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RESEARCH ARTICLE

Dairy crossbreeding challenges the French dairy cattle sociotechnical regime

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Abstract

Rotational crossbreeding can be faster and more effective than pure breeding in improving the functional traits of cows and developing robust dairy cattle systems. However, this practice remains uncommon worldwide. This is largely assumed to be due to a scarcity of knowledge on dairy crossbreeding schemes and their benefits for cows and herd performance. However, crucial questions remain: Why do so few technical references exist? Why and how do some farmers embrace this practice despite the lack of guidance? To answer these questions, we adopted a sociotechnical view of dairy crossbreeding to characterize the factors that drive, support, and impede its development in France. We qualitatively analyzed 73 articles from two French technical journals on dairy cattle and semi-structured interviews of 17 dairy cattle farmers who practice crossbreeding and 15 representatives of key stakeholders in the sector. Using all these data, we identified three drivers of using dairy crossbreeding: technical problems related to breeding highly specialized purebred cows, the shift towards more sustainable and resilient dairy cattle systems, and a desire to regain decision-making autonomy in farm management. Based on farmers' interviews, it became evident that they developed know-how "on the job" and created new support networks to overcome impediments that were primarily cognitive/cultural but also technological and market-driven; with these resources, they progressively turned away from the mainstream sociotechnical regime. Based on stakeholders' interviews, we characterized four groups that limited the development of dairy crossbreeding and one that supported it, and we identified organizational, cognitive/cultural, technological, and economic barriers—many of which were interrelated and self-reinforcing—to its use. These findings demonstrate that dairy crossbreeding is widely recognized as beneficial for the sustainability of dairy cattle farms but remains uncommon in France due to the sociotechnical lock-in of the dairy sector around both pure-breeding and high-specialization paradigms of herd management.

Keywords Agrobiodiversity · Livestock farming system · Sociotechnical transition · Agroecology · Sustainability · Agency · Practices

1 Introduction

In the second half of the twentieth century, livestock farming systems were intensified to increase productivity; this was achieved by selecting animals and plants based on production traits, using inputs (e.g., concentrated feed, chemical fertilizers, veterinary products) to reduce environmental heterogeneity and the effects of limiting factors, and standardizing production technologies (Thornton 2010). These efforts were thus associated with the specialization of animals, plants, farms, and regions. In dairy cattle farming, this agricultural model, grounded on a genetic system organized for each breed, has led to the specialization of certain breeds for milk yield and their massive and widespread dissemination to farmers. The best example of this is the Holstein breed, which has been strongly selected for milk productivity and is the most widely used dairy breed worldwide (Oltenacu and Broom 2010; Labatut and Tesnière 2018), including in France, where in 2019 it represented 64% of all dairy cows (Idele and CNE 2019). However, the high yield of Holstein cows comes at the expense of their fitness traits (Oltenacu and Broom 2010) and their ability to adapt to restricted diets and climate change (Knaus 2009). Conversely, cows selected for more diverse target criteria (e.g., dual-purpose breeds) often

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have lower milk production but better fitness traits, which may be particularly suitable for low-input or grass-based dairy cattle systems, and sustainable and resilient systems in general (Nauta et al. 2005; Rodríguez-Bermúdez et al. 2019).

Transitioning towards more sustainable and resilient dairy cattle herds raises the question of selecting cows that are best adapted to less artificial conditions (Rodríguez-Bermúdez et al. 2019). Changing the breed entirely is rarely an option for farmers because of the financial burden involved in selling a herd and purchasing another one. Furthermore, there are health risks associated with introducing large numbers of animals from another farm. Finally, merging one breed to another (e.g., through continuous backcrosses) can challenge farmers' expectations about animal performance, particularly when combining milk yield and functional traits. Instead, rotational crossbreeding between two or more dairy breeds (hereafter, "dairy crossbreeding"; Figs. 1 and 2), by making use of both heterosis and breed complementarity, can be faster and more effective than pure breeding in improving the functional traits of cows, developing efficient and robust livestock farming systems (Sørensen et al. 2008), and customizing cows that are best suited for a farmer's goals and circumstances. Dairy crossbreeding has been developing in recent years in the USA and Europe (Rinell and Heringstad 2018) but remains rare worldwide, with the notable exception of New Zealand (Sørensen et al. 2008). Similar trends are evident in France: even though the number of dairy crossbred cows in lactation increased by an average of 4% per year between 2013 and 2018, they still only represented 6% of lactating dairy cows at the end of that period (REPROSCOPE 2018).

In a system of bovine genetics organized for and within individual breeds, dairy crossbreeding can be seen as a novelty, i.e., "a new technical concept or a new way of doing things" on a farm, which may "lead to significant changes in the regime actors and prelude a [sustainability] transition" if conditions are right (Elzen et al. 2012). According to Geels (2002), a sociotechnical regime is "the semi-coherent set of rules carried by different social groups" that guide and coordinate their activities and thus provide the system with stability, leading to locking phenomena that prevent the emergence and development of novelties. These system innovation and transition theories assume that a novelty emerges outside or on the fringes of the sociotechnical regime (a niche) and that a transition requires an alignment between the visions and practices within the regime and those within the niche. Elzen et al. (2012) proposed the concept of "anchoring" to conceptualize emerging forms of linkage between a novelty and its environment (either its niche, other niches of novelty, and/or the regime). For these authors, "anchoring is a process in which the activities of individuals or individual organizations are crucial to actively create the new connections between a novelty and its environment," and they distinguished three types: technological, network, and institutional. In general, studies have addressed these processes of anchoring based on retrospective analyses of successful pathbreaking novelties, and to a lesser extent, through the analysis of a promising novelty in the making. With few exceptions (e.g., De Herde et al. 2019), they have not examined this process from a pragmatic point of view, i.e., based on the practices of individuals and the justifications they give for them.

To date, research on dairy crossbreeding has mainly focused on comparing the performance of purebred and crossbred cows among different crossbreeding schemes (Sørensen et al. 2008). The outcomes of such investigations are technical references on crossbreeding schemes that are intended to be used by and for farmers, and the scarcity of such references is assumed to be responsible for the limited use of dairy crossbreeding on farms. However, crucial questions remain: Why do so few technical references exist for dairy crossbreeding? Why and how do some dairy cattle farmers adopt herd management based on this approach, even though few references exist? The answers to these questions require an analysis of the sociotechnical conditions of the development of dairy crossbreeding, which to our knowledge has not yet been addressed.

