the development of minor crops.

Although the agronomic benefits of diversification are well demonstrated (IPES-food 2016), the farmers in the survey emphasized that precise references as to the agronomic consequences, in a given region, from the introduction of a given crop into a given rotation were missing (confirmed by Duc et al. 2010; Zimmer et al. 2016, for grain legumes). Some experts mentioned the source of funding of Technical Institutes, based on a contribution proportional to the volume of harvest of each crop, as an obstacle to the amount of knowledge production on minor crops. Farmers stressed that the advice given by cooperatives or Chambers of Agriculture on minor crops often only concerns their management, and seldom the management of the subsequent crop. They added that agricultural accounting organizations calculate economic margins per crop, and not per couple of successive crops or per rotation. When questioned, these organizations confirmed this fact, indicating that annual accounting data do not allow such multiannual calculations to be made. So, while price fluctuations push them to short-term reasoning about their rotation, farmers and their advisors tend to lose sight of the interest of reasoning at the rotation level, which would be favorable to diversification.

The bibliometric analysis of the technical documents intended for farmers made it possible to specify this result (see Table 3). Of the 220 analyzed documents, dealing with the 11 minor crops, 100 tackled their effects on the following crop. These generally concerned the control of weeds and pests (in 40% of the references), or the nitrogen fertilization of the following crop (37%), and less frequently the soil structure (23%). However, these effects were not always quantified: although the reduction of nitrogen fertilization permitted by a previous legume was usually specified, it was seldom the case for the reduction in herbicide use permitted by lengthening the rotation. On the 100 documents mentioning the effects of diversification on the following crops, only 17 gave an economic quantification at rotation level, relating primarily to pea, alfalfa, and linseed. In these 17 documents, diversification always appeared economically interesting, compared to the current simplified rotations. On the opposite, when compared to a major crop at the annual level (generally wheat, 20 documents), the margin of the diversifying crop appeared higher in only a quarter of cases (Table 3). These results are consistent with those of Zander et al. (2016), underlying that the economic interest of grain legumes was seldom quantified at the rotation scale. One scarce example, quantifying the

Table 3 The bibliometric analysis of the technical documents intended for farmers: only few documents quantify the economic interest of the minor crops at the rotation level

Number of documents dealing with the 11 minor crops	Number of documents tackling the effect of the minor crop on the following crop	Number of documents quantifying the economic interest of the minor crop (number of documents showing a positive economic interest to diversification)		
		total	At annual level	At rotation level
220	100	37 (22)	20 (5)	17 (17)

effect of longer rotations on the economic margin, was given by Schneider et al. (2010), widely quoted in technical journals: they showed that the introduction of pea into short cereal rotations made it possible to maintain or improve profitability at rotation level, in spite of its lower annual gross margin. This resulted from yield increase and input use reduction on the subsequent wheat (compared to wheat following wheat). The lack of similar references for all minor crops, in the different agro-climatic areas, is an impediment to diversification, as confirmed by Zimmer et al. (2016) in Luxembourg.

3.1.3 Collection and storage of farming products

In line with Filippi et al. (2008), the consulted experts emphasized that most cooperatives and brokers of major crops products have adopted strategies based on economies of scale, which disadvantages minor crops. Indeed, marketing large volumes for a small number of species confers greater market power than marketing low volumes for a large number of species. For example, collection by Dijon Céréales, which is a group of 12 cooperatives, was mainly turned towards cereals (80% of collected volumes in 2012) and rapeseed (10%). Moreover, unions of cooperatives, e.g., InVivo, offered, to their members, services based on the grain market analysis, which primarily concerned major crops, while minor crops did not benefit from such skills.

