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Managing animal diversity in livestock farming systems: types, methods and benefits

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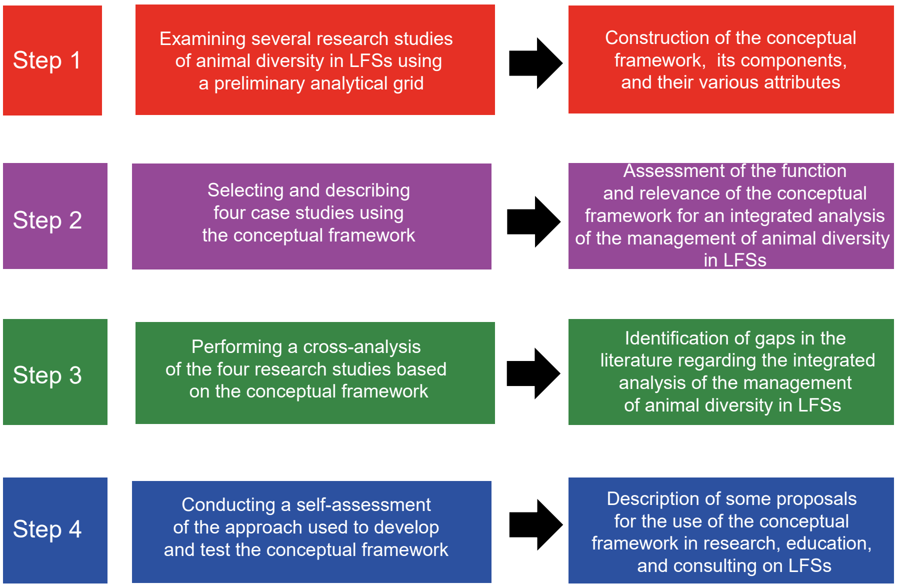
■ Increasing biodiversity, and in particular animal diversity, is often described as a promising means of adapting livestock systems to potential hazards and facilitating the agroecological transition. However, the majority of farmers, consultants, teachers, and researchers still find it difficult to view biodiversity as an asset in livestock management. Here, we develop a conceptual framework and provide perspectives to support the analysis of animal diversity and its management in livestock farming systems, in order to realise the benefits of this approach.

Introduction

During the second half of the 20th century, the development of a productivist model of livestock farming led to an increase in animal production through *i)* the selection of plants and animals based on production traits; *ii)* the use of inputs (e.g. concentrated feed, agrochemical fertilisers, and veterinary products) to reduce environmental heterogeneity and the effects of limiting factors; and *iii)* the standardisation and modernisation of production methods as well as the specialisation of farms and regions (Mazoyer, 1982). The limitations of this model have now been well documented (Brussaard *et al.,* 2015; Duru and Therond, 2015). First, it has contributed to a decline in biodiversity, including agrobiodiversity — the diversity of cultivated plants and domestic animals (Altieri, 1987) — which ultimately calls into question the ability of agricultural systems to adapt to global change (Hoffmann, 2013). Second, the resulting short-term increases in productivity are often negatively correlated with long-term productivity (Weiner, 2003). For example, the selection of dairy cows for high milk yields has led to a deterioration in their fertility (Mackey *et al.,* 2007; Sørensen *et al.,* 2008) and longevity (Knaus, 2009), and to an increased susceptibility to health problems (Oltenacu and Broom, 2010), to climatic variations (Gauly *et al.,* 2013), and fluctuations in feed intake (Delaby *et al.,* 2009).

To overcome these limitations, breeding programmes in all livestock sectors have been adjusted to better integrate functional traits, particularly in dairy cattle (Phocas *et al.,* 2014). However, the effectiveness of breeding adjustments in overcoming these limitations has been questioned. For this reason, alternative livestock farming systems (LFSs) have been proposed, whose strength lies in their ability to meet the needs of the agroecological transition. Agroecology is based on the hypothesis that biodiversity, and in particular agrobiodiversity, is an essential resource to ensure the sustainability of livestock

Figure 1. ***The sequential approach used to build, test, and apply the conceptual framework for an integrated analysis of animal diversity management in livestock production.***



farms and increase their adaptive capabilities in suboptimal and variable environments (Darnhofer *et al.*, 2010; Biggs *et al.*, 2012; Dumont *et al.*, 2013; Duru *et al.*, 2015). To date, the evidence that has been collected to support this has focused mostly on plant agrobiodiversity, particularly that of grasslands (Damour *et al.*, 2018). Studies on animal agrobiodiversity (hereafter referred to as animal diversity) are fewer, more recent, and scattered. We hypothesise that this is primarily the result of a lack of a shared conception among stakeholders in livestock production of what is meant by animal diversity and its management at the scale of the LFS.

The aims of this article are thus to develop a conceptual framework for an integrated analysis of the management of animal diversity at the scale of the LFS and to propose areas for future research to explore the conditions under which it is beneficial in the long term. To do this, we implemented a four-step sequential approach (Figure 1).

First, we examined several studies from the literature that explored animal diversity in LFSs, and characterised them using an analytical grid we constructed based on our own expertise. This enabled us to develop and consolidate the different components of our conceptual framework and to identify the various attributes of each (Section 1). In the second step, we selected four research studies and described them using the conceptual framework we developed. These studies were selected with the goals of obtaining different perspectives on animal diversity in LFSs and examining the ways, and the degree to which, research on animal diversity can be broken down into the different component parts of the framework. We used these to test the functionality and relevance of the conceptual framework in different contexts for the integrated analysis of the management of animal diversity in LFSs (Section 2). In the third step, we performed a cross-analysis of the four research studies, with which we identified some commonalities and differences in the application of the conceptual framework. With this, we were also able to identify some areas for future research with respect to the integrated analysis of the management of animal diversity in LFSs (Section 3). Finally, we conducted a self-assessment of our approach for developing and testing the conceptual framework in order to provide some proposals for its use in research, education, and consulting for LFSs (Section 4).

1. Presentation of the conceptual framework for analysing animal diversity and its management in livestock farming systems

The conceptual framework we developed has four main components (Figure 2).

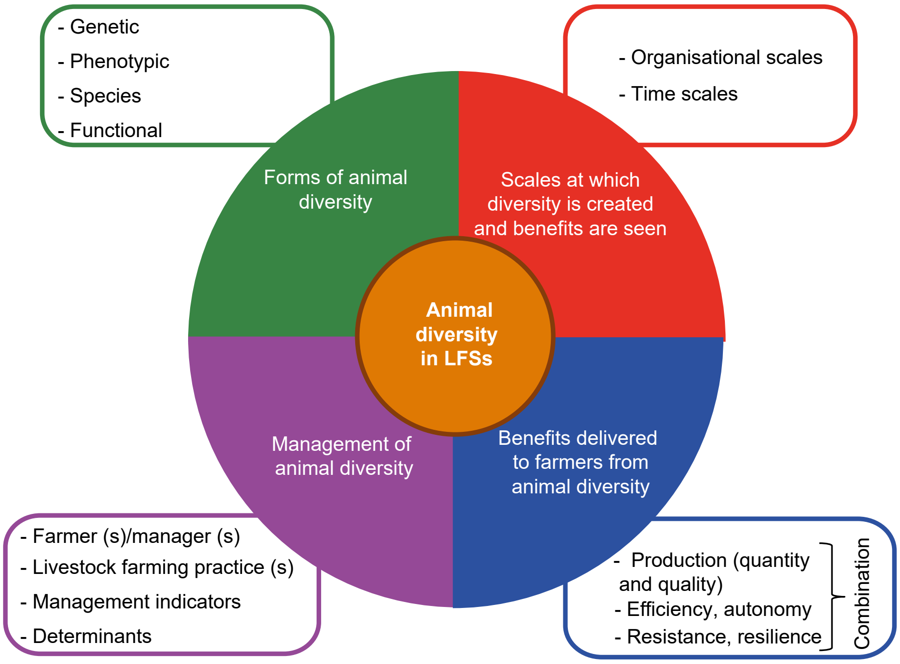
Two components (Figure 2, top) aim to analyse animal diversity in the context of the different forms it takes (described in detail in § 1.1) and the organisational and time scales at which it is created and benefits are seen (§ 1.2). The two other components (Figure 2, bottom) aim to analyse its management in the LFS (§ 1.3) and the benefit(s) that the farmer derives or expects from it (§ 1.4). It should be noted that, while diversity at the population scale is fundamental to the long-term management of diversity within species and breeds, we focus here on its management at the scale of the LFS. Therefore, animal populations are viewed as resources available to farmers in the acquisition of animal diversity to be used, maintained, and enhanced within the LFS.