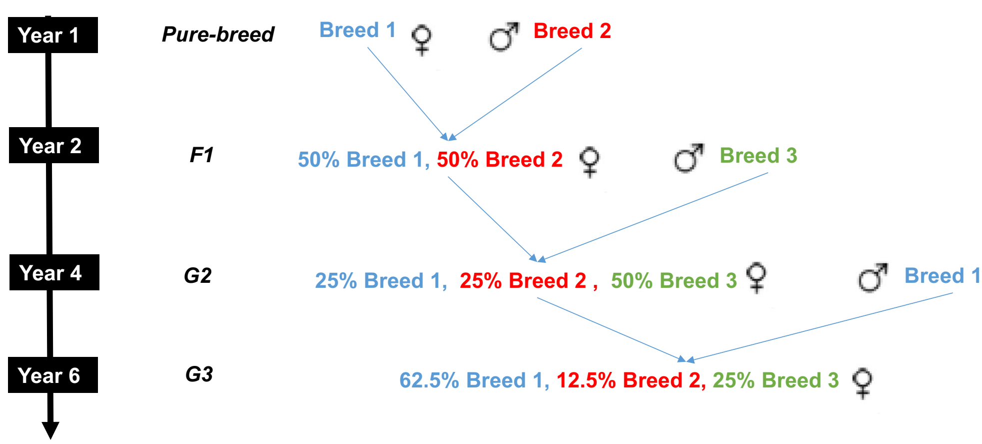

Fig. 1 Three-breed rotational crossbreeding scheme in a dairy cattle herd. F1, G2, and G3 are successive generations of crossbred females in the herd. The signs ♀ and ♂ refer, respectively, to the female used for herd replacement and the male used for insemination or mating. In this example, females are mated at 24 months, so that 5 years elapse between the first crossing and the 3rd generation of crossbred females

Fig. 2 Crossbred cows in pasture and housing and crossbred heifers for herd replacement (source of photos: Oasys, 2017 and Quénon, 2018)

We hypothesized that, although widely recognized as beneficial for the sustainability transition of dairy cattle farms, dairy crossbreeding remains uncommon due to sociotechnical lock-ins in organizational, technological, cultural, cognitive, and economic aspects of farming. We anticipated that evidence of such lock-ins would be apparent in reports from members of the dairy cattle industry who have changed their practices and in the justifications they gave for these changes. Here we tested this hypothesis in France, by focusing on the interplays between the novelty (dairy crossbreeding) and the sociotechnical regime in dairy cattle farming and pragmatically analyzing the practices of farmers and other stakeholders, their determinants, and the resources these individuals drew upon. Our objective was thus to understand the factors that drive, support, and impede the development of dairy crossbreeding in France.

2 Materials and methods

We constructed three datasets from May 2016 to June 2018. One contained articles on dairy crossbreeding from two relevant French technical journals and was intended to provide an overview of the knowledge disseminated on this topic to farmers and other stakeholders in the dairy cattle sector in France (Section 2.1). The second and third datasets contained data from interviews with, respectively, dairy cattle farmers who performed crossbreeding as a long-term breeding strategy (Section 2.2) and representatives of stakeholders involved in dairy cattle farming in France whose activities could affect and be affected by the use of crossbreeding (Section 2.3). We performed a thematic analysis (Guest et al. 2012) of each dataset by coding data around themes to identify the drivers of the use of dairy crossbreeding (all three datasets), the changes farmers made in order to use it (dataset 2), and the contributions of stakeholders to its development (dataset 3). Each theme was broken down into sub-themes, for which variables were generated for each individual (datasets 2 and 3) or technical article (dataset 1).

2.1 A review of articles from two French dairy cattle technical journals

From March to June 2018, we performed a literature review of articles on dairy crossbreeding from two relevant French technical journals: *L'éleveur Laitier* and *Réussir Lait*. These journals were selected because they specialize in dairy cattle farming and are widely distributed among French farmers and dairy cattle stakeholders. To search articles on the journals' websites, we used the query *(crossbreeding OR "crossbred cows") AND (dairy AND cattle OR farm)* (with terms in French). We excluded all articles that addressed only crossbreeding with beef breeds. The final dataset consisted of 73 articles published from 2008 to 2017. There was a detectable increase in the number of articles published over time, especially after 2012. Articles were based on farmers' reports and research experiments, mainly in France, although some of the described studies were in the USA (6), Ireland (3), and New Zealand (3). For each article, we coded the drivers underlying the use of dairy crossbreeding, which could be, for example, the motivations behind its use, the types of dairy cattle systems associated with it (e.g., conventional, organic, grass-based, or low input), and the benefits derived from its use. We also coded the type of crossbreeding schemes involved and the disadvantages of crossbreeding to triangulate data with datasets 2 and 3.

2.2 Interviews with farmers who perform dairy crossbreeding

We interviewed dairy cattle farmers who performed dairy crossbreeding as a long-term breeding strategy, which we defined using two criteria: the percentage of crossbred cows in the herd was above 10% in 2015, and the purpose of farmers was not to absorb one breed into another but to shift to partially or integrally crossbred herds. We used the "snowball" method for sampling, which is suited for targeting hard-to-reach populations (Biernacki and Waldorf 1981). To start, we obtained the contact information for three farmers from farm consultants or agents from selection companies. Each contact was chosen from one of three geographical areas in France (Finistère, Aveyron, and Rhône-Alpes) to explore different contexts of dairy production; different group dynamics could influence why and how farmers adopted this method in different regions and the resources available to them.

We conducted 17 semi-structured interviews with farmers from May to June 2016. The interviews were organized in five parts and were targeted at farmers' motivations for adopting dairy crossbreeding, their changes in herd management, the resources they used to make the change, the difficulties they encountered, and the benefits they obtained. Each interview lasted 90 min and was recorded. We coded data from the five parts of the interviews. To identify the drivers of using dairy crossbreeding, we coded data from the parts related to farmers' motivations and the benefits derived. We coded data from the other three parts to identify changes they made: the obstacles they had to overcome in their shift towards a crossbred herd, what they did to overcome these, and how they learned what to do.

2.3 Interviews of key dairy cattle stakeholders

We interviewed a variety of key stakeholders involved in the dairy cattle sociotechnical system in France, including those involved in the management of animal genetics, farm consultancies and services, and the downstream sector, especially livestock trading companies (Fig. 3). We selected individuals who had strategic positions in the targeted organizations, as well as those who had daily contact with farmers (e.g., inseminators, consultants) in the three geographical areas where we had interviewed farmers in 2016. We used companies' websites and collaborated with several secretarial services and professional networks to organize the sample pool. The final sample consisted of 15 individuals, of whom two were involved in public genetic research and R&D, two were from breeding societies, three were from two dairy cattle selection companies, two worked as inseminators, three were advisers from public organizations (one from a Chamber of Agriculture and two from milk recording services), and three were livestock traders (Fig. 3).

We conducted the semi-structured interviews from May to July 2018; these were divided into three parts: a brief presentation of the person's professional activities within the company; his/her view of dairy crossbreeding, including the type of livestock systems in which it is set up and used, the presumed reasons farmers adopt it, and its advantages and disadvantages; and changes in his/her practices related to dairy crossbreeding and the reasons why they changed or not. All interviews were recorded and completely transcribed. To identify the drivers underlying the use of dairy crossbreeding according to the stakeholders, we coded data regarding the reasons they presumed farmers would use crossbreeding and the benefits they presumed farmers would derive. To characterize stakeholders' contributions to its development, we characterized them according to the degree to which their professional activities had been changed (no/minimal change, or the development of specific practices) and their degree of interest. For each group of stakeholders, we coded and analyzed the factors that determined their contribution to dairy crossbreeding. Factors were defined as organizational (e.g., institutional, political, regulatory, professional network), cultural (e.g., professional standards), and cognitive, technological, or economic.