At collection level, strategies of reduction in logistical costs, which go hand in hand with economy of scale strategies, appeared adverse to minor crops. The frequent dispersal of minor crops within the collecting areas, resulting in long distances between fields, entails high logistical costs compared to the volume collected: in the south-western hemp production area, some producers are located dozens of kilometers away from the defibering factory. As reported by Magrini et al. (2013), when the collection-storage organizations set up a specific diversification strategy, they intend to mitigate these logistical difficulties. We identified an option consisting in encouraging farmers, via premium prices, to deliver their harvest to a dedicated silo, sometimes rather distant (strategy implemented by the Vegam cooperative, surveyed on linseed).

Grouping crop areas was another option, mobilizing farmers whose fields are relatively close to a dedicated silo (strategy developed by the Cavac cooperative for hemp straw). The harvest period of minor crops sometimes overlaps the major crops harvest: in the South-West, for example, sorghum is collected at about the same time as maize, which is usually a priority for the allocation of transport and storage resources. Finally, the silos availability was mentioned by experts as a major impediment to the development of minor crops. Indeed, the specialization of farming systems has resulted in investments in large silos, less suited to low volumes. To free the silos for the major crops, the collection organizations quickly sell their small batches of minor crops, which thus are not sold at the best price. Logistical problems also result in the mixing of batches of different quality, stored for convenience sake in the same silo: the consulted experts observed mixtures of various pulse species, or varieties of faba beans, selected for their lack of anti-nutritional factors, mixed with standard faba beans. This creates difficulties for any quality valuation for these products.

3.1.4 Industrial processing and distribution

From among the 11 crops studied, more than half are used for manufacturing animal feed (Table 1). The formulation, a process aimed at designing compound feeds, is performed considering the substitutability of agricultural raw materials in relation to their nutritional composition, in particular their energy value and their protein content (Charrier et al. 2013). This logic places the different raw materials in direct competition. Pulses (pea, lupin, faba bean) or alfalfa pellets are confronted by very severe competition from soybean meal, and by co-products of the agrofuel industry, mainly rapeseed meal and wheat draff. The incorporation of a raw material into a compound feed depends on its price, compared to competing products, but also on its accessibility, i.e., costs associated with routing and regularity of supply. As indicated by the interviews conducted in animal feed industry (Table 2), it is generally more interesting for the processors to stock up on the international market, where raw materials are always available with steady compositions and at costs reduced by volume

strategies, than to try to set up a supply of pulses of French origin. A limited available volume, spread over the territory and/or far away from the users, increases transaction costs and penalizes minor species.

In these highly competitive markets, it could be thought that quality signaling, through labels and brands, supports segmentation favorable to minor crops. But the experts pointed out that the specifications from downstream stakeholders are sometimes not restrictive enough (private specifications prohibiting genetically modified organisms favored the incorporation of non-GMO soybean of Brazilian origin, rather than French pulses or French non-GMO soybean), or too restrictive. For example, before 2006, breeding “Label Rouge” chickens required feed composed of 75% cereals, which forced, for the remaining 25%, to incorporate only raw materials with high protein concentration, such as soybean meal. Although, since 2006, the label standard has changed to integrate 5% of pea, faba bean, or lupin in the diets, the processors affirmed to have difficulties in obtaining enough French pulses to match this standard. Another example of restrictive specifications is the requirement of the “Label Jaune” regarding the color of egg yolks: as poultry feed containing sorghum did not enable the necessary pigmentation to be obtained without recourse to synthetic pigments, feed with maize was preferred by the processors.

However, in this context overall unfavorable to minor species, some of them are being used more often, thanks to specific qualities promoted in the value chains. For instance, the particular nutritional properties of linseed, especially its high omega-3 (alpha-linolenic acid) lipid content, have encouraged a feed processor (Valorex) to set up a value chain of omega-3-rich food products (dairy products, eggs, ham), based on animal feed made from linseed, and identified by the “Bleu-Blanc-Cœur” label. To aid its digestibility by the animals, linseed is submitted to an extrusion cooking process (Martin et al. 2008). The cost of this treatment makes it difficult to promote for traditional animal feed outlets. It is easier to upgrade in a quality chain, such as Bleu-Blanc-Cœur, thanks to added-value from the sale of the products. The “niche market” created by the label has tremendously increased in the past 10 years and became a key factor of the linseed area development in France.