1.1. The different forms of animal diversity

Diversity is characterised by variation, heterogeneity, and differences, as opposed to the concepts of uniformity, homogeneity, and similarity.

Genetic diversity refers to the degree of variation (or polymorphism) of genes

Figure 2. ***Conceptual framework for an integrated analysis of animal diversity management in livestock farming systems (LFSs).***



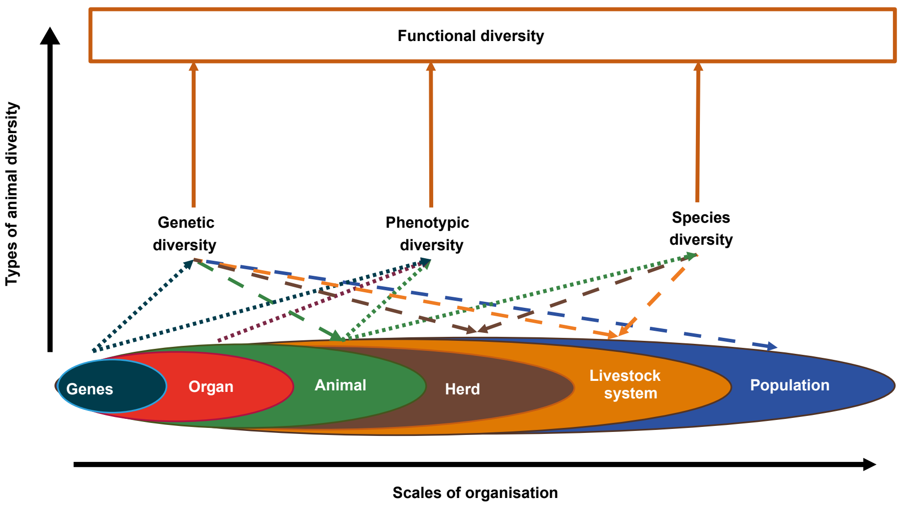
within a single species, breed, or line. It is the basis of genetic selection, the basic principle of which is to choose for reproduction, from the existing variability in a given population, animals that have favourable versions (or alleles) of genes of interest, in order to pass them on from one generation to the next and thus enable the genetic improvement of the population (species, breed, or line). The genes of interest can be related to production traits or functional traits, such as resistance to pathogens or the ability to reproduce in a given environment (Phocas *et al.*, 2017; see § 2.4). Genetic diversity is also the basis for actions designed for the conservation and promotion of rare or limited-number breeds (Audiot, 1995).

Phenotypic diversity describes the variability of observable and measurable traits in an animal. These traits can be physical (size, coat colour, horn configuration), physiological (age, parity, digestive efficiency, milk production, weight, conformation), behavioural (activity on pasture, relationship with humans), or biochemical (blood groups). They are the joint result of genetic diversity and the effects of the physical, chemical, and social environment. Phenotypic diversity (e.g., age, weight, conformation) can have direct effects on the type and quality of animal products produced for the market.

Species diversity refers to the associations of different animal species on farms. To date, most studies have focused on associations between cattle and sheep (Cournut *et al.*, 2012; Meisser *et al.*, 2013; D'Alexis *et al.*, 2014) and cattle and horses (Martin-Rosset and Trillaud-Geyl, 2011). Few studies have focused on associations between ruminant and monogastric species, even though they may play potentially complementary roles in the food chain of an ecosystem (respectively, forage intake and polymer degradation of plant cell-wall constituents *vs.* seed and tuber intake and degradation of other constituents).

These three types of diversity may all contribute to the final form examined here, that of *functional diversity* (Figure 3; Tichit *et al.*, 2011). This concept refers to the association of animals with different biological or ecological functions or aptitudes (e.g. meat breed *vs.* dairy breed), or with different biological and ecological responses to disturbance (e.g. climate-stress tolerant *vs.* sensitive phenotype). For example, in aquaculture, ecosystem functioning can be optimised by constructing an assemblage of fish species (detritivores, vegetarians, carnivores) with complementary characteristics, functions, and

Figure 3. ***The different forms of animal diversity and the organisational scales at which it is created and is expressed.***



Dotted arrows: organisational scales at which animal diversity originates; Dashed arrows: organisational scales at which the benefits of animal diversity are seen; Solid arrows: functional diversity supported by other forms of animal diversity.

habitats (with respect to, e.g., reproduction, thermophilia, or feeding; Néori *et al.,* 2004).

■ 1.2. Organisational and time scales at which animal diversity is created and expressed

Because an LFS is, by definition, composed of two sub-systems — a management system and a biological system (Dedieu *et al.,* 2008) — it integrates different coexisting and nested forms of animal diversity across the various organisational scales inherent in all living organisms. Its overall functioning and dynamics emerge from those of the underlying organisational scales and their interactions, which are in turn driven by the practices of the farm manager. Specifically, the functional dynamics of a livestock production enterprise arise from those of the constituent groups of animals, which are in turn the product of the functional dynamics of animals' constituent organ systems (e.g. organs of the digestive, reproductive, and respiratory systems). Furthermore, in addition to the nesting within organisational scales, there is also nesting that occurs within different time scales. Indeed, the dynamics of LFSs are based on processes specific to each organisational scale, which take place according to different rhythms and at different time scales. For instance, cellular metabolic processes take place on a scale of minutes, while herd processes such as female replacement take place on a scale of several years.

To characterize, and realise the benefits of animal diversity in LFSs, it can be helpful to understand the interrelationships of these different scales and the ways in which they nest. This involves distinguishing (Figure 3): *(i)* the organisational and time scales at which animal diversity is created, *i.e.* the scales at which constituent elements interact through biological processes; and *(ii)* the organisational and time scales at which animal diversity is expressed, *i.e.* the broader scale at which animal diversity delivers its potential benefits to the farmer. The scales at which animal diversity are created are thus intrinsically linked to the forms of diversity present (§ 1.1), while the scales at which it is expressed are closely linked to methods of management (§ 1.3) and the benefits (potential or realised) the farmer derives from such management (§ 1.4).

Thus, for models of LFSs to accurately assess the benefits of different management approaches, the organisational and time scales in question must be clearly identified. For example, to assess the benefits of animal diversity in goat herds in terms of its effect on resilience, a model was developed that combined analyses at the scale of the individual animals and that of the herd (Tichit *et al.,* 2012). The individual animal and the production campaign were defined as the relevant organisational and time scales, respectively, at which the phenotypic diversity of goats is created; here, the functional diversity supported by this phenotypic diversity was quantified as differences in the allocation of feed resources to the biological functions of reproduction and lactation. "Generalist" goats were defined as having good reproductive performance (kidding rate = 90%) and average milk performance (700 L/lactation) regardless of environmental conditions. "Specialist" goats were instead defined as having average reproductive performance (kidding rate = 70%) and high milk production in favourable environments (1,000 L/lactation) and low milk production in unfavourable environments (600 L/lactation). Then, the expression of this diversity and its benefits were assessed at the organisational scale of the herd and a time scale of several production campaigns. Simulations based on this model revealed that increased phenotypic diversity of goats in the herd, *i.e.* the combination of "specialist" and "generalist" goats, was beneficial in reducing inter-annual variability in the herd's milk production in response to environmental variations.

■ 1.3. The management of animal diversity in livestock farming systems

Characterising and understanding the management of animal diversity first requires the identification of the person(s) managing the diversity, the management practices that influence it, the management indicators in use, and the determinants of these practices.

Within LFSs, the farmer and his/her working partners on the farm are the main managers of animal diversity. However, depending on how animal breeding and selection are organized, it may be necessary to identify the type of farmers who play a relevant role. This is particularly true in the pig or poultry sectors, in which animal diversity can be managed by nucleus breeders, multipliers, and/or producers (§ 2.4).