3 Results and discussion

3.1 Three main drivers of dairy crossbreeding represent a response to the high-specialization dairy cattle regime

Based on the analysis of all datasets, three main driving forces emerged as pushing and pulling French farmers to use dairy crossbreeding (Table 1). Together, these drivers highlight that belief that dairy crossbreeding is a means for farmers to address tensions with the current sociotechnical regime, which is characterized by the dominance of highly specialized but ill-suited breeds, and the associated agricultural knowledge system, which prevents the sustainability of dairy cattle farms.

The first driver pushing farmers to use dairy crossbreeding is problems with the breeding and health of highly specialized purebred cows. Four indicators were identified (Table 1).

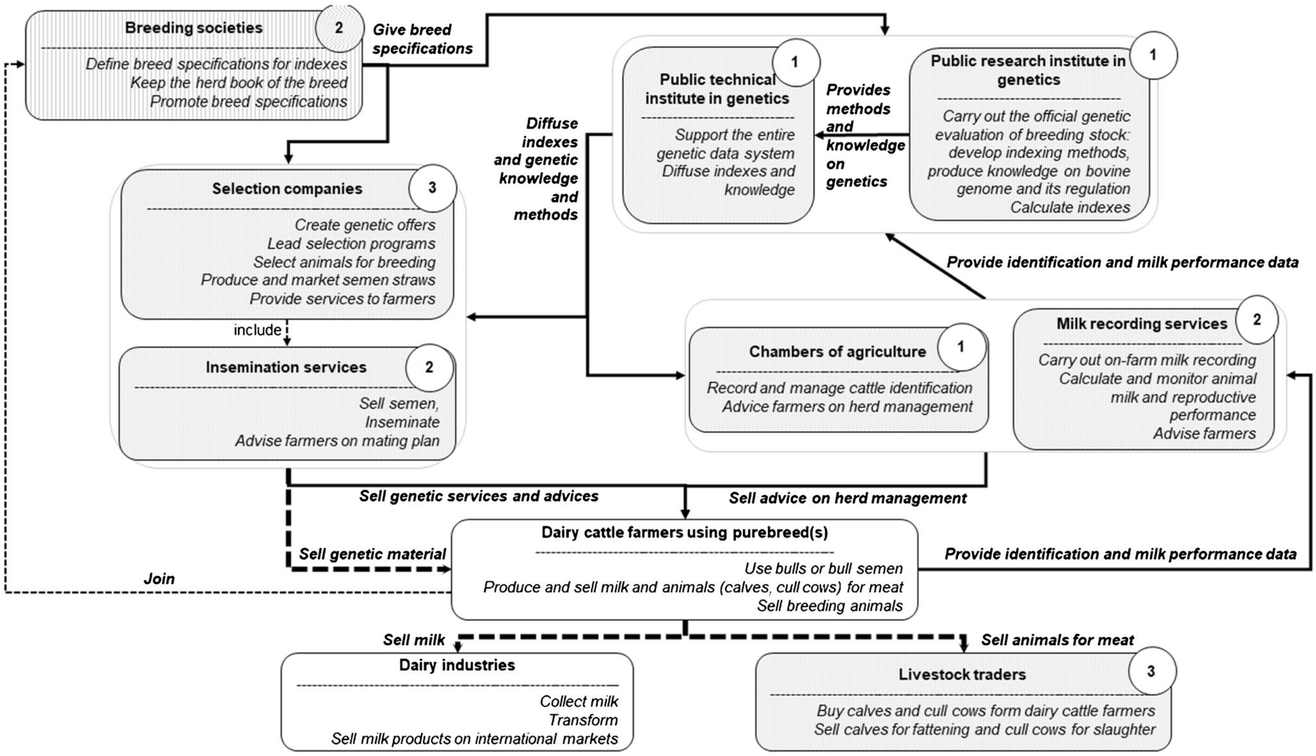

Fig. 3 Missions and interrelations among the key stakeholders of the dairy cattle sociotechnical system. Each is represented by a box, with its missions in italics within the box. Three types of relationships are represented according to whether they refer to the exchange of information, data, or knowledge (solid arrow); the exchange of materials or products (thick dotted arrow); or membership (thin dotted arrow). The stakeholders interviewed here are shaded in grey. The number of the individuals interviewed in each group is shown in the associated circles

Overall, the Holstein breeds, and to a lesser extent Montbéliarde, were mentioned as the primary breeds for starting a dairy crossbreeding program (79% of technical articles, 94% of farmers, and 100% of stakeholders). The Holstein breed alone was mentioned in 79% of the technical articles, by 82% of the farmers, and by 87% of the stakeholders. These two breeds are the two main commercial dairy cattle breeds in France (Idele and CNE 2019) and worldwide and have historically been selected for milk production at the expense of functional traits (Knaus 2009). In accordance with

Table 1 The drivers identified as pushing and pulling French farmers to adopt dairy crossbreeding long-term, according to interviews with 17 French farmers and 15 representatives of dairy cattle stakeholders, and a review of 73 articles from two French technical journals on dairy cattle farming

Drivers of the use of dairy crossbreeding		Frequency		
		% of technical articles	% of farmers	% of stakeholders
Overcoming breeding and health problems of highly specialized purebred cows	Improving performance of initial herds composed of purebred Holstein and Montbéliarde cows	79	94	100
	Improving functional traits	57	94	100
	Increasing milk protein and fat content	12	59	80
	Managing inbreeding in the herd	0	24	53
Moving towards more sustainable and resilient dairy cattle systems	Adapting cows to grassland-based, low-input, and organic farming	37	76 (organic farming) 86 (grass-based system)	86
	Increasing farm economic profitability	26	82	60
	Improving working conditions		100	
Regaining decision-making autonomy in farm management		18	26	47

The frequency with which each driver appears in each data source is shown (in %)

this, the most commonly cited motivation for dairy crossbreeding was to improve functional traits, primarily cow fertility, health, and robustness (57% of articles, 94% of farmers, and 100% of stakeholders). Dairy crossbreeding can also be used to increase milk protein and fat contents, although these benefits were reported more by farmers (59%) and stakeholders (80%) than by technical publications (12% of articles). Finally, a smaller proportion of interviewees (24% of farmers, 53% of stakeholders) also mentioned another issue specifically linked with pure breeding: the management of inbreeding, which was viewed as being easier in a crossbred herd (Sørensen et al. 2008).