Beside animal feed, other case studies also confirmed the main role of quality product and signaling strategies in value chains of minor crops. In Burgundy, mustard industrialists succeeded in creating a local source of mustard grains, by working with cooperatives, and benefiting from the increase in varieties used as catch crops. Although it is still marginal, compared to imports, this crop contributes to the image of Dijon mustard as a regional specialty. In contrast, in the building sector, insulation panels made of hemp, whose manufacturing costs are rather high, have difficulty in breaking into a market dominated by glass wool panels. Indeed, the

standards existing in the sector only evaluate product quality on the basis of its insulating power. The absence of clear indications, for the consumer, of the positive environmental externalities of hemp panels, compared to glass wool (particularly in recycling), thus hampers the development of the hemp crop.

3.1.5 Coordination of the value chain stakeholders, from downstream to upstream

The comparison, permitted by the deeper analysis of their value chain, between linseed and pea, highlighted the importance of stakeholder coordination in diversification value chains. The linseed chain is characterized by a strong vertical coordination, through production contracts and quality specifications of the raw material, for the development of traced production, as evoked in the previous paragraph. To secure a steady supply, the processors contract with the collecting firms (either cooperatives or brokers), and with farmers to provide incentives to integrate minor crops in their rotations. For instance, the linseed production contracts propose prices indexed on the dominant crops in the rotation, but also a program of technical support and training for farmers. As stressed by the surveyed farmers, in line with Hart and Holmstrom (1987) and Fares (2006), it is essential that contracts are multiannual: the adoption of a new crop involves specific investments (in machinery, but also in training and new knowledge). To encourage farmers to make such investments, it is crucial to guarantee them, over the long term, a profitable outlet and technical support. Coordination also results from an institutionalization of dialog, aiming at periodically renegotiate standards, such as observed for linseed when growers faced with the difficulties in satisfying the constraints imposed on the omega-3 fatty-acid content (Charrier et al. 2013). A similar organization was observed in several human food sectors (condiment mustard, faba bean for food, chickpea), structured by multiannual contracts and associative networks bringing together the various links in the value chain. The surveyed stakeholders emphasized that this governance facilitates the share of information among the various operators, but also between the operators and the research and development structures.

In contrast, the pea value chain is little coordinated: transactions are mainly short term and driven by spot markets. Such an organization is characterized by a strong competition between easily substitutable raw materials (see Sect. 3.1.4) and by a weakness of the coordination links between upstream and downstream, without production contracts that could facilitate the exchange of information (knowledge, technical references). Most animal feed chains, in which our 11 minor species are used (except linseed and alfalfa), are involved in this kind of organization. The impediments to the development of pea, faba bean, lupin, and sorghum originate in this

spot-market coordination type (see Magrini et al. 2016 for grain legumes).

Some value chains, like those related to hemp, fiber flax, or alfalfa, are in an intermediate situation: they display relatively strong vertical coordination upstream (production contracts between collecting firms and farmers), but products downstream are subjected to strong competition on a more undifferentiated market, vis-a-vis other products which have similar properties (for example, hemp panels are in competition with glass wool panels, linen clothing with cotton, alfalfa pellets with soybean meals, etc.). The processors, who are often structurally linked to cooperatives seeking to diversify their outlets, would like to encourage farmers to integrate these crops into their rotations, but the competition encountered downstream does not enable them to obtain sufficient added value to finance incentives to adopt diversifying crops.