Livestock farmers manage animal diversity through a variety of practices: herd management (e.g. feeding and pasture management, reproduction, and health management), herd configuration (e.g. plans for replacement, culling, and mating), and processing, sale, and marketing (sale of a range of animal products: animals sold for reproduction or fattening, milk, eggs, meat, fish, and their derivatives). These three kinds of management practices make it possible to create or acquire animal diversity, to manipulate it (e.g. to allocate and segment it, to exploit it), and to maintain it or not (to reduce or increase). Thus, a farmer who sells all of his lambs under a quality and origin certification may be compelled to reduce the phenotypic diversity within his sheep enterprise by grouping births and/or increasing supplementation of twin lambs, in order to create batches of lambs that are as homogeneous as possible in terms of weight, conformation, and fat content. Conversely, a farmer raising lambs for direct sale may seek to increase phenotypic diversity by organising lambing and rearing, particularly through breeding and feeding practices, in such a way as to have heterogeneous lambs available throughout the year and thus meet the expectations of individual consumers (Nozières, 2014). Among livestock management practices, arguably the three most important for the management and exploitation of animal diversity in LFSs are the choice of animals for breeding and replacement, the differentiation of feeding practices according to the end use of products, and batching practices. These practices, and the land use that is associated with them, can all be organised at different time scales (within a year, over many years) and organisational scales (§ 1.2). Thus, in LFSs that mix cattle and sheep species, grassland can be grazed separately, alternately, or simultaneously by the different species, depending on the farmer's objectives for each species in terms of production and the use of forage resources (§ 2.3). In some situations, instead, farmers do not implement different practices to manage on-farm animal diversity; this is the case, for example, with farmers who feed all dairy cows in their herd in the same way (homogeneity in practices), even if the animals are of different breeds and/or milk potential (§ 2.2). Finally, it is worth identifying if the animal diversity is managed by the farmer consciously or unconsciously. In the latter case, the diversity naturally results from farmers' livestock management practices without being explicitly desired or managed. In the former case, animal diversity is intentionally managed by farmers based on objectives and indicators, whether explicitly stated or not.

To implement animal diversity management practices, farmers seek out, gather, and use information both on and off the farm (Magne *et al.,* 2011). For example, they may examine data on the biotechnical system as a whole, *i.e.* the indicators they use to characterise on-farm animal diversity and to assess the benefits they derive from it (and that their partners derive indirectly from it; § 1.2). However, they may also analyse data on the physical, social, and economic environment of the farm, and on how animal diversity may be affected by both internal and external changes. All or a part of this information can be formalised through the use of indicators, including performance indicators such as milk yield and inter-annual variations on a given farm or between farms, as well as selection indexes built for an entire population.

The choice of practices for the management of animal diversity depends on two types of determinants: those that are internal to the farm or the individual farmers (e.g. his/her values, standards, and objectives) and those that are external (e.g. orientation of supply chains, resources available in the environment). These determinants are factors that hinder or facilitate the implementation of animal diversity management practices in LFSs. For example, by strongly restricting the genetic variability available in the breeding stock placed on the market, animal breeding societies and enterprises can hinder the development of animal diversity in LFSs. Similarly, downstream marketing operators and animal-product industries create a demand for homogeneous or heterogeneous animals depending on the marketing chains and periods in question, sometimes even providing farmers technical advice or financial incentives to meet their expectations. The management of the diversity of animal products, which operates on its own scales, complements that carried out by farmers. The goal of this type of organisation is to ensure that the supply of animal products, which is unevenly distributed, fluctuating, and by nature subject to uncertainty across both time and space, meets the constant demand (consumption) that is concentrated in urban centres (Malassis, 1979).

■ 1.4. The benefits to livestock farmers of managing animal diversity

The fourth component of our conceptual framework addresses the potential or real benefits derived or expected from the management of animal diversity in LFSs. Here, we only considered farm manager(s) as beneficiaries, although there are other possibilities (e.g. breeding organisations, citizens, consumers, etc.). The benefits are the advantages that the farmer derives from the biological and ecological processes supported by the animal diversity under his/her management.

The first potential benefit concerns improvement in the production of goods (i.e. animal products and by-products) that contribute to the gross production on which the farmer's income relies. Proper management of animal diversity can promote complementarity in animal production cycles and thus enable the expansion of the range of products available at a given time and over a production campaign.

Similarly, by supporting functional complementarity, it is possible to improve the quality and/or quantity of animal products. For example, mixing specialist and generalist dairy cattle breeds within a herd has been shown to generate worthwhile performance trade-offs between milk yield, milk content, and meat yield, thanks to complementarity in breed features (§ 2.2). Similarly, co-grazing of cattle heifers and dairy goats was shown to improve goat weight gain and overall animal production while improving pasture management (D'Alexis *et al.,* 2014).

The second potential benefit is improvement in the efficiency of the LFS, defined here as the ratio between the value of the products obtained and the resources expended for their production. When the focus is on enhancing the value of internal farm resources, then efficiency includes self-sufficiency. Thus, the management of animal diversity in LFSs can be a strategy for better use of the available on-farm resources (feed resources, labour, land, equipment) and a means by which to develop the complementarity of the constituent elements of the system to "*better use the whole range of resources and conditions offered*" (Reboud and Malezieux, 2015). As an example, mixing meat sheep and dairy cows on the same farm enables better use of the diversity of on-farm grassland resources (both in space and time), as the two species have different feeding behaviours, feed requirements, and susceptibilities to gastrointestinal strongyles. The association of livestock species with different production cycles can also increase working efficiency by spreading labour demands more evenly over the production campaign.

A third potential benefit concerns improvement in the resilience of the LFS, defined here as its capacity to maintain itself, but also to adapt to changes in its environment (Dedieu and Ingrand, 2010). Animal diversity can buffer a hazard, whether climatic, economic, sanitary, or zootechnical, and offer options for adaptation and transformation of the LFS based on current or predicted conditions (Darnhofer *et al.,* 2010; Nozières *et al.,* 2011). In such a way, associations between meat sheep and dairy cattle permit readjustments in the use of grassland resources and stock according to the respective feeding requirements and purpose of each species (Cournut *et al.,* 2012), which can be used to adapt to climatic hazards; likewise, management of phenotypic diversity in sheep (breeding, feeding, and batching) allows marketing practices to adapt to market changes (Nozières and Moulin, 2016).

While each of these three types of benefits can be assessed independently, they are more often considered in combination in discussions of the management of animal diversity on farms (§ 3 and 4).

2. Four studies of animal diversity in livestock farming systems characterised using the conceptual framework

Understanding what types of animal diversity are beneficial in LFSs and the conditions under which these benefits arise involves consideration of all four components of the proposed conceptual framework. To demonstrate this, we applied the conceptual framework to four research studies carried out at the National Institute for Agricultural Research (INRA) in order to analyse their approaches with respect to animal diversity and its management in LFSs (Table 1).

■ 2.1. Study 1: Within-herd animal diversity and its benefits from the perspectives of dairy cattle farmers

The work of Ollion (2015) described how dairy farmers characterise the forms of animal diversity in their herds, how this diversity changes over time, the driving factors behind these changes, and the benefits that motivate change. This research thus analysed intraspecific animal diversity from the point of view of the farmers themselves. It was based on interviews carried out in a sample of 39 farmers. Twenty-five farmers had purebred herds: 11 Holstein, 7 Montbeliarde, 6 Normande, and 1 Ferrandaise. Nine farmers had multi-breed herds that contained Holstein cows along with those of one or two other breeds, which comprised 10 to 75% of the herd; the breeds considered were Montbeliarde (5 herds), Normande (2 herds), Simmental (1 herd), and both Montbeliarde and Abondance (1 herd). Finally, five farmers had crossbred herds, with crossed cows representing 50 to 100% of the herd. These herds were based on three- to five-breed crossbreeding schemes, involving Holstein, Normande, Jersey, Montbeliarde, Scandinavian Red, New Zealand Holstein, and Brown Swiss. Almost all of the farmers interviewed (*n* = 37/39) stated that they had animal diversity in their herd (Figure 4).

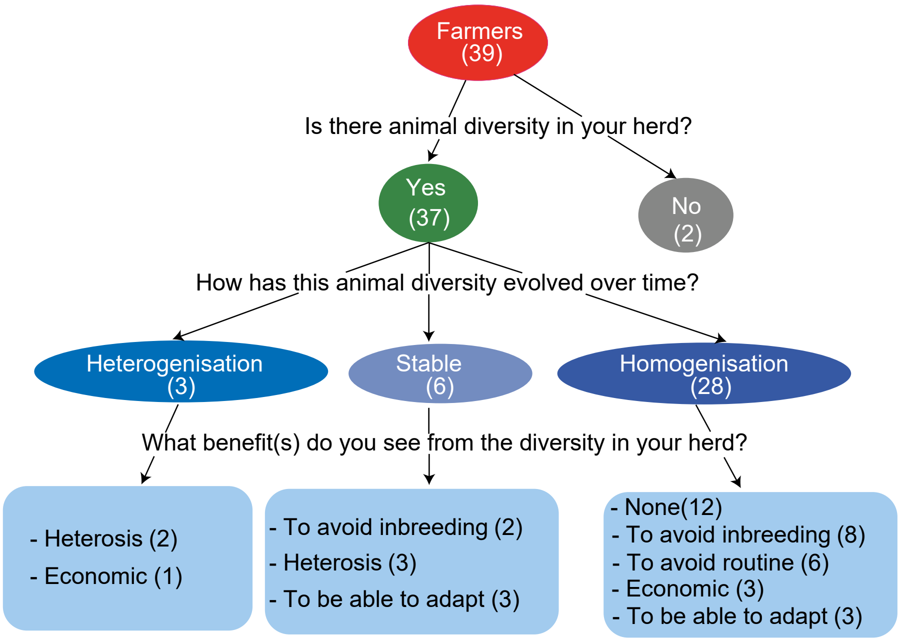
In their narratives, the farmers addressed two forms of animal diversity: genetic and phenotypic. For a majority of the farmers (24/39), within-herd diversity was based on the genealogy of each animal: 19 farmers distinguished their cows according to the genetic origin of the dam ("*Olympus, well, all her daughters have the same character: they are going to be docile*"), while 5 farmers based their statements on the genetic origin of the sire ("*some bulls disappointed us while others we wouldn't have bet on provided us four or five daughters about which we have nothing bad to say*"). For the other sampled farmers (15/39), animal diversity referred instead to the genetic variation among breeds or crossbreeds ("*Montbeliarde and Abondance breeds are more vigorous and spiteful than Holstein; they have more character*"). The farmers also characterised the phenotypic diversity of their animals according to physical traits (morphology, coat colour, horn type; *n* = 31/39), behavioural traits (character, feeding behaviour; *n* = 18/39), ability to adapt milk production to hazards (*n* = 34/39), or physiological traits (biological trade-offs such as milk yield *vs.* milk content, milk *vs.* longevity or fertility; n = 9/39).