The second driver pulling farmers to use dairy crossbreeding is the desire to move towards more sustainable and resilient dairy cattle systems. Three indicators were identified. Dairy crossbreeding was viewed as a way to adapt cows for the transition of dairy cattle systems to grassland-based, low-input, and organic farming. In the technical literature, 37% of articles addressed dairy crossbreeding as a technique to adapt cows to such farming systems and mentioned dairy cattle farming in New Zealand as sources of inspiration. Overall, 76% of farmers interviewed practiced organic farming (against 4.6% in France in 2018 (Agence Bio 2019)), and their farms had a mean percentage of grassland of 86%. Similarly, 86% of stakeholders associated dairy crossbreeding with low-input, organic, or grassland-based systems; 38% also mentioned that dairy crossbreeding could be used in conventional or high-input systems but that, according to them, there would be little benefit of using crossbred cows in these environments compared to high-yield pure-breeds such as Holstein. More globally, dairy crossbreeding was mentioned as a way to increase the economic profitability of farms by reducing operational costs and/or increasing the value of milk products, by increasing milk protein and fat content without significant negative effects on milk production (26% of technical articles, 82% of farmers, 60% of stakeholders). Finally, farmers indicated that dairy crossbreeding improved their working conditions by generating more robust cows that required fewer interventions and by creating a more efficient and more profitable dairy cattle system that induced less mental stress.

A sizable minority of farmers cited a third driver that pulled them to use dairy crossbreeding: the desire to regain decision-making autonomy in farm management. Almost a quarter (24%) of farmers said they had previously felt locked into the mainstream agricultural knowledge system (AKS) in dairy cattle. They mentioned becoming increasingly skeptical of its tools and recommendations following a lack of progress in overcoming the fertility problems of purebred cows and/or transitioning towards grass-based or low-input dairy systems. For these farmers, adopting dairy crossbreeding was a way to regain autonomy over their breeds and to shape the genotypes in their herds in a way that enabled them to achieve their goals. This re-appropriation of animal selection and breeding led these farmers to be less dependent on the dominant actors of the genetic and dairy cattle regime, to leave behind some of its recommendations and tools (see Section 3.2), and to develop their own resources and skills to instead manage their herds in a direction that made sense for them. Strengthening farmers' autonomy was also a driver stressed by 47% of stakeholders: they mentioned that dairy crossbreeding was a means for farmers to challenge and differentiate themselves from the larger sociotechnical regime. In a similar vein, 18% of technical articles highlighted a farmer's personality (e.g., capacity to innovate) as having a major influence on the adoption of dairy crossbreeding.

The three drivers of using dairy crossbreeding that we identified were inter-related and referred to both the "practical difficulties" experienced by farmers (Coquil et al. 2017) as a result of the high degree of specialization of commercial dairy cattle breeds (Oltenacu and Broom 2010) and the awareness that their routine use of mainstream knowledge sources, in this case on animal breeding and herd management, locked them into these difficulties (Dosi 1982). Hence, within the three datasets, dairy crossbreeding was considered as a means of overcoming these practical difficulties, which were mainly related to the lack of fertility and robustness of their initial purebred cows (Sørensen et al. 2008). Such problems undermine herd profitability (De Vries 2006) and farmers' working conditions. They can also prevent farmers from moving towards grass-based or organic farming systems, which require that cows be able to reproduce at the appropriate time (i.e., when grassland resources are available) and that they are adapted to this kind of feed (Berry et al. 2013). Therefore, dairy crossbreeding was largely recognized by the sampled individuals as a novelty that offers a more sustainable perspective for dairy cattle than pure breeding: it can improve herd profitability by restoring multi-functionality to cows (Dezetter et al. 2017; Clasen et al. 2020) and, in particular, adapt cows for the conversion to organic farming (Nauta et al. 2005) and the transition towards or the management of grass-based systems (McClearn et al. 2020; Quénon et al. 2020). Beyond the issue of high specialization of breeds and dairy cattle systems, our results showed that, for some individuals, a driving force behind the use of dairy crossbreeding was the desire to counter the "expert knowledge and specialization" paradigm (Sievers-Glotzbach and Tschersich 2019) within the regime, which separates those who know about animal breeding and selection from those who perform it. Thus, as previously shown for the use of seeds by farmers (Coolsaet 2016), to overcome the practical difficulties they were experiencing, these dairy farmers felt the need to regain autonomy over their breeds and reacquire situational knowledge, which for some of the individuals interviewed was the most important driver. Dairy crossbreeding was a way to first reclaim autonomy and then to rebuild an individual or collective identity (Coolsaet 2016) and therefore represents a part of the process of "re-peasantization" (van der Ploeg 2008).

3.2 Farmers' practical experiences of using dairy crossbreeding: "learning by doing" and creating new support networks to turn away from the mainstream sociotechnical regime

When farmers adopted dairy crossbreeding, most reported that they developed their know-how for the new system through "learning by doing" and developing their personal and professional networks, which enabled them to turn away from the mainstream sociotechnical regime. Our analysis revealed that such know-how enabled them to face four commonly cited impediments, mainly related to a lack of knowledge and cultural, technological, or market-driven barriers (Table 2).

First, as there was very little formal knowledge available about the management of dairy crossbreeding, farmers taught themselves by experimenting, evaluating what worked or did not work, and readjusting their practices according to the results they obtained. As reported by Quénon et al. (2020), the farmers we interviewed consistently mentioned two elements of herd management as critical for the introduction of dairy crossbreeding: (i) the choice of crossbreeding scheme (the breeds included and how) and (ii) the rhythm of introduction

Table 2 Synthesis of the four main kinds of impediments farmers face in moving from purebred to crossbred dairy cattle herds: knowledge, cultural, technological, and economic

Category of impediments	What did farmers have to overcome? *(% of farmers who mentioned it)*	What did they do to overcome? *(% of farmers who did it)*	How did they learn what to do?
Knowledge	Lack of knowledge about:		
	Types of crossbreeding schemes and their benefits/costs	Customized dairy crossbreeding scheme by trial and error *(73%)* *vs*. purchased and applied a commercial dairy crossbreeding scheme (e.g., ProCROSS) *(17%)* Used a single dairy crossbreeding scheme *(76%)* *vs*. several *(24%)*	E, I
	Rhythm for introducing crossbreeding in the herd	Introduced rapidly to see benefits *(41%)* *vs*. slowly to minimize risks in case it did not work *(59%)*	E
	Effects of crossbreeding on herd performance, including during the transition from purebred to crossbred herd	Tracked and analyzed their cows' performance data (23%) *vs*. estimated the effect of crossbreeding qualitatively through the economic profitability of the farm *(77%)*	E , I
	Unavailability of genetic tools and advice		
	No indexes for crossbred females to plan cows' mating	Planned mating based on cow performance and indexes of purebred males	E
	A single code "39" for crossbred dairy cows in milk-recording databases that prevents following the genealogy of crosses *(18%)*	Developed individual methods of tracing cows' genealogy Disregarded the advice of milk recording consultants and inseminators	E I
	A top-down system of knowledge production	Developed know-how via informal networks for creating and sharing ad hoc knowledge *vs*. developed know-how but remained connected to mainstream dairy cattle knowledge and innovation system	E, I
Cultural	Professional norms		E, I
	- Purebred dogma - High-yield cows - Homogenized herd	Turned away from mainstream networks of dairy cattle farmers and advisors Constructed new professional norms within farmers' groups focused on grassland-based or organic dairy cattle systems *(76%)*	
Technological	Equipment not adapted to the heterogeneous size of crossbred cows (e.g., milking parlors) *(24%)*	nd	nd
Market/economic	Low-economic return on some crossbred calves	Sold at loss	E
	Low-economic return on females for breeding and replacement	Developed peer networks, Revisited mating strategies	E, I
	Lack of supply of semen for breeds that are less common in France (e.g., Jersey) or crossbred sires *(18%)*	nd	E