Insufficient coordination between the actors, from downstream to upstream, therefore appears to be a major cause of the failure to construct diversification value chains. Spot-market coordination, marked by difficulties in the vertical flow of information and incentives, is detrimental to diversification. On the other hand, successful diversification dynamics are linked to contract agreements leading to tightly coordinated value chains. In the analyzed cases, these value chains were generally initiated at a local level, where strong coordination was easier to build. Sometimes the value chain remained limited to the local production area (chickpea, mustard); sometimes it extended to distant areas (linseed, hemp). We observed that cooperatives often played a significant role in constructing such coordination, thanks to the quality of their networks with the chains downstream, and with their privileged upstream relationship with the farmers.

3.2 A socio-technical lock-in around the major crops

3.2.1 Interconnected self-reinforcement mechanisms

This panorama shows that the main stakeholders in agriculture and in the agro-industry organized their strategy around the major crops, which explains most impediments to the development of minor crops. All the stakeholders have very good reasons to have done so: mainly to optimize their organization or their logistics, to fulfill the demand or the supply of their economic partners, to make economies of scale, and/or to reduce transaction costs. The position of the major crops is consolidated by a whole interconnected set of self-reinforcement mechanisms (David 1985): (i) these crops are well known, at both agronomic and technological levels; (ii) improved seeds, specific inputs, and machinery are proposed by upstream value chain partners; (iii) the products of the major crops are easily available for the processors who are interested, and match standards recognized by value chains and consumers (since these standards were defined according

to the characteristics of these dominant products); (iv) stakeholders in the value chains are involved in tight social networks and are used to working together.

In contrast, minor crops are not very much studied, and slightly bred. Their products are not easily available on the markets, poorly adapted to the dominant industrial processes, and not always in conformity with the dominant standards. Moreover, the stakeholders who could build value chains have not necessarily the relevant social network to achieve their goal. All these impediments are interdependent and self-reinforcing: as the minor species do not cover much area, they are not very much bred or studied; and as they are slightly bred or studied, they are less competitive, and so less and less grown by farmers.

The concept of socio-technical lock-in (David 1985) refers to such situations, where a technology (here, systems specialized around major crops) has become such a standard for society that it seems difficult to change it, even if there are other technologies (here diversification), which would better fulfill society requirements. Lock-in around major crops is a typical case that illustrates the concept of “increasing returns to adoption” (Arthur 1989): the more a technology is adopted, the more its performance improves (by the combined effects of economies of scale, learning by doing, and network externalities), and the more other compatible technologies develop jointly around common standards, creating a process of path dependency. The competitive advantage of major crops is thus constantly reinforced by numerous innovations (varieties, pesticides, fertilization tools, etc.), because private companies expect a higher return on investment than on minor crops, but also because the strategy of Research Organizations and Technical Institutes results on focusing their activities on the most grown species (Bonneuil and Thomas 2009). In France, several of the 11 studied species do not currently benefit from any research investment, such as lupin, condiment mustard, and chickpea. The problem is similar for other species, not involved in our study, such as lentil, buckwheat, oat, or poppy. Within the agricultural research system, the lock-in around genetic engineering, hindering the development of agroecology, shown by Vanloqueren and Baret (2009), contributes to this situation, as it entailed focusing research on a small number of model species, major crops being among them. Moreover, short rotations being only possible with high pesticide use, the lock-in around major crops contributes to reinforce the lock-in of intensive agriculture around pesticides, already largely demonstrated (Cowan and Gunby 1996; Wilson and Tisdell 2001; Vanloqueren and Baret 2008; Lamine 2011). On the opposite, in organic agriculture, long rotations are essential to control weeds and diseases, thus leading R&D organizations to study diversifying crops (Ponisio et al. 2015).

