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Review

# Potential of multi-species livestock farming to improve the sustainability of livestock farms: A review

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## ABSTRACT

Diversified farming systems are proposed as a major mechanism to address the many sustainability issues of today's agriculture. Multi-species livestock farming, i.e. keeping two or more animal species simultaneously on the same farm, is an option that has received little attention to date. Moreover, most studies of multi-species livestock farming are limited, usually focusing on selected dimensions of farm sustainability and addressing lower organizational levels (i.e. within the farm) and rather limited time horizons (e.g. a few weeks in a grazing season). Thus, a comprehensive assessment of multi-species livestock farming in terms of farm sustainability is lacking. In this context, we outline and discuss potential benefits and limitations of multi-species livestock farming for livestock farm sustainability from existing literature and list issues on multi-species livestock farming requiring further research. We show that multi-species livestock farming has the potential to improve the three dimensions of sustainability reviewed - economic viability for farmers, environmental soundness and social acceptability by being respectful of animals and humans - as long as locally relevant farming practices are implemented, especially an appropriate stocking rate during grazing. If relevant practices are not observed, multi-species livestock farming may produce undesirable effects, such as competition for resource acquisition during grazing, parasitic cross-infection and more intense work peaks. Therefore, we identify four focal research areas for multi-species livestock farming. First, characterizing the management of multi-species livestock farms. To do this, we suggest considering the integration of production enterprises (e.g. cattle and sheep enterprises) within the farm from three perspectives: farming practices (e.g. grazing management), work organization and sales. Second, exploring the complementarity of livestock species on multi-species livestock farms. This is especially true for species combinations that have been largely ignored (e.g. ruminants and monogastrics), even though they may have potential due to complementary diet compositions and resource-acquisition strategies. Third, assessing the sustainability of multi-species livestock farm scenarios (current or alternative) according to the management practices and production conditions, which requires adapting existing methods/models or developing new ones. Fourth, characterizing conditions for success and obstacles for multi-species livestock farming along the value chain from production to consumption, considering stakeholders' objectives, work habits and constraints. Increasing understanding should help prioritize actions and organize them to scale up multi-species livestock farming.

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## 1. Introduction

Globalization, urbanization, population growth and climate change necessitate more sustainable agricultural models. In the context of livestock farming, this means models that provide the farmer with a reasonable and stable income, without negative side effects on the environment, and that are acceptable to society by ensuring both animal and farmer welfare (ten Napel et al., 2011). Several visions have been proposed to drive the redesign of agricultural systems toward improved sustainability, including agroecology (Tomich et al., 2011) and ecological modernization of agriculture (Horlings and Marsden, 2011). These visions rely on greater plant and animal diversity in agricultural systems (Dumont et al., 2014; Duru et al., 2015) and therefore more diversified farming systems. Diversified farming systems intentionally include functional agrobiodiversity (Kremen et al., 2012): crops, sown and permanent pastures, rangelands, and animal genotypes and species chosen by farmers to manage their farms. These systems presumably provide ecosystem services by reducing input use and increasing the stability of production (Kremen et al., 2012). Indeed, diversified farming systems may promote interactions over space and time among farm enterprises (e.g. crops, pastures and animals) and create opportunities for synergies (e.g. resource transfers among enterprises to increase nutrient cycling, joint use of products from different enterprises through on-farm processing, better work organization to mitigate work peaks) (Hendrickson et al., 2008).