Each category is broken down into specifics that emerged from the analysis of farmers' practical experiences; these are further described with the identification of the problem, what farmers did to overcome it, and how they learned what they had to do (*E* experiential learning, *I* interactions with peers/networks) of crossbreeding in the herd. Most of the farmers had adopted a single rotational crossbreeding scheme, mainly three-breed (or more; 71%) and, to a lesser extent, two-breed (6%). Likewise, three-breed and two-breed rotational crossbreeding schemes were the most referenced in technical journals, in 59% and 23% of the reviewed articles, respectively. The other 24% of farmers used several rotational crossbreeding schemes simultaneously, a strategy that was not mentioned in the technical articles or by stakeholders. Furthermore, 73% of farmers customized their schemes by testing different breed combinations through trial and error, while 17% applied the ProCROSS commercial three-breed rotational crossbreeding program, based on Holstein × Montbéliarde × Viking Red breeds, which is jointly marketed internationally by two selection companies, Coopex Montbéliarde (Roulans, France) and Viking Genetics (Randers, Denmark). Information on this scheme has been increasingly available since 2012 both in French technical journals (14 articles among the 18 identified as dealing with this scheme) and in scientific journals (Dezetter et al. 2017; Shonka-Martin et al. 2018). While these publications may have given farmers some knowledge on the benefits of this crossbreeding scheme for herd performance, and presumably reduced uncertainty, only a small number of farmers chose to use it. This may be due to the fact that the ProCROSS program was mainly studied in conventional dairy cattle herds largely based on the use of feeding inputs, and not in organic or grass-based systems, which here represented 76% and 86% of the sampled cases, respectively. With respect to the rhythm of introducing crossbreeding in dairy cattle herds, 59% of farmers began crossbreeding with only a few inseminations, to observe the results before fully engaging in this management practice. Instead, the remaining 41% of farmers crossbred a large number of cows right away, as they viewed this as being the best way to quickly realize the benefits of crossbreeding.

Although all farmers had extensive experience in managing dairy cattle herds, a few of them explicitly mentioned impediments related to knowledge, technology, and market factors (Table 2). For 29% of the farmers, their efforts were complicated by a lack of technical references and knowledge about crossbred herd management and performance (e.g., types of crossbreeding schemes, herd management pathways for transitioning to crossbreeding, effects of crossbreeding on herd performance). This gap was also identified in the review of technical literature; although some articles did give information about the effects of dairy crossbreeding on herd performance, data were provided only for certain times and not for the long term or in the transition period from purebred to crossbred herds. Only one article, from 2016 and based on a French PhD thesis (Dezetter et al. 2017), addressed the transition period. Beyond the lack of reference material, some genetic tools commonly used in purebred herd management are unsuited for crossbred herds. Indeed, 35% of farmers reported that the lack of genetic indexes for crossbred animals, particularly females, complicated the management of mating plans and herd replacement; these farmers had previously predicted cow performance before conception using tools for purebred herd management and could no longer apply this approach to their crossbreeding programs. Moreover, 18% of farmers had difficulty building their own reference databases of the performance of genetically heterogeneous individuals within the herd, because all crossbred cows are currently identified with a single code (code "39") in milk-recording databases. To address this problem, some farmers took it upon themselves to trace the genealogy of all of their crossbred cows. In addition to impediments related to knowledge (including resource materials), a few farmers mentioned technological barriers. In particular, 24% of farmers mentioned specific and sometimes daily problems using milking parlors or stalls that are designed for uniformly sized cows and are unsuited to genetically, and thus phenotypically, heterogeneous herds. Finally, a few farmers cited market impediments either upstream or downstream, as was previously reported by Leroy et al. (2015) in a study of crossbreeding (in its broadest sense) in multiple animal species. Specifically, 18% of farmers mentioned difficulties obtaining semen for less-common breeds such as Jersey and even more difficulties for crossbred sires. Downstream, 24% of farmers who used the Jersey breed in their crossbreeding scheme mentioned a lack of economic return from crossbred calves. Similarly, 24% of farmers said that crossbred females had no economic value for replacement and breeding because they were not indexed.

Finally, our analysis revealed that the main resource that farmers used in developing their skills and knowledge on crossbred herd management was interpersonal and local support networks. Such networks enabled them to (1) address the absence of relevant information and knowledge from the mainstream AKS for dairy cattle farming and (2) break out of the "expert knowledge and specialization paradigm" which "refers to the prevailing beliefs about the right forms of knowledge creation and use" (Sievers-Glotzbach and Tschersich 2019) and the cultural standards in which this system is embedded. All the farmers interviewed said that they had consulted informal informational resources and interpersonal networks to make the decision to move toward dairy crossbreeding and to make a plan for the transition (Table 2). Indeed, they all mentioned they had mainly based their decisions on other farmers' experiences of managing crossbred herds, whether through farmer profiles in technical journals or their own interpersonal contacts, which was also the main way they found networks for selling crossbred cows. Beyond peer-to-peer exchanges, 76% of the farmers relied on groups of farmers that shared similar ideas on the management of dairy cattle farms beyond just the use of crossbreeding. Thus, 47% of farmers joined or helped to establish groups organized primarily around the management of grassland-based dairy cattle systems, which were led by an adviser from the Chamber of Agriculture. For these farmers, the issue of animals' adaptation to such systems led to the idea of using dairy crossbreeding, and these groups offered resources and support for building shared knowledge on and local solutions for crossbred herd management and performance. The other 29% of farmers belonged to a network of organic farmers within the structure of a dairy enterprise that collected organic milk. Unlike the previous group, this network supported interpersonal exchange but lacked a communal dynamic to enable collective learning. Finally, only 12% of farmers, all in conventional farming, mentioned relying preferentially on genetic advice and offers from a few selection companies, such as the one promoting and selling the ProCROSS scheme, in addition to interpersonal exchanges between farmers practicing crossbreeding. By creating alternative networks, whether interpersonal or collective, the majority of the farmers we interviewed had managed to turn away from the expert knowledge and specialization paradigm and cultural standards underlying the mainstream AKS. We found three types of evidence for this shift. First, they generated their own agricultural knowledge ad hoc, as well as their own systems of validation, which stands in contrast to the top-down mode of knowledge production underlying the mainstream AKS. Second, they had turned away from the cultural/professional standards that define the mainstream AKS. Thus, although 41% of the farmers mentioned the difficulty of breaking free from the dogma of pure breeds in France, all of the farmers interviewed had abandoned the norm of homogenized herds, with 88% of them stating that they had accepted a decrease in individual milk productivity because they viewed the benefits of dairy crossbreeding as being elsewhere. Third, a large proportion of the farmers no longer consulted inseminators on mating plans and milk recording services for performance monitoring, as their tools for these (female indexes and genealogy tracing for crossbred cows, respectively) were no longer relevant. Moreover, according to these farmers, such individuals were too focused on upholding professional standards of pure breeding and high specialization of dairy cows and herds.