Of the 37 farmers who identified animal diversity in their herd, 28 found that it had declined over time, whether intentionally or not. An analysis of their practices showed that this decrease

Table 1. ***Presentation of the four research studies within the conceptual framework developed to describe and understand animal diversity in livestock farming systems.***

Type of animal production	**Forms of animal diversity**	**Scales at which animal diversity is created and expressed**		**Potential or real benefits of animal diversity to the farm managers**	**Animal diversity management: modality (M), indicator (I), or determinant (D)**
		Organisational scale	**Time scale**		
Study 1. Dairy cattle	Genotype and Phenotype	Animal ➔ Herd	From the cows' careers to the ongoing campaign of production	Production of goods (through heterosis, complementarity of milk/ meat, milk yield/milk content) ; Efficiency (economic, labour); Resilience (to climate variability)	M: unintentional management *vs.* intentional management I: behavioural, genetic, physical, and performance D: Avoiding inbreeding and routine at work; increasing heterosis
Study 2. Dairy cattle	Genotype and Functional	Animal ➔ Herd	Year (campaign of production)	Production of goods (milk/ meat; milk yield/milk content); Efficiency (of concentrates); Resilience (cows' ability to reproduce); Trade-offs between the above-mentioned benefits	M: three management strategies differing in their approach to animal diversity (reduction, segregation, amplification) and the ways of using and valuing it (complementarity of production and efficiency) I: functional diversity supported by breed diversity D: degree of standardisation and intensification of the livestock system
Study 3. Dairy cattle and meat sheep	Species	Herd ➔ Farm	Year (campaign of production)	Production of goods (cow's milk/lamb meat; fodder production); Efficiency (feeding, labour, economic); Resilience (to climate and economic variability)	M: four management strategies differing in the degree of interaction between livestock species I: functional diversity supported by species diversity (dairy cattle and meat sheep) D: work organisation, degree of standardisation and intensification of the livestock system, product certification under protected designation of origin
Study 4. Pigs	Genotype and phenotype	Animal ➔ Herd	Batch of animals	Economic efficiency for nucleus breeding farmers; Resistance to heat stress and economic efficiency for producers	M: Sorting and directing the sale of breeding stock according to their heat-resistance phenotype I: predictors of pigs' robustness to heat D: degree of standardisation and intensification of the livestock systems at every stage of the chain

Figure 4. ***Responses from 39 dairy cattle farmers regarding the dynamics of change and the benefits of animal diversity in their herds.***



resulted from using the same herd management practices (selection for replacement, culling, mating management) for all the animals in the herd to produce an "optimal" cow. For the nine other farmers, animal diversity was maintained or increased (n = 3) over time thanks to the use of dairy cross-breeding practices.

Finally, 25 farmers indicated that they derived various benefits from within-herd animal diversity (Figure 4). For them, behavioural and physical diversity improved labour efficiency by facilitating the management of inbreeding, which requires the maintenance of a broad range of genetic variability for female replacement and diversification of the bulls used for mating. Breed diversity (4/37) was said to improve the production of goods in an LFS when breeds have contrasting strengths: milk yield (Holstein) *vs.* milk content (Montbéliarde, Simmental), or iconic cultural status (Abondance) and high milk-yield performance (Holstein). Animal diversity was also cited as an aid in managing uncertainties (6/37) and adapting to the changing marketplace, e.g. steering production towards milk yield or milk content according to milk prices, and buffering the impacts of various hazards: "*What I am saying is that if you have climate variability over the years, with some feeding situations that are not optimal, in a mixed herd, some animals will resist better than others, and if the situation is reversed, some animals will be able to optimise their performance. So it should buffer the various fluctuations.*"

■ 2.2. Study 2: Management practices and benefits of multi-breed dairy cattle herds

Magne *et al* (2016) studied the performance and management of multi-breed dairy cattle herds in Aveyron (Southern France), which represented 16% of the milk-recording farms in this region in 2010. The type of diversity studied was functional diversity supported by genetic diversity (specialist *vs.* generalist breed). The Holstein breed (Ho) was defined as a milk-specialist breed, while other breeds, including Montbeliarde (Mb), Normande (No), Simmental (Si), and Brown Swiss (Br), were labelled generalist breeds. A herd was said to be multi-breed (MB) if it was composed of cows of both types of breeds and neither type of breed represented more than 80% of the total number of cows in the herd. An analysis of the individual performance of cows of both breed types within 22 MB herds (of which 13, 3, 3, and 3 combined Ho with Mb, Si, Br, and No respectively) confirmed the functional complementarity of the two breed types with respect to certain traits. Thus, within a herd, specialist-breed cows produced more milk (on average +1,137 kg/year) for a longer lactation length (on average +38 d) than generalist-breed cows. However, the latter group produced milk with more protein (average +2.1 g/kg) and fat (average +2.2 g/kg) contents and had a higher lactation rank (+5 months).

The benefits of managing the diversity of breed types within MB herds were first assessed by comparing the performance of all milk-recording MB herds in Aveyron (*n* = 83) to that of milk-recording single-breed herds, whether composed of a specialist breed (SB) (405 SB herds) or a generalist breed (GB) (117 GB herds) (Table 2).

Compared to SB herds, MB herds were shown to have a better trade-off among milk production (both milk yield and milk contents), reproductive performance (which translates into herd resilience through the ability to regenerate), and feed concentrate efficiency. Specifically, while MB herds produced less milk than SB herds, they were more efficient in converting feed-concentrates, had better reproductive performance, and their milk had a higher protein content. Instead, MB herds demonstrated poorer reproductive performance than GB herds, but

Table 2. *Average performance of 83 multi-breed (MB) herds, 405 single-breed herds composed of specialist-breed (SB) cows, or 117 single-breed herds composed of generalist-breed (GB) cows from milk-recording farms in Aveyron (France) in 2010.*

Performance, expressed as average (standard deviation)	Single specialist breed (SB) herds	Multi-breed (MB) herds *	Single generalist breed (GB) herds **
Milk yield (kg/cow/year)	7,497^{a}(1,091)	6,457^{b}(1,059)	6,028^{c}(879)
Protein content (g/kg)	33.1^{c}(0.9)	33.6^{b}(1.2)	34.9^{a}(1.1)
Fat content (g/kg)	41.8^{b}(1.6)	42^{ab}(1.8)	42.5^{a}(2.1)
Somatic cell count (1,000 cells/mL)	266.9^{a}(100.2)	265.8^{a}(105.2)	205.8^{b}(86.3)
Calving interval (days)	430^{a}(30)	414^{b}(26)	399^{c}(27)
Concentrate distributed (kg/cow/year)	1,747^{a}(416)	1,537^{b}(397)	1,581^{b}(342)
Concentrate efficiency (g/kg milk)	234^{b}(52)	239^{b}(50)	266^{a}(64)

a, b, c: averages with a different letter differ at the threshold of $P < 0.05$.
*Of the 83 MB herds, 53 had Holstein as the dominant breed, 19 had Montbeliarde, 5 had Brown Swiss, and 6 had Simmental.
**Of the 117 GB herds, 50 were composed of purebred Montbeliarde, 34 Simmental, 32 Brown Swiss, and 1 Normande.

they produced more milk, with equivalent protein and fat contents, and had higher feed-concentrate efficiency and self-sufficiency. However, MB herds did not present any advantages with respect to udder health compared to single-breed herds.