Within diversified farming systems, integrated crop-livestock farming is considered one of the most promising options to meet sustainability goals (Kirkegaard et al., 2014; Liang et al., 2018) due to its demonstrated environmental and economic benefits (Bell and Moore, 2012; Veysset et al., 2014; Ryschawy et al., 2017). Multi-species livestock farming, i.e. keeping two or more animal species (Fig. 1) on the same farm simultaneously (and possibly integrating them with crop production or agroforestry), is another way to diversify farming systems, but it has received less attention, with most studies focusing solely on co-grazing at the field level (e.g. Animut and Goetsch, 2008; Fig. 1). Multi-species livestock farming is often implemented to promote functional diversity, a concept which in recent years has gained increasing interest within agricultural science (Gunton et al., 2011; Rolo et al., 2016). Applied to livestock farming, functional diversity builds on a diversity of animal morphological characteristics (e.g. body size, incisor arcade), physiological characteristics (ruminants vs. hindgut fermenters), feeding preference (herbivore vs. grain feeder, grazer vs. browser, generalist vs. specialist animals) and/or behavioral traits (temperament, previous grazing experience). According to ecological theory, trait diversity promotes resource-use efficiency, productivity and stability of ecosystems (Hooper et al., 2005; Isbell et al., 2015).

Most studies of multi-species livestock farming (e.g. D'Alexis et al., 2014; Fraser et al., 2007; Wright et al., 2006) are limited to selected dimensions of farm sustainability and address lower organizational levels (usually the field level) over rather limited time horizons (e.g. a few weeks in a grazing season). Thus, a more comprehensive assessment of potential benefits of multi-species livestock farming on farm sustainability is lacking. In this context, this review outlines and discusses potential benefits and limitations of multi-species livestock farming for livestock farm sustainability and identifies four issues related to multi-species livestock farming requiring further research. Here, livestock farm sustainability is understood as the combination of economic viability for farmers, environmental soundness and social acceptability by being respectful of animals and humans (ten Napel et al., 2011).The review is limited to free-ranging systems and excludes confined livestock farming that does not allow for interactions among livestock species.

## 2. Potential benefits and limitations of multi-species livestock farming for livestock farm sustainability

Sustainability in the context of livestock farming is considered as a multi-dimensional concept (Lebacq et al., 2013) as in other agricultural systems (Zahm et al., 2019). According to the above definition (based on Ten Napel et al., 2011), the three dimensions often found in sustainability assessments apply to livestock farms (Bernués et al., 2011; Lebacq et al., 2013):

- Environmental sustainability that encompasses resource-use efficiency, climate change mitigation and biodiversity conservation in grazing lands and crop-livestock areas: reducing the inputs required for production by making more efficient use of internal resources (e.g. pasture biomass in t DM/ha) may address several of the critical points identified by Bernués et al. (2011) by closing nutrient cycles to reduce nutrient leaching (assessed as kg of excess N, P and K per ha) while limiting greenhouse gas emissions (assessed as kg of $CO_2$ equivalent emitted per ha per year or per kg of product) and sequestering carbon in grassland soils. However, this should not occur at the expense of biodiversity conservation (assessed via the species richness and limitation of invasive species in agricultural landscapes) which requires grazing at a stocking density that does not exceed grassland carrying capacity, and limiting the risks of trampling and pasture degradation (e.g. by pigs).
- Technical and economic sustainability that encompasses productivity and profitability (Bernués et al., 2011): free ranging livestock farms are criticized (e.g. Toro-Mujica et al., 2011) for their sometimes low productivity (assessed as g of meat, milk, egg or wool per day or per unit area) but productivity is at the root of profitability (assessed via farmer income in monetary units) which is key to maintaining farms in the long run (Uematsu and Mishra, 2012). Then, to remain competitive, farms may have to achieve a level of productivity sufficient to ensure their profitability. The latter not only provides farmers with a reasonable income, it helps keep farming attractive despite the high degree of technical skills often

**Fig. 1.** Examples of multi-species livestock farming with (left) co-grazing of heifers and broilers and (right) cattle and sheep (Photo credits: Severin Hübner and Sophie Prache).

needed to produce livestock, and the higher workload and work constraints (e.g. for dairy production) compared to managing cropping systems.