These findings show that a transition from purebred to crossbred dairy cattle herd management requires farmers to break free of norms of the mainstream sociotechnical system, which is generally achieved through self-taught know-how (doing, adapting, assessing) and through interaction with alternative networks; similar technical and social learning processes have been described in transitions towards alternative or sustainable agricultural practices (Ingram 2010, 2018). Our results also emphasize the ways that the mainstream AKS hinders the development of dairy crossbreeding: first, through the lack of support for farmers who are willing to try dairy crossbreeding, and second, its dogmatic insistence on modern methods of scientific livestock management that are unwilling or unable to meet the needs of farmers using dairy crossbreeding. Instead of predicting herd performance with indexes, farmers are forced to develop adaptive herd management approaches based on ad hoc references; beyond information about the best genetic schema to use, farmers need knowledge about the pathways that can be followed to implement and derive long-term benefits from dairy crossbreeding within a herd (Quénon et al. 2020). This suggests that, instead of merely making a technical shift from one system to another, these farmers have been making a cultural and professional transition (Coquil et al. 2017; De Herde et al. 2019). Dairy crossbreeding requires farmers to become comfortable with and take advantage of genetic and phenotypic variability rather than reducing it (Magne et al. 2019), which entails turning away from standards of pure breeding and high specialization in dairy cattle herds; a similar phenomenon was described for crop systems in France (Meynard et al. 2018). However, our results also show that there is heterogeneity among farmers in terms of their disconnection from the mainstream AKS, suggesting that patterns of knowledge acquisition, exchange, and networking are complex (Ingram 2010). Although all of the farmers looked for the support of fellow crossbreeders, only some engaged in networking to share and build local knowledge, while a few others chose to remain connected to players on the fringe of the mainstream AKS, and others felt isolated. This supports the existence of different paths of hybridization between dairy crossbreeding and the mainstream AKS, which can be indicative of the first stage of a potential transition (Elzen et al. 2012). Moreover, the farmers' experiences of dairy crossbreeding showed that, while it cannot yet be considered an institutionalized niche of novelty as such, it is anchored together with other more institutionalized niches of sustainable farming such as organic or grassland-based livestock farming. These findings suggest that the emergence and development of dairy crossbreeding is the result of two processes that are considered separately in the literature: the process of anchoring (Elzen et al. 2012) in more or less institutionalized niches of novelty in cattle farming and the process of insularization, i.e., growing from within and progressively detaching from the mainstream sociotechnical system (Vankeerberghen and Stassart 2016), particularly with respect to pure breeding.

3.3 Stakeholders' perspectives on dairy crossbreeding highlight sociotechnical lock-in

3.3.1 Four groups of stakeholders limited the development of dairy crossbreeding; one supported it

We discriminated among five groups of stakeholders according to their degree of contribution to the development of dairy crossbreeding and their interest in it. Four groups (groups A to

D) limited its development by considering it mostly or entirely incompatible with their activities: group A was resistant to dairy crossbreeding, while groups B to D made some changes (mostly minor) to cope with it. Conversely, members of group E supported dairy crossbreeding and integrated it into their activities. The barriers cited by each group of stakeholders to justify their position highlight their path dependency on pure breeding (Fig. 4).

Group A—Breeding societies: no change and no interest This group was composed of two breeding societies; they had not changed their practices and were not interested in rotational crossbreeding. Indeed, this practice challenges their main activities: defining and promoting purebred specifications that are then used in public genetic research to calculate indexes. One representative said: "For us, a three-breed cross cow is a cow we have nothing to do with and about which we have nothing to say!" These individuals did not believe that change was necessary because dairy crossbreeding is uncommon and would remain uncommon in France. The only form of crossbreeding which they found interesting and relevant for the breeding society was crossing to absorb another breed into the breed they promoted. Their positions on rotational crossbreeding were defined by four main barriers. The first was cultural, relating to pure-breed and homogenous herd standards: "We are not accustomed to having mixed-color herds, and we have a few barriers in our minds as traditional breeders." The other barriers were (i) economic, because according to these individuals, the development of rotational crossbreeding could challenge the profitability of breed selection programs; (ii) organizational, as the development of crossbreeding "is a question that goes beyond the breeding societies; it is a national decision"; and (iii) technological, related to the ability to index crossbred animals to be integrated into selection programs.

Group B—Public research institution and R&D in genetics: small proportion of their main activities, but a growing interest This group contained a representative of a public research institution and a person working in R&D in dairy cattle genetics. Both had previously carried out some work related to dairy crossbreeding and were interested in its development in France**.** Since 2010, these organizations have participated in a few studies in France to increase awareness of and methods for the genetic assessment of crossbred dairy cows (e.g., experiments and Ph.D. theses on dairy crossbreeding, European multibreed projects). However, less than 10% of the activities of their employers pertained to crossbreeding. Their main efforts remain focused on developing knowledge and specific methods for managing purebred genetics to meet the needs of most dairy farmers. These individuals saw two main types of barriers in their profession, with the first being organizational. They referred to the regulation of bovine selection, which is organized within pure breeds in France and Europe: "In European and French and almost all regulations worldwide...you can only exist in [research] genetics if you focus within breeds." They also referred to networking and political constraints. According to these two representatives, public research and R&D in genetics must focus on subjects that are relevant to most dairy cattle professionals, including farmers. Because crossbreeding is uncommon in France, research investment in it will serve only a small minority of farmers, which makes it difficult to justify. Moreover, farmers who use dairy crossbreeding are not represented in professional organizations such as breeding societies, so their needs are not advocated for on a large scale. Indeed, one of the

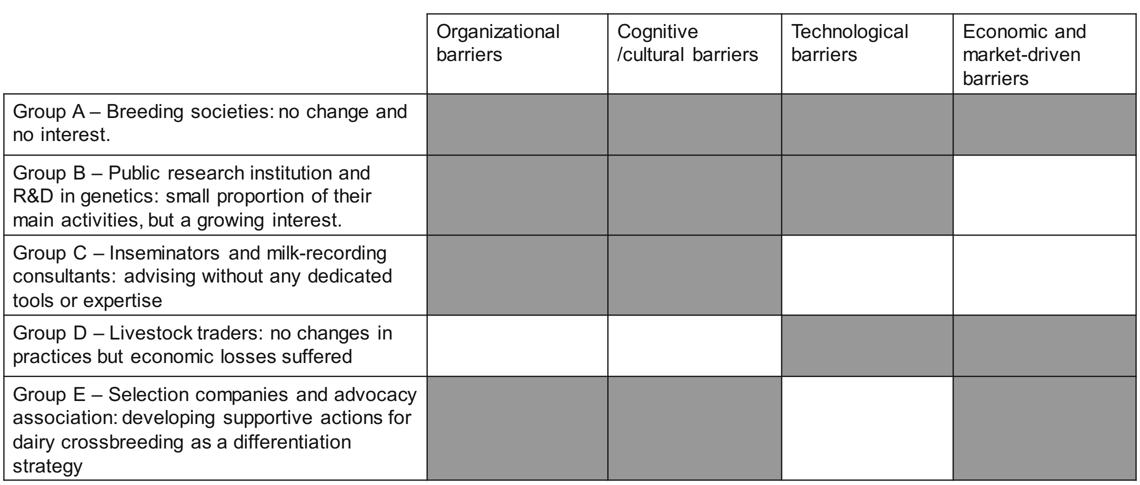

Fig. 4 The five groups of stakeholders delineated according to their degree of contribution to the development of dairy crossbreeding (in grayscale) and the sets of barriers mentioned by each to justify their contribution. Groups A to D hindered the development of dairy crossbreeding, and group E facilitated it. Four main sets of barriers were identified: organizational, cognitive/cultural, technological, and economic/market-driven, from the most to the least cited (as indicated by the number at the bottom right of the white boxes)