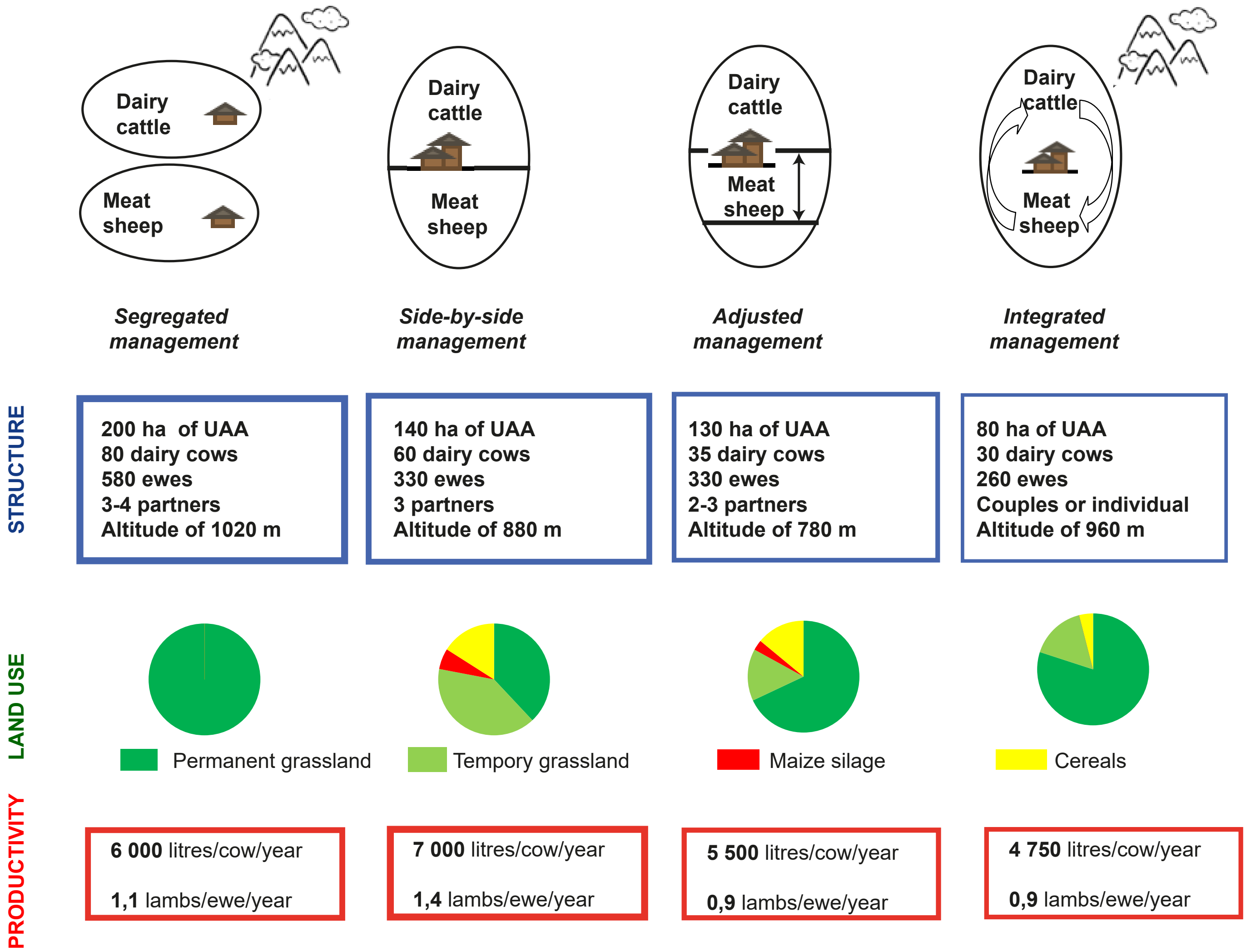
Based on an analysis of farmers' management practices in the 22 MB herds, three groups of farmers were identified based on differences in their approaches to using, replacing, and exploiting the diversity of breed types. Regardless of the group, farmers always used the Ho breed to increase herd milk yield. Instead, the choice of generalist breed to pair with Ho depended on the exact type of functional complementarity that was desired, which differed among the three groups. Group 1 had six farms, in which the generalist breeds were Si (2 farms), No (2 farms), or Br (2 farms). Three of these farms were predominantly based on Ho cows (accounting for 60% to 80% of the herd) and three were predominantly based on generalist-breed cows. Farmers in this group used the generalist breed for its functional complementarity with Ho in terms of better reproductive performance and the ability to produce milk with higher protein and fat contents using local fodder resources and fewer feed-concentrates. Three of these farmers even sought to combine these functional complementarities into a new genotype by using rotational dairy crossbreeding. In accordance with their desire for feed-concentrate efficiency, farmers in group 1 practiced late calving (so that heifers could use low-feed-value fodder resources) and distributed the same amount of feed-concentrates to all cows based on the feed requirements of generalist-breed cows selected for their milk yield traits. Group 2 was composed of eight farms; the generalist breeds were Mb (four farms), Br (two), Si (two), and No (one). Five farms were predominantly composed of Ho cows and three had equivalent proportions of Ho and generalist-breed cows. These farmers managed MB herds to optimise two production goals, milk and meat, and used the generalist breed for its functional complementarity with Ho in terms of producing less milk but more meat. These farmers differentiated some of their practices according to breed type: *i)* they used beef-breed crossbreeding on a mean of 30% of their generalist cows to optimise their growth potential and increase the slaughter value of their calves, but they did not use this practice on Ho cows unless insemination failed three times; *ii)* four of them practiced early calving for Ho cows and late calving for generalist cows; and *iii)* they adapted the amount of concentrates distributed to cows based on milk production. Group 3 was composed of eight herds: seven combined Ho and Mb cows and one used Ho and Br cows. Four farms had predominantly Ho cows, three had equivalent proportions of both breeds, and one had predominantly generalist-breed cows. In this case, the functional complementarity desired was between the milk yield of Ho cows and the disease resistance of generalist-breed cows. However, all practices were centred around the management of Ho cows, to try to reduce the degree of dissimilarity between the two types of breeds to optimise milk yield and streamline work processes. For this reason, one farmer even practiced absorption crossbreeding. The age at first calving was 24 months for all cows, in order to minimise the length of unproductive periods and prevent the fattening of generalist cows. The amount of concentrates was adapted to an animal's level of production regardless of breed. Although their goal was to maintain the functional complementarities of the two breeds, the farmers also took care to maintain the genetic composition of the breeds because they were invested in it.

Finally, a comparison of herd performance in these three groups provided evidence that MB herds were beneficial for their demonstrated complementarity between milk yield and feed-concentrate efficiency. Indeed, herds in the three groups did not significantly differ in terms of performance except for milk yield/cow/year (in decreasing order: group 3, 2, and 1) and feed-concentrate efficiency (equal for group 1 and 3 and less for group 2). Meat production benefits could not be assessed due to a lack of data.

■ 2.3 Study 3: Management strategies of livestock systems that combine dairy cattle and meat sheep

Cournut *et al* (2012) analysed the management of 18 farms that combined dairy cattle and meat sheep in Auvergne (Central France). They characterised, spatially and temporally, how farmers managed the interactions between the two species and between the animals and grassland and crop resources, in the context of the farms' structural characteristics and the farmers' production objectives. They also identified some options these farmers chose to deal with climate variability. Four strategies were described for the management of mixed-species systems; these were characterised by differences in *i)* the regime(s) of land use and grazing for the two species, and *ii)* the degree of productivity expected by the farmer for the grassland and the herds (Figure 5). Because these management strategies were based on different degrees of integration and overlap between species, the tactics used by farmers to adapt to climate hazards also differed.