- Social sustainability that encompasses both animal and farmer welfare: consumers expect livestock farmers to decrease their use of veterinary medicines (assessed via the frequency of treatments per animal per year), in particular antibiotics and anthelmintics and to protect animals from predators (assessed via a mortality rate due to predators) (Lebacq et al., 2013). Moreover, in an era in which livestock farming is discussed controversially, livestock farmers must consider animal welfare in their management strategies (Zander and Hamm, 2010). Also the increase in farm size observed in Europe for several decades (Eurostat, 2019) has led to serious welfare issues for farmers and agricultural workers. Livestock farmers need to address this issue to remain functional in the long term and keep their activity attractive for following generations (Jansen, 2000) despite a sometimes critical image of livestock farming in the media.

## 2.1. Environmental sustainability

### 2.1.1. Resource use efficiency

In a farming context, the diversity of traits within the components of agrobiodiversity determines the complementarity of resource use, or the competition for these resources resulting from overlapping diets. Livestock species are commonly classified according to their digestive system: foregut (ruminant e.g. cattle) and hindgut (cecal e.g. equids) herbivorous fermenters, and monogastrics. Ruminants and equids are well adapted to digesting forage cell walls, while monogastrics are the most efficient convertors of feed concentrates. In line with differences in body-size, physiological, morphological and behavioral traits, herbivore species exhibit distinct feeding behaviors and have complementary effects on plant community structure. Body size determines intake capacity and nutrient requirements of ruminants and equids (Rook et al., 2004; INRA, 2015), their ability to feed selectively because of mouth size and, to a lesser extent, their ability to digest forage (Dulphy et al., 1994). Small ruminants generally require more energy relative to their intake capacity than large ones such as cattle, and thus have to select higher-quality diets (Rook et al., 2004). Large ruminants are restricted by a reduction in their bite depth on short swards (Illius and Gordon, 1987). Horses have a higher intake capacity and a double row of incisors, allowing them to graze short swards (Menard et al., 2002); they are thus better adapted to low-quality and hard-to-access herbage than other herbivores (Thériez et al., 1994). Goats are agile climbers (Sanon et al., 2007) with a mouth and tongue highly adapted for selection of specific parts of plants, unlike cattle, which have a mouth and tongue that maximize intake rate when grazing tall swards (NRC, 2007). These factors determine the feeding niche of each livestock species on pastures and their impacts on plant community structure and biodiversity (Rook et al., 2004).

Competition and complementarity for feeding can be analyzed through the lens of dietary overlap (Walker, 1994). Different feeding habits among two or more livestock species raised on the same farm reduce competition for feed. As Walker (1994) indicated, “While a high degree of dietary overlap does not necessarily indicate interspecific competition, a low level of overlap indicates reduced potential for competition”. Comparing several studies conducted across the world, Walker (1994) concluded that dietary overlap between sheep and cattle grazing together remains low unless forage availability becomes too low (Table 1), forcing both sheep and cattle to graze the most available plants, even though they may be less preferred or of lower quality. While sheep were more selective than cattle on a productive pasture, co-grazing of cattle and sheep also led to a more homogeneous defoliation pattern; both species decreased selection of highly preferred *Taraxacum* sect. *Ruderalia* and increased selection of less preferred *Festuca pratensis* (Cuchillo-Hilario et al., 2018). On pastures grazed by sheep and goats or cattle and goats all together, dietary overlap also increased when forage availability became low (Squires, 1982; Norton et aI., 1990). Cattle and horses have high dietary overlap, which indicates a high risk of competition (Menard et al., 2002). In forage-limited conditions, horses maintain diet quality at the same high level (Fleurance et al., 2016) and can thus outcompete cattle on pastures because of their ability to graze short swards. In productive pastures, cattle may, however, benefit from an increase of competitive *Trifolium repens* abundance in the short sward patches created and maintained by grazing horses (Fleurance et al., 2016). Grazing sows prefer clover to grass, and grass leaves to grass stems (Sehested et al., 2004). Yet, herbage-use efficiency of co-grazing heifers and sows can increase overall herbage intake on productive pastures. For example, herbage intake was 9–10 t DM/ha on pastures grazed simultaneously by heifers and sows vs. 5.7–8.8 t DM/ha on pastures grazed by either heifers or sows (Sehested et al., 2004). Potential overlap between feeding niches calls for appropriate management of co-grazed pastures depending on livestock species, sward diversity, season, and herbage availability in order to increase herbage-use efficiency (Jordan et al., 1988; Menard et al., 2002; Cuchillo-Hilario et al., 2018).