interviewees was of the opinion that "the majority of dairy farmers and […] professional organizations are against crossbreeding." The second type of barrier was technological, as there is a technological incompatibility between genomic indexing and dairy crossbreeding: "The difficulty is that we are now in the genomic era and that, inevitably, our small population of crossbred females has no genomic estimation." Analysis of genetic determinism and genomic indexing of crossbred animals are currently impeded by the lack of genotypes for these animals and the lack of a reference population of crossbreed animals to determine crossing parameters (heterosis and recombination losses). This is further complicated by the diversity of crossbreeding schemes on farms: "To go further, we need to have data on crossbred animals and enough data to be representative, not just special cases." Genomic indexing has also been hindered by the multitude of index expression databases (one per breed), which has complicated the comparison of possible indexes of crossbred females, and by difficulties in tracing the genealogy of crossbred individuals, who are currently identified only with the code "39" regardless of the breeds crossed.

Group C—Inseminators and milk-recording consultants: advising without any dedicated tools or expertise This group contained three inseminators and two milk-recording consultants. These individuals had all tried to adapt the classical management tools for purebred herds to advise farmers using or wishing to use dairy crossbreeding. Among these tools (male indexes, genotyping, female indexes, performance data), only male indexes and female performance data can be used to plan crossbred mating. As proposed by Sørensen et al. (2008), to manage crossbred herd replacement, many consultants recommended two strategies: (i) inseminating the best crossbred cows (i.e., those with the best performance according to farmers' objectives) with sexed semen (based on male indexes) and keeping all the female offspring, and (ii) inseminating the worst-performing crossbred cows with beef sires to increase the value from beef crossbred calves. However, these individuals felt their advice to farmers was of limited value due to the difficulties in predicting crossbreeding results, which is further complicated by the use of a single code to record crossbred cows regardless of the parental breeds or the generation of crossbreeding. The main obstacle to their contribution to the development of dairy crossbreeding was therefore cognitive. They indicated that they lack reliable tools to manage crossbreeding, i.e., tools based in genetic research to predict the performance of crossbred females. There is therefore an underlying organizational barrier: all of these individuals depend on the tools and knowledge produced by public and private research and R&D to carry out their activities. Their uncertainty about dairy crossbreeding makes them feel that they are losing credibility among farmers and can cause dissatisfaction in their job.

Group D—Livestock traders: no changes in practices but economic losses suffered This group was composed of three livestock traders; they had not changed their practices but had felt some negative economic repercussions due to the development of dairy crossbreeding on farms. Because dairy crossbred calves are more heterogeneous (in terms of conformation and growth rates) than purebreds and are not adapted to the equipment on downstream fattening farms, traders must sell them at low prices, give them away, or sometimes even euthanize them. For them, these net economic losses are not problematic at the moment because crossbred animals represent only a small fraction of their business (5–10% of the calves marketed). However, they mentioned that if dairy crossbreeding were to become more common, it would constitute a real economic problem for their business: "It must remain at these levels. It's true that otherwise it's going to be more complicated. Because giving away merchandise that we buy won't support us for very long." For these stakeholders, barriers to the development of dairy crossbreeding were not only economic and market-driven but also technological (fattening equipment requiring homogeneous animals).

Group E—Selection companies and advocacy association: developing supportive actions for dairy crossbreeding as a differentiation strategy This group represented two selection companies and the Chamber of Agriculture; these organizations have invested in supporting dairy crossbreeding management to differentiate themselves in a competitive market for genetic and breeding supplies and advice. In addition to standard services to pure-breeding farmers, these groups have developed technical references, services, and management tools to compensate for the lack of genotyping and genomic indexing of crossbred females and to address the need for an index to manage mating and replacement. In particular, the two selection companies have developed commercial supplies specifically for crossbred mating, including semen and associated breeding advice. One has been strongly involved in the development of the ProCROSS scheme in collaboration with Viking Genetics in Northern Europe. To date, this scheme is the first and only "product" available to farmers that is accompanied by a complete crossbreeding strategy. The other company has been expanding its genetic supply of sire breeds in France to meet the demand for cow traits and certain crossbreeding schemes (e.g., with Jersey sire). The Chamber of Agriculture, instead, has assembled and promoted a local network of farmers around grass-based dairy cattle systems, which ultimately distinguished itself by using dairy crossbreeding. Within this local network, the Chamber supports the sharing of farmers' practical experiences with dairy crossbreeding and has developed contextualized references on the performance of crossbred herds based on calculations of the gross margin. To develop a supportive environment for crossbreeding among French dairy cattle farmers, the stakeholders in this group had to overcome two types of barriers: (i) economic, i.e., the lack of financial resources allocated for research and development on dairy crossbreeding due to its small market share, and (ii) cognitive and cultural, i.e., the need to replace genomic indexes and the knowledge associated with them.

The delineation of these five groups highlights the extent to which dairy crossbreeding challenges the regime actors: overall, it poses a challenge to their established practices but has also invigorates some of them. This suggests that there is a subtle set of overlapping processes at work, involving some contested diffusion of dairy crossbreeding ideas into the AKS, as well as some potential co-learning and the emergence of fresh perspectives and opportunities for innovation (Ingram 2018).

3.3.2 Sociotechnical lock-in around pure breeding and high specialization in dairy cattle farming

These findings highlight four main types of interrelated and self-reinforcing barriers to the development of dairy crossbreeding in France (Fig. 4). They provide a better understanding of the mechanisms behind the inertia of the French dairy cattle sociotechnical regime, which is defined by the promotion of pure-breeding and high-specialization paradigms of herd management and from which the interviewed farmers had, to varying extents, broken free (cf. Section 3.2).