Figure 5. ***Four different livestock management strategies for the coexistence of dairy cattle and meat sheep in the region of Auvergne, France.***



In the segregated management strategy (three farms), the two species were raised separately on different sites, essentially operating as two distinct farms. Here, farmers prioritised the production of high-quality milk for processing into PDO cheeses (Saint-nectaire, Fourme d'Ambert) and the production of milk and sheep meat based on higher-altitude grassland. These extensive LFSs, based on permanent grassland, had a low animal stocking rate (0.8 livestock units per ha of principal forage area (LU/PFA)). Farmers used species diversity to maximise the potential of upland meadows for producing cow's milk and sheep meat. In summer, ewes and heifers grazed in open mountain pastures, increasing the resilience of these LFSs to climate variability. In the side-by-side management strategy (five farms), the two species were also managed on separate grassland areas, but these pastures were all grouped around a single farm site. Farmers prioritised the productivity of each species (an average of 7,000 litres of milk/cow/year and 3 lambs/ewe/2 years) and, to support this goal, also sought to maximise crop productivity through a crop rotational system based on productive temporary meadows, cereals, and maize. The animal stocking rate here was the highest of the four strategies (1.1 LU/ha of PFA) and fodder was frequently purchased to overcome limitations arising from climate variability. In this case, species diversity was used to diversify the farms' products (cow's milk and sheep meat) and distribute them over the year. Fodder resources were managed intensively to meet the requirements of all animals; farmers made little use of the species' functional complementarity to better exploit pasture resources. In the adjusted management strategy (six farms), both species grazed their own dedicated pastures, but sequential grazing (cows followed by ewes) was carried out to make use of forage left behind by cows. Farmers promoted their economic security in several ways: expanding the range of animal products offered (milk and cheese processed on-farm, beef-crossbred calves, and small lambs produced at low cost), improving product values (through organic farming certification and/or direct sales), diversifying on-farm activities (e.g. agritourism), and increasing feed self-sufficiency (through crop rotation including cereals and temporary meadows and a low animal stocking rate: 0.7 LU/ha of PFA). On these farms, increased species diversity enabled the expansion of the range of products offered, as well an increase in the value of milk cows (from the use of on-farm forage resources and cheese processing) and low-cost lambs. The functional complementarity of the different species was used to extract further value, through sequential grazing and potentially co-grazing. When confronted with climate hazards, farmers preferentially adapted their management of the sheep herd using a wide range of changes, from adjusting the fodder resources allocated to them to decreasing their numbers. Finally, in the integrated management strategy (four farms), all grassland areas were available for grazing by the two species, with a primary focus on sequential grazing. Crop rotation included some cereals and temporary grasslands, and the animal stocking rate was low (0.7 LU/ha of PFA). Farmers' priorities were simplifying the organisation of work (labour efficiency) and enhancing the quality of products by using on-farm fodder resources (efficiency). On these farms, the low production requirements expected for all animal species rendered the entire farm resistant to climate and economic variability.

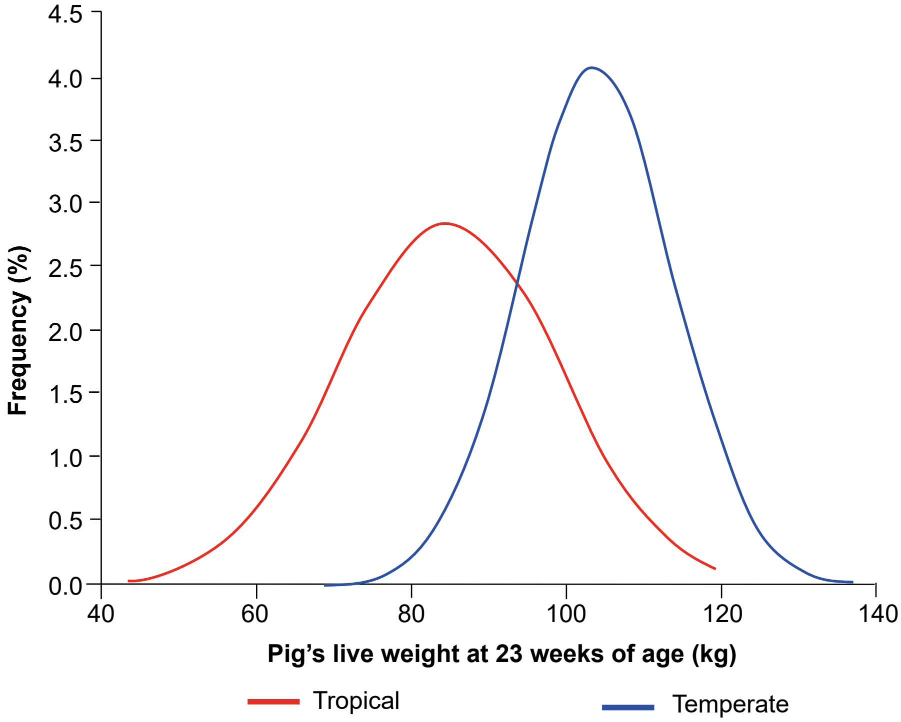
Overall, this study revealed that the benefits derived from mixed-species in dairy cattle and meat sheep farming systems differ according to farmers' management strategies, which are tied in particular to the desired compromise between production, efficiency, and resilience.

■ 2.4. Study 4: Managing phenotypic diversity for heat tolerance in pig farming systems

In commercial pig farms, environmental and especially climate variability prevents farmers from realising the full genetic potential of their animals, which results in decreases in the farm's economic efficiency. Improvements in animal robustness, defined here as the ability of an animal to express its genetic potential in a wide range of environments, have therefore become a priority for the whole pig sector, most particularly for nucleus breeding farmers and multipliers. However, even within the same breeding line, heat sensitivity varies from one pig to another: some animals have a lower and more variable growth rate in tropical environments than in temperate environments (Figure 6). Study 4 focused on characterising and using this phenotypical variability to discriminate among animals according to their robustness (Dou *et al.,* 2017). The expected benefit was improvement in the resilience and economic efficiency of pig systems (at the multiplier or producer stages) by making animal performance less sensitive to climate variability.

The purpose of this study was to provide tools to identify the least heat-sensitive (*i.e.* most robust) individuals in an animal population using biomarkers from easily accessible sources (such as blood, saliva, or faeces). It showed that robust or heat-sensitive animals can be identified with good precision from a blood sample and plasma metabolome

Figure 6. ***Live weight distribution at 23 weeks of age in two populations of pigs of the same line (backcross LW_xCR) reared in temperate (blue, n = 634 pigs) or tropical conditions (orange, n = 664 pigs; adapted from Rosé et al. 2017).***



analysis. Although these markers have not yet been tested in farm management, they could be used by multipliers to guide the phenotypic diversity of breeding stock and avoid (for example) the export of heat-sensitive animals to hot regions. These predictive biomarkers could also be used to identify the genetic markers influencing the complex trait of heat sensitivity for applications in breeding programmes, which could construct a robustness index of breeding animals. In commercial farms, this phenotypic diversity could be managed by selecting animals for reproduction who are adapted to the targeted climatic context.

3. Cross-sectional analysis of the four studies and research perspectives

The analysis of these four studies based on the conceptual framework reveals that animal diversity is often incompletely studied with respect to its four components. Study 4 focuses mainly on the first two components (the forms of animal diversity and the organisational scale at which it originates), because the challenge in that study was to objectively characterise the functional diversity of pigs (thermotolerance) at the scales at which it is created, based on the definition of predictors intended to provide tools for management in LFSs. This study therefore represents processes that are upstream of the characterisation of management practices and the assessment of benefits in LFSs. Conversely, the three other studies reviewed here focused mainly on the other two components of the conceptual framework, related to animal diversity management in LFSs and its benefits. However, each study took a different approach to these two components (Table 3). Studies 1 and 3 were based exclusively on farmers' narratives (opinions and/or practices), while study 2 combined farmers' narratives with quantitative analyses of within-herd performance data. Study 1 identified key indicators that were actually used by dairy cattle farmers to characterise, manage, and assess the benefits of animal diversity in their herds; however, it did not test their objectivity or validity. In studies 2 and 3, characterisation of animal diversity was defined *a priori* based on the functional complementary of breed types (study 2) or theoretical species (study 3); the validity of these descriptions were then evaluated *a posteriori* through assessments of performance between breed types within MB herds and through farmers' narratives, respectively. Finally, studies 1 and 3 identified the benefits derived from the management of animal diversity on farms based on farmers' narratives. Instead, study 2 assessed benefits by *(i)* comparing the performance of MB herds with that of single-breed herds and *(ii)* comparing farmers' management strategies among different MB herds.

The analysis also enables identification of the partial contributions of each research study to three main research areas: characterising animal diversity and understanding the underlying biological and ecological mechanisms; characterising management options for animal diversity to take advantage of it in LFSs; and assessing the benefits derived from the management of animal diversity in LFSs, including their trade-offs (Table 3). Based on a brief review of the literature, in addition to a thorough analysis of these four research studies, we identified the need for a precise description of these research areas and we formulated a set of concrete research directions for each.

■ 3.1. Better characterising and understanding animal diversity for management in livestock farming systems

We propose two areas for future research to better characterising and understanding animal diversity in LFSs.