Magrini et al. (2016) pointed out a similar lock-in resulting in the marginalization of grain legumes in Europe. Whereas

these authors analyze the historical anchoring of this process, our paper put forward the systemic interdependency between agronomic and economic impediments, which exist not only on grain legumes but also on most other minor crops. Due to these strong links between impediments, the lock-in is systemic: any path towards diversification will necessarily rely on the simultaneous and organized mobilization of many actors (Geels 2002). It seems clear that a public policy, which would only contain measures intended for farmers, cannot be sufficient to enhance diversification (Louhichi et al. 2017). The proof was given in France in 2010–2011, when public authorities aimed to increase land areas in pulses, by proposing a specific incentive to farmers. This was effective the first year (doubling areas of pulses in 2010 compared to 2009), but these areas collapsed again the following year, because downstream actors were not particularly interested in native pulses. In contrast, from the end of the 1970s and during the 1980s, a policy guaranteed high prices for producers, support for plant breeding, and support for the animal feed manufacturers using pulses, ending in the spectacular expansion of pea areas (from less than 100.10^3 ha at the beginning of the 1980s to 700.10^3 ha at the beginning of the 1990, Magrini et al. 2016). Our results therefore refer back to the need for a critical analysis of the models on which agricultural policies are based, which rely on optimizing farmers' income, generally without taking into account the way the other stakeholders act.

3.2.2 Levers for unlocking

According to the multilevel theory of socio-technical transitions (Rip and Kemp 1998; Geels 2002), the unlocking process is based on the hybridization of some innovation niches with the dominant system. The emerging diversification value chains we have described, such that associated with the Bleu-Blanc-Cœur label around linseed, or that combining hemp cropping with industrial manufacturing of insulation panels, can be considered as innovation niches, as they are socio-technical systems emancipated from the dominant system's rules, where radical novelties emerge (Rip and Kemp 1998). Strategic niche management is a governance approach aimed at creating a protected space around a promising technology, stimulating collective learning, the alignment of expectations, and the building of social networks (Geels 2002; Schot and Geels 2008).

The analysis of impediments to diversification, and of the way they have been overcome in various cases, leads to identifying three major conditions which must simultaneously come together so that a diversification value chain emerges and consolidates (Fig. 2): (i) adaptation of standards and official quality signs, to improve the positioning of products from minor crops with the end consumer (Sect. 3.1.4); (ii) good coordination between the stakeholders, which allows fair distribution of added value and fluid share of information (Sect.

3.1.5); (iii) combination of genetic, agronomic, technological, and organizational innovations, essential to remove the obstacles to crop development and ensure higher added value (Sects. 3.1.1, 3.1.2, 3.1.3, and 3.1.4).

The emergence of a niche around a minor crop requires breaking dependence on commodities market, to create added value, which compensates for the handicaps related to the modest size of the value chain. In this aim, products from minor crops should be differentiated from the others by nutritional, technological, or environmental qualities recognized by the market. The public authorities can encourage niche building around minor crops by adapting the standards and official quality signs, in order to improve the positioning of their products with the end consumer, by stressing their specific quality (Zander et al. 2016). To the benefit of several of the 11 crops, a "health-agriculture" quality sign could be established for products of high nutritional quality (such as animal products rich in omega-3 fatty acids, or pulses), or for the clarification of recycling costs when marketing insulation panels. Similarly, the development of organic farming in arable crops (in 2016 around 3% in France) might enhance the emergence of value chains linked to minor crops. However, as shown by the results in Sects. 3.1.3 and 3.1.4, this differentiation may involve transaction costs (collection, storage, traceability, etc.) likely to reduce its economic interest, particularly when the supply is scattered over the territory. Good coordination of the actors in the value chain can make it possible to reduce these transaction costs (Fares 2006).

But how can different stakeholders, who do not necessarily know each other (plant breeders, cooperatives, processors, distributors, research organizations, advice organizations, farmers, etc.) coordinate their strategies around a diversification project? To this end, it would be relevant for public authorities, at local or regional level, to support the construction and long-term functioning of partnership arrangements, which would serve to encourage the people concerned to get to know each others, and contribute to the incubation and assessment of the technological, agronomic, and organizational innovations required to make the value chain competitive. Blesh and Wolf (2014) have shown the interest of building such actor networks for change. One example of such a device is the *European Innovation Partnerships for agricultural productivity and sustainability* (Eip-agri 2015), implemented by the European Commission, which aims at developing local innovation groups to encourage the learning process of various stakeholders involved in local joint agricultural projects. As underlined by Sol et al. (2012), social learning in such multiactor innovation networks is "a means for enabling stakeholders to take advantage of the diversity in perspectives, interests and values for generating more sustainable practices and policies."