Co-grazing can increase sward nutritive value, especially its crude protein content and organic matter digestibility (Walker, 1994; Sehested et al., 2004), but this is not always the case (Abaye et al., 1994; Sormunen-Cristian et al., 2012; Wang et al., 2019). An increase in sward nutritive value is likely to increase diet quality, either directly or as the result of positive feedback between grazing and vegetation regrowth that remains of high nutritive value. Also, the different livestock species may have more opportunity to select their preferred plant species as long as forage availability remains high (Jordan et al., 1988; Sehested et al., 2004). Co-grazing, for instance of cattle and horses or cattle and goats, may lead to more uniform sward defoliation (Menard et al., 2002) and higher nutritive value of the pasture regrowth. In addition, sheep (Nolan and Connolly, 1989) and sows (Sehested et al., 2004), either under simultaneous or sequential grazing, have been observed to graze herbage close to cattle dung, an area that cattle avoid. This herbage has a comparatively higher crude protein content and dry matter digestibility, and thus increases diet quality (Nolan and Connolly, 1989).

### 2.1.2. Climate change mitigation and biodiversity conservation

The benefits of multi-species grazing for climate change mitigation have not been studied extensively. Only Fraser et al. (2014) compared methane emissions of several systems with varying ratios of cattle and sheep grazing together with a mono-species sheep grazing system. They showed that the sheep grazing system emitted less methane per unit area than the multi-species systems (62.15 kg $CH_4$/ha vs. 78.08 to 91.18 kg $CH_4$/ha; Table 1). However, when considering the live weight gain of animals in the assessment, three out of the four multi-species systems had lower emission intensities than the sheep grazing system (438 g $CH_4$/kg live weight gain/ha vs. 398 to 443 g $CH_4$/kg live weight gain/ha).

How herbivores shape plant community structure and ecosystem functioning can be analyzed through the lens of ‘patch grazing’ behavior, as herbivores preferentially feed on previously grazed short areas of high nutritive value (Adler et al., 2001). At a lenient stocking rate, this leads to the creation of relatively stable short patches in a matrix of tall vegetation. Patch stability can persist over successive grazing seasons and results in divergent local vegetation dynamics, which benefits biodiversity according to the ‘habitat heterogeneity hypothesis’ (Kruess and Tscharntke, 2002; WallisDeVries et al., 2007). The scale at which stability of vegetation patterns took place during two successive years depended on pasture productivity and livestock species; horses created the more stable patches followed by cattle, while sheep were less able to shape vegetation structure (Dumont et al., 2012). Simultaneous grazing of sheep and cattle, however, provided suitable habitats for butterflies. On Welsh upland pastures, bird species density was significantly higher when sheep alone grazed pastures (Fraser et al., 2014; Table 1), but

**Table 1**
Summary of benefits (+), limitations (−) and absence of effects (=) on farm sustainability for the reviewed multi-species livestock systems and related knowledge gaps.