Table 3. ***Types of research approaches applied in each of the four studies reviewed using the conceptual framework, and the contribution of each to three research areas identified for the integrated analysis of animal diversity in livestock farming systems.***

		Study 1 Dairy cattle	**Study 2 Multibreed dairy cattle**	**Study 3 Dairy cattle and meat sheep**	**Study 4 Pigs**
Research approaches used	Farmers' narratives (opinions and/or practices)	X	X	X	
	Data on herd/animal		X		X
Research areas	Characterising animal diversity and understanding the underlying mechanisms	**	**	*	***
	Characterising options for animal diversity management	*	***	***	
	Assessing the benefits derived from the use of animal diversity	***	***	*	

The number of stars reflects the degree of contribution of each of the four studies to the three research areas identified as key for the understanding of the management of animal diversity in livestock farming systems : * marginal; ** important; *** major

The first is to better describe and understand functional diversity and its links with other forms of animal diversity (Figure 2). Indeed, the four studies examined here reveal that a key role in LFSs is played by functional diversity supported by other forms of animal diversity. That is, increased species diversity, such as an association between two livestock species for co-grazing, is only beneficial if the species have complementary grazing abilities (e.g. diet preferences, grass heights in pastures) that make different contributions to the functioning of the LFS as a whole (e.g. regulating the dynamics of vegetation in time and space, regulating gastro-intestinal strongyles). As has already been discussed in the fields of ecology, livestock production, and agronomy (Petchey *et al.*, 2004; Tichit *et al.*, 2011; Duru *et al.*, 2013, respectively), it is functional diversity that must be studied rather than species richness *per se*.

The second research direction is closely related to the first: to refine the variables (e.g. morphological and behavioural traits; animal performance; parameters/biomarkers) that are used to categorise functional groups of animals (or describe functional diversity) within LFSs and to understand the biological and ecological mechanisms behind them. Here, in reviewing the approaches used in the literature for assigning animals to functional groups within an LFS, we identified several limitations. The first is the lack of available and easily accessible variables to carry out this type of characterisation. Indeed, this was the main challenge in study 4, the aim of which was to identify biomarkers that can be easily measured in bodily fluids such as blood and urine for the description of pigs according to their heat sensitivity. In studies 2 and 3, individuals were grouped based on the theoretical functional complementarity of animals; however, it was not always possible to test these assumptions due to the lack of available data on animal performance. To overcome this limitation, it would be helpful to have routine monitoring of useful phenotypic or genetic parameters in livestock farming. The second limitation regards the type of variables that can be used to characterise animal diversity. Here, the frameworks developed in ecology by Biggs *et al.* (2012) and Vigglizo (1994) to describe biodiversity could help to refine the differentiation and characterisation of animal entities on a farm. These authors proposed the identification of: the variety of the different entities, *i.e.* their nature and number; their relative abundance; their degree of dissimilarity; and the nature and intensity of interactions between them. The concept of 'variety' corresponds to the forms of animal diversity in our conceptual framework and was used in each of the four reviewed research studies. By contrast, relative abundance was only addressed in study 2, in analyses of the proportions of generalist and specialist cows within MB herds. The degree of dissimilarity refers to the variables used to differentiate animals into functional groups (e.g. heat stress response of pigs in study 4, differences in the biological abilities of generalist and specialist cows in study 2). Finally, the nature and intensity of interactions between entities refers to the functional complementarity effects we identified in the reviewed studies, such as the functional complementarity in grazing between meat ewes and dairy cows in mixed-species herds or the complementarity between milk yield and milk content in MB herds. However, other types of interactions, such as those commonly studied in ecology (e.g. neutralism, cooperation, competition, learning) remain to be described and documented in LFSs. The frameworks proposed by Biggs *et al.* (2012) and Vigglizo (1994)can thus be used to better characterise animal diversity, regardless of the organisational scale under consideration (e.g. herd, farm, territory, country).

■ 3.2. Characterising animal diversity management options for long-term benefits

To better characterise different options for the management of animal diversity and maximise the long-term benefits that can be derived from them, we propose three directions for future research.

The first is to more thoroughly explore the effects of basic and combined livestock management practices on animal diversity, and vice versa, at different time and organisational scales. Indeed, our analysis consistently identified a lack of formal knowledge of the practices (and combinations thereof) that make it possible to create animal diversity, to use/enhance it, and to regenerate/replace it over time. An example of this type of knowledge was provided by study 2, which identified and described three management strategies in MB herds. Another critical question regards the effects of such management practices over the long term and at different organisational scales, depending on the type of animal sector under consideration: from producers to multipliers and nucleus breeders and from LFSs to animal populations. As an example, in study 4, biomarkers for heat sensitivity in pigs were developed for use in sorting breeding stock before they were sold to producers. Depending on the geographical origin (temperate or tropical) or season in question, multipliers can use this tool to enhance the value of animal diversity on their farms and provide breeding animals or semen that are adapted to the climatic conditions of different pig producers. This strategy would lead to a reduction in the diversity of traits associated with heat-stress robustness within a given producer's farm, but would maintain trait diversity at the population scale (regardless of the stage considered). In the future, such biomarkers could be used as phenotypes to identify the genetic markers related to heat tolerance. The use of these genetic markers in breeding programmes would then make it possible to select animals that are less sensitive to climate variability. However, such a selection process could eventually lead to a reduction in animal diversity not only on individual farms, which may prefer pigs that are robust in any climatic environment, but also in the animal population as a whole. Finally, as shown in studies of crop-livestock integration (Moraine *et al.,* 2017), a key issue in the management of animal diversity is the spatial scale under consideration (within-farm, groups of farms, territory, etc.). The development of management programmes whose scope extends beyond the scale of an individual farm would aid in overcoming barriers related to specialisation in livestock sectors, farms, and farmers' skills. However, the organisational barriers present at such a scale are not insignificant; addressing these would require a collective restructuring of animal configurations, management, and marketing practices at the farm scale to enhance animal diversity at the territorial scale.

The second research direction is to analyse the changes in farmers' work (physical, interpersonal, and cognitive work) that are linked with the management of animal diversity in LFSs. In studies 1 and 3, work requirements were shown to determine certain choices regarding animal diversity management. In the literature, managing agrobiodiversity in agricultural systems is often mentioned as being accompanied by a necessary reorganisation of work (Duru *et al.,* 2015; Darnhofer *et al.,* 2010). However, no study has yet provided empirical evidence for this, particularly when the agrobiodiversity under study is animal diversity in LFSs. Specifically, farmwork should be studied in both its *(i)* organisational dimensions (How are the tasks to manage animal diversity, and the workforce available for them, organised in space and time?) and *(ii)* cognitive dimensions (What information do farmers use to manage animal diversity? How do they construct new indicators to manage it and adapt their objectives according to the benefits they achieve?).

The final research direction is to identify factors that help or hinder the management of animal diversity in LFSs. In the studies reviewed here, some of these factors became apparent, such as market organisation and liberalisation, the organisation of animal genetic selection, and farmers' standards. However, few studies have explicitly analysed the factors that support or impede the management of animal diversity in LFSs (Magne *et al.,* 2017). The challenge is therefore to identify and categorise them according to whether they arise from human (e.g. values, standards, knowledge), socio-economic (e.g. market organisation), technological (e.g. phenotyping techniques), or biophysical (e.g. level of exposure to climatic, economic, and health hazards) influences. It will be critical to analyse these elements not only from the point of view of farmers but also from the point of view of other stakeholders in the socio-technical environment of LFSs.

■ 3.3. Assessing the benefits of managing animal diversity in livestock farming systems

Our comparative analysis of the four studies revealed that research efforts should focus on assessing the benefits derived from the management of animal diversity in LFSs in order to broaden the base of evidence for its use. For example, in study 4, the expected benefit of using heat-tolerant animals is increased resilience on the producers' farms. This outcome, though, remains to be experimentally verified; the effective resilience of such farms must be compared to those composed of pigs with different degrees of robustness. Similarly, in studies 1 and 3, the benefits that farmers said they derived from managing animal diversity on their farms need to be assessed using quantitative data analysis. Based on these observations, we propose two research directions to increase knowledge on the benefits of managing animal diversity in LFSs.

The first is to assess the benefits derived from the management of animal diversity in LFSs in combination, not in isolation. Indeed, studies have shown that what is expected or gained from the management of animal diversity in LFSs is most often a combination of several benefits (e.g. production of goods, resilience, efficiency, self-sufficiency in terms of inputs, quality of life at work) rather than just one. These combinations can also involve different trade-offs that livestock farmers must be willing to make. Before such assessments can be conducted, though, methodological questions must be addressed, similar to those raised by multi-criteria assessments (Lairez *et al.,* 2017). In particular, systems and methods must be developed to acquire and process herd performance data of different types (e.g. health, reproduction, production of different products, product quality, work efficiency and quality) and at different time and organisational scales.