The first type of barrier is organizational, in that the system of French dairy cattle farming is a socio-economic, political, and cultural organization focused on purebred breeding. The use of dairy crossbreeding raises questions about the function of within-breed selection and challenges the very notion of a breed. Because breeds are a social construct rather than a biological entity (Labatut and Tesnière 2018), dairy crossbreeding challenges the foundations of the entire system of genetic exchange and more particularly the exchange of animals' information for mutual gain and the development of knowledge for the common good. Indeed, farmers who have adopted dairy crossbreeding benefit from genetic progress in the form of purebred males, but they do not contribute to it because crossbred females cannot be indexed. We show here that the interdependence of the stakeholders in the genetic system precludes the commitment of any one of them to actions related to dairy crossbreeding. That is, the stakeholders in genetic research and R&D (group B) stated that their commitment to studying dairy crossbreeding depended on the decision of the breeding societies (group A), which represent only purebred dairy farmers. This is a way for them to ensure that their work serves the greatest number of farmers, which is the main characteristic of a dominant practice/system (Magrini et al. 2019). However, the breeding societies had no interest in dairy crossbreeding as it calls into question their very existence. Furthermore, most genetic services and advice to farmers depend on the knowledge and tools produced by genetic research and R&D, particularly public research (group B). This organizational lock-in has crystallized around breeding societies as structures representative of the majority of farmers, from which those who practice dairy crossbreeding are excluded. This situation could be further exacerbated by new European regulations, in place since November 2018 (Official Journal of Europen Journal 2016), by which the missions of the breeding societies have been extended to encompass the calculation of indexes and their publication. Finally, dairy cattle farms' downstream dependence on finishing farms, and the demand for a homogeneous population of calves, could also jeopardize the development of crossbreeding.

The second set of barriers is cultural and cognitive. Dairy crossbreeding seems to challenge several sets of professional norms and standards, with two of the most central being the desire for purebred, homogeneous animals and herds, and the goal of maximizing milk productivity. These two elements represent the "materialistic culture and growth" paradigm (Sievers-Glotzbach and Tschersich 2019), which has already been identified as an obstacle to the development of other sustainable novelties in agriculture, such as crop diversification in France (Meynard et al. 2018) or on-farm dairy processing in Belgium (De Herde et al. 2019). However, two other aspects of the mainstream cultural and cognitive paradigm are also challenged here: the concepts of "control and autonomy of humans over nature" and "expert knowledge and specialization" (Sievers-Glotzbach and Tschersich 2019). The purpose of indexes is to predict herd performance and overcome genetic variability; the associated top-down model of knowledge production is exclusively centered around the precise and intentional manipulation of genetic factors. For the vast majority of stakeholders (groups A to C), genomic indexes produced by proven methods are reliable tools for herd management. Instead, tools for the management of crossbred herds, such as the performance references produced ad hoc by individual farmers or the pseudo-index produced by the stakeholders of group E, are considered unreliable or unproven. As previously pointed out in work on alternative novelties in agriculture (Meynard et al. 2018; Magrini et al. 2019), these uncertainties are not an inherent feature of dairy crossbreeding, but the result of the fact that it has not been the focus of nearly as much investment in research as purebred management, whose knowledge has been consolidated over time. Conversely, stakeholders in group E changed how they advised and provided services to farmers and developed ad hoc references and tools for crossbred herd management. These organizations can be considered "hybrid actors," as defined by Elzen et al. (2012): "individuals and organizations that share some of the important rules with the regime actors but [that] also bring in new requirements that most regime stakeholders consider to be at odds with those rules." These stakeholders thus operate within both the mainstream sociotechnical system and dairy crossbreeding niche and take advantage of and strengthen both through "mutual adaptation," by which the niche learns to frame its lessons in a way that is of use to the regime and the regime acts on some of these lessons (Ingram 2015). This not only entails technical translation but also a wider appreciation of new approaches for producing and legitimizing knowledge (Coolsaet 2016).

The third set of barriers is closely related to cognitive and cultural barriers but is distinguished by its reliance on technology. Technological incompatibilities are visible both upstream and downstream of crossbred dairy farms. Upstream, at the level of the genetic system, extensive public and private research and R&D have created a methodological and technological arsenal for genotyping, genomic indexing, and tracing of animal genealogy. However, these systems are simply not adapted for crossbred animals (i.e., code "39" for all crosses). A similar incompatibility between a genomic revolution in agriculture and agroecological-based systems was previously identified by Vanloqueren and Baret (2009). However, based on the case of the USA where crossbred females have already been started to be indexed, such an incompatibility might no longer exist in a few years. Downstream, certain equipment (e.g., milking parlors, stalls), and production processes (e.g., automated fattening) are incompatible with the heterogeneous animals generated by dairy crossbreeding.

The last set of barriers is economic and market-related. Most stakeholders have adopted economy-of-scale strategies by investing in dairy cattle farming techniques (pure-breeding and highly specialized dairy farming) that concern the largest number of farmers and are therefore secure in terms of return on investment. A similar explanation was proposed to explain the paucity of investment in research on minor crops in France (Meynard et al. 2018). Downstream, because of their incompatibility with the technology of finishing farms, crossbred calves can have negative economic impacts on the activity of livestock traders and, by extension, on the economic performance of crossbreeding farms. However these results have to be investigated further, as the slaughter value of crossbred calves depends on the potential growth of the breeds involved (Clasen et al. 2020). Furthermore, crossbred females, whose numbers can quickly become significant due to the improved fertility of crossbred cows (Sørensen et al. 2008; Dezetter et al. 2017), are struggling to find a market due to the absence of "real genetic value" and the small number of farmers who would be potentially interested in this type of female. These findings suggest that, to accurately estimate the true economic benefits of dairy crossbreeding on farms (Clasen et al. 2020) and on the entire economic sector (Leroy et al. 2015), there is a need to take into account all aspects of these operations, including meat products and breeding females.

4 Conclusion

Here we show for the first time that, although rotational crossbreeding is widely recognized as a means to support the sustainability of dairy cattle farms, it remains uncommon in France due to organizational, technological, cultural, cognitive, and economic impediments. These barriers are interconnected and affect the professional activities of all stakeholders in the dairy cattle sector. Their breadth and pervasiveness demonstrate the extent to which the mainstream sociotechnical system is locked into pure-breeding and high-specialization paradigms of herd management. From the perspective of transition management theory, our results provide some original insights into the ways in which a novelty interacts with the sociotechnical regime. The emergence and development of dairy crossbreeding is the result of two processes usually considered separately: "anchoring" in more or less institutionalized niches, such as organic and grass-based dairy cattle farming, and "insularization," by emerging from within the sociotechnical regime and progressively detaching from it, particularly with respect to purebred and high-specialization breeding. This research focused on the sociotechnical conditions of the emergence and development of dairy crossbreeding in France, but to enrich, consolidate, and strengthen these findings, two complementary investigations should be carried out. The first extends this study to other European and Western countries in order to validate the generality of our results. The second takes a transdisciplinary approach to identify avenues by which to unlock the sociotechnical dairy cattle system. Livestock systems research, with its systems-based analytical frameworks and comprehensive on-farm approaches, has a major role to play in developing such transdisciplinary arenas.

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Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Verbal informed consent was obtained prior to the interview.

Consent for publication The authors affirm that human research participants provided informed consent for publication of the images in Fig. 2.

Conflict of interest The authors declare no competing interests.

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