Concerning the development of genetic, agronomic, technological, and organizational innovations, our results show

that private investments are not usually sufficient to remove the obstacles to the development of value chains and ensure additional added value. Lock-in does not leave any hope of seeing these investments increase, and a nudge in the right direction by public authorities is clearly essential. Public research should have a pro-active strategy to enhance knowledge production on these species, but also provide methodological support to stakeholders in the emerging value chains (for example, low-cost plant breeding methods, cropping system design approaches, management principles for collection logistics, etc.). Support for innovation also concerns the provision of integrated pest management solutions for minor species. A sustained effort (by R&D and advice organizations) seems crucial for the production of quantified information on the compared margins of more or less diversified rotations; the same is true for the organization of support to farmers in learning about new crops, by reinforcing experimentation and advice networks, and by sharing innovative experiences within farmer groups (Chantre and Cardona 2014; Blesh and Wolf 2014). Jordan et al. (2016) and Meynard et al. (2017) have shown the importance of coordinating innovation fields, between breeding, agriculture, processing, and food distribution. Generally speaking, crop diversification challenges the public policies of support for innovation (Levidow et al. 2014; Meynard et al. 2017).

4 Conclusion

This article makes a clear analysis of the various interconnected impediments that create a socio-technical lock-in in favor of the dominant species, which hinders the development of minor crops, whereas greater crop diversification is required for agroecological transition. Analyzed in France, similar lock-in could exist in most European countries. These impediments occur at every link of the value chains of minor crops: poor availability of improved varieties and methods of plant protection, scarcity of quantified references on crop rotations, complexity of the knowledge to be acquired by farmers, logistical constraints concerning collection, and difficulties of coordination within the emerging value chains. As this lock-in is systemic, any path towards diversification will necessarily rely on the simultaneous and organized mobilization of many stakeholders. Concerning public authorities, agriculture and food policies are questioned, but also research and innovation policies. Based on our lock-in analysis, we propose ways to reinforce niches and prepare unlocking, whose effectiveness will have to be tested.

Such a study would not have been possible without close interdisciplinarity between agronomists and economists. Other approaches and theoretical frameworks, in agronomy or economics, could have been used to analyze the increase in areas of major crops and the decline of minor crops, and to

model these trends. Several studies, based on such disciplinary approaches, are quoted in our paper (for example, in agronomy, Schott et al. 2010; Ponisio et al. 2015; Zimmer et al. 2016; in economics, Fares 2006; Filippi et al. 2008; Louhichi et al. 2017). However, the complex and systemic characters of specialization led us to overpass these disciplinary approaches, to adopt a holistic perspective of the involved socio-technical factors. We used the interdisciplinary framework of socio-technical systems and lock-ins, which performed in the analysis of impediments to pesticide reduction. Socio-economical approaches could enrich our results, such as the analysis of the design of public policies and the building of actor networks around minor crops to favor learning paths. In agronomy, the analysis of the lock-in, and the on-going action-research on unlocking open up numerous new questions: the role of agronomists appears essential to understand the technical dimension of lock-in (analyses of cropping and farming systems, varietal selection or collection), to characterize the nature of technical information exchanged between the actors, or to analyze the specifications imposed on or proposed to farmers by the downstream actors. In a perspective of unlocking, they can contribute to designing agronomic innovations (innovative crop management or cropping systems, diagnostic tools for minor crops) or to proposing ways of producing technico-economic references. But it will be important that they also take part in designing genetic or organizational innovations (such as collection logistics), striving to ensure coherence between fields of innovation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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