The second research direction is an improved integration of the coevolution of management practices, animal diversity, and LFS performance into the assessment of the benefits derived. Assessments of benefits must take into account two key challenges: *i)* the influence of the techniques used by farmers to manage animal diversity; and *ii)* their evolution over the medium to long term, to account for the dynamics of the biological processes underlying animal diversity and their interactions with farming practices. This last point is particularly important when seeking to assess the resilience derived from animal diversity management. However, current research methods are not always suitable (or available) for long-term assessment. For this, two promising tools are livestock monitoring and modelling/simulation. Modelling also has the advantage of being able to separate the management component of livestock farming systems from the biological component (Tichit *et al.,* 2011; Blanc *et al.,* 2013).

4. Scientific and practical implications

■ 4.1. An integrative framework to support discussion between stakeholders

The conceptual framework we propose here is a mental map of elements to be integrated and questions to be asked regarding the management of animal diversity in LFSs. Its application to case studies could facilitate discussion between experts from different backgrounds around the steps to be taken toward this goal. Indeed, its use here on different research studies has initiated these types of discussions between livestock production researchers with different research objectives and working on different kinds of livestock systems. The discussion space provided by the framework can be opened up to other researchers and, more broadly, to other stakeholders in livestock-related sectors.

Specifically, it would be useful to share and discuss the framework with researchers in:

(i) livestock production, working on species or production systems that were not examined here (e.g. poultry or fish). This could confirm the general applicability of the conceptual framework and highlight differences in the management of some under-explored types of animal diversity, such as monogastric-ruminant associations or intra- or interspecific functional complementarities that were not described in the studies reviewed here;

(ii) genetics, to merge and communicate research on animal diversity at the scales of LFSs and animal populations (Phocas *et al.,* 2017). Indeed, it appears that at these two scales of creation, the organisation and use of animal diversity are intimately linked, even though they are often considered independently;

(iii) microbiology and veterinary medicine and *agronomy*, to better formalise the relationships between animal diversity in LFSs and the associated biodiversity. Such biodiversity can be microbial diversity hosted by farm ani-

mals (see the review of Calenge *et al.*, 2014 on the links between the microbiota and animal phenotypes), microbial diversity hosted by the environment surrounding the animal (building, pasture), or even cultivated or uncultivated plant diversity;

(iv) human and social sciences, particularly economics, to enable more accurate assessments of the benefits derived from animal diversity in LFSs and to better understand the socio-technical and sociological determinants of different ways of managing it (or the lack thereof) in LFSs.

The framework can also be used by researchers and stakeholders in the livestock sector (e.g. farmers, consultants, breeding organisations, downstream operators) to express and promote different points of view (convergences and divergences) and to integrate these into the design of different options for managing animal diversity in LFSs.

■ 4.2. Contribution and implications for training and advice in livestock farming systems

This article is not an exhaustive and systematic review of the literature on animal diversity and its management in LFSs, and is not intended to define "good management practices of animal diversity", as these must be considered in context. However, we think that the conceptual framework we developed is generic enough to be applied to different livestock farming situations and used by different livestock stakeholders, particularly teachers and consultants.

The framework, and more generally the approach underlying its use in this article, has strong educational potential, for three reasons. First, the framework structures the analysis of animal diversity management in LFSs around four unambiguous components (Figure 2). Second, the four studies examined with respect to these four components constitute concrete cases that help to establish the framework. Finally, the cross-analysis of these four studies enables the identification of commonalities and differences in the management of animal diversity in LFSs. These three kinds of elements have been shown to facilitate learning and understanding of complex subjects (Barth, 2013), such as the management of animal diversity in LFSs. The framework could therefore be used by teachers of livestock production in universities or technical agricultural schools to provide students with the ability to apply biodiversity, one of the key agroecological concepts, to the management of LFSs. Indeed, the French curriculum for technical agricultural schools specifically mentions the goal of training future livestock farmers and livestock consultants to consider animal diversity as a resource for managing LFSs from an agroecological perspective. Finally, the framework can also serve as a tool for the exchange of information on the current barriers and support systems for the management of animal diversity in LFSs. In doing so, it provides an opportunity to imagine technical, organisational, cognitive, and economic means for overcoming current barriers.

For livestock consultants, the application of the framework to the four studies presented here serves as a concrete example of how animal diversity can be managed in LFSs and provides evidence that this diversity can be successfully managed by farmers and be beneficial to them. This makes it possible to counterbalance the often-negative view that these stakeholders have of animal diversity in LFSs, which tends to be unwanted and minimised because it is thought to be inefficient in the current socioeconomic context. For example, consultants often consider multi-breed dairy cattle herds to be in a phase of transition to single-breed herds, or that they are a consequence of the purchase of a second herd, whereas for many farmers, multi-breed herds are beneficial and should be maintained. In addition, the conceptual framework can be used by and with consultants for a collective reimagining of the data that should be collected in LFSs to produce benchmarks on the benefits (or lack thereof) of managing animal diversity. It would then be useful for advisory organisations to fund, build, and monitor, over the long term, networks for livestock farmers centred around the use of animal diversity.

Conclusion

In this article, using a review of research studies conducted at INRA and a brief overview of the literature on LFS research, we developed an original conceptual framework for an integrated analysis of animal diversity and its management at the scale of LFSs. We then proposed some directions for future research to identify the conditions under which animal diversity could be beneficial in the long term. In so doing, we promote a formal concept of the management of animal diversity in LFSs, a key concept in agroecology but one that livestock stakeholders, including researchers, find difficult to grasp and use. By applying the framework to four research studies, we illustrate the forms that animal diversity can take at different organisational and time scales, the way it can be managed in LFSs, and the benefits that can be derived from it for farmers. This conceptual framework is a tool for integrating the knowledge produced, or to be produced, on the management of animal diversity in LFSs and is an aid for discussions and plans for future research projects, both theoretical and applied. It is also a resource that can be used in training and advising farmers on the design and development of options for the management of animal diversity that are beneficial to them in their individual contexts and over the long term.

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We dedicate this article to Muriel Tichit, who died in April 2019. She served as research director at INRA within the Department of Action and Development Sciences and held a PhD in livestock production science. Her work on the role and services provided by biodiversity in agriculture was pioneering and opened up innumerable research perspectives. Muriel, thank you for the scientific legacy you have left us on this theme.

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Abstract

Biodiversity, and particularly animal diversity managed by farmers, is often viewed as a valuable resource for effecting the agroecological transition and improving the resilience of livestock farming systems (LFSs). However, this topic has not been thoroughly studied; what little research is available tends to be recent and scattered. This paper aims to develop a conceptual framework for an integrated view of the management of animal diversity in LFSs and identify some avenues for future research on this topic. The framework addresses four interrelated components: the form(s) of animal diversity under consideration, the organisational and temporal levels at which it is created and has relevance, the forms of its management in LFSs, and the benefits for farmers that arise from this management. Here, we apply this framework to four research studies that took contrasting approaches to the topic of animal diversity. Through the evaluation of these four components, a cross-analysis of these case-studies revealed that this approach enables the management of animal diversity in LFSs in an integrated way and ensures its benefits in the long term. Our work also highlights three novel research directions aimed at strengthening the characterisation of animal diversity, the understanding of its management in LFSs, and the assessment of the various benefits derived from its management. Finally, some applications for the use of the framework in research, teaching, and consulting on LFSs are suggested.

Résumé

Gérer la diversité animxxale dans les systèmes d'élevage : laquelle, comment et pour quels bénéfices ?

La biodiversité, et en particulier la diversité animale, est présentée comme un levier prometteur pour la transition agroécologique et la résilience des systèmes d'élevage. Or, les travaux traitant de cette question sont peu nombreux, récents et épars. Cet article vise à développer un cadre conceptuel pour analyser de manière intégrée la diversité animale et ses modalités de gestion à l'échelle des systèmes d'élevage et à proposer des pistes de recherche pour y contribuer. Ce cadre est structuré en quatre composantes : i) les formes que recouvre la diversité animale, ii) les niveaux organisationnel et temporel auxquels elle se construit et s'exprime, iii) ses modes de gestion et iv) les bénéfices retirés par l'éleveur. Quatre études de recherche contrastées en termes de diversité animale analysée ont été revisitées au travers du cadre conceptuel proposé. Leur relecture et leur analyse transversale montrent l'intérêt d'articuler les quatre composantes du cadre pour raisonner de manière intégrée la gestion de la diversité animale en élevage afin d'en tirer parti sur le long terme. Elles permettent aussi d'identifier trois fronts de recherche à investiguer conjointement : affiner la caractérisation de la diversité animale en élevage, mieux caractériser ses modes de gestion y compris ses déterminants et approfondir l'évaluation des différents bénéfices retirés de sa gestion. Des pistes d'utilisation du cadre en recherche, en enseignement et dans conseil en élevage sont enfin proposées.

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