| Sustainability dimension | | Sheep-cattle | Sheep-goat | Goat-cattle | Cattle-horse | Cattle-pig | Knowledge gaps |
|---|---|---|---|---|---|---|---|
| Environmental | Resource use efficiency | + ( ± forage availability)<br>(Cuchillo-Hilario et al., 2018; Jordan et al., 1988; Nolan and Connolly, 1989; Walker, 1994) | + ( ± forage availability)<br>(Squires, 1982; Norton et al., 1990) | + ( ± forage availability)<br>(Squires, 1982; Norton et al., 1990) | + ( ± forage availability)<br>(Fleurance et al., 2016) | +<br>(Sehested et al., 2004) | Sub-dimension poorly studied<br>Effects of pasture composition and forage availability via grazing management requiring further investigation |
| | Clim. chang. Mitigation | Methane emissions +<br>(Fraser et al., 2014) | | | | | Sub-dimension poorly studied |
| | Biodiversity conservation | Pasture plant diversity + Insects + Soil organisms +<br>(Wang et al., 2019)<br>Butterflies + Birds +<br>(Fraser et al., 2014) | | | Pasture plant diversity + (Loucougaray et al., 2004)<br>Invasive sp. control +<br>(Loiseau and Martin-Rosset, 1988; Loucougaray et al., 2004; Menard et al., 2002) | | Few studies on sheep-cattle and cattle-horse systems but many other unexplored combinations<br>Strong management effect (e.g. stocking rate at grazing) remaining underexplored<br>Consistent indicators needed |
| Technical and economic | Overall productivity | +<br>(D'Alexis et al., 2014; Fraser et al., 2014; Walker, 1994) | | | | +<br>(Sehested et al., 2004) | Sheep-cattle systems well studied but many other unexplored combinations |
| | Species productivity | Sheep + Cattle =/+<br>(Abaye et al., 1994; D'Alexis et al., 2014; Fraser et al., 2007; Fraser et al., 2014; Jordan et al., 1988; Nolan and Connollly, 1989; Taylor Jr, 1985; Walker, 1994; Wright et al., 2006)<br>Sheep +; calves –<br>(Olson et al., 1999) | Sheep + Goat =<br>(Taylor Jr, 1985) | Cattle = Goat =<br>(Taylor Jr, 1985) | | Sows + Heifers +<br>(Sehested et al., 2004) | Strong management effect (e.g. simultaneous vs. sequential grazing) remaining underexplored |
| | Profitability | Net income +<br>(Umberger et al., 1983)<br>Fixed costs -<br>(Walker, 1994)<br>Economic efficiency / Economies of scale -<br>(Meyer and Harvey, 1985) | Fixed costs -<br>(Walker, 1994) | Fixed costs -<br>(Walker, 1994) | | | Sub-dimension poorly studied<br>Strong management effect (e.g. ratio between species, sales management) remaining underexplored<br>Consistent indicators needed<br>Analysis of lock-ins needed |
| Social | Animal health and welfare | Nematodes - for sheep<br>(Arundel and Hamilton, 1975; Brito et al., 2013; Jordan et al., 1988; Marley et al., 2006) but cases of inter-species transmissions for nematodes<br>(Almeida et al., 2018; Chaudhry et al., 2015; Riggs, 2001) and bacterial and viral diseases<br>(Belay et al., 2004; Braun et al., 2014; Göktuna et al., 2017; Moloney and Whittington, 2008; Passler and Walz, 2010; Raymond et al., 2000; Rogdo et al., 2012; Syrjälä et al., 2006) | Nematodes =<br>(Deplazes et al., 2013)<br>Cases of inter-species transmissions of bacterial and viral diseases<br>(Nettleton et al., 1998; Minguijón et al., 2015; de Pablo-Maiso et al., 2018) | Nematodes - for both cattle and goat<br>(Mahieu, 2013) | Nematodes - for horse<br>(Forteau et al., 2020) | Cases of inter-species transmissions of bacterial and viral diseases<br>(Göktuna et al., 2017; Passler and Walz, 2010) | Incomplete knowledge due to the diversity of nematodes, bacterial and viral diseases<br>Livestock management effect especially grazing management effect (e.g. simultaneous vs. sequential grazing) underexplored |
| | Farmer welfare | | | | | | Subdimension not studied yet<br>Consistent indicators needed |

butterfly species density was higher with sheep and cattle co-grazing (in a 6:1 ratio). A recent study corroborated the benefits of co-grazing in more fertile pastures. Abundance and diversity measurements made across six groups of above-ground and below-ground organisms (plants, herbivorous insects, predatory insects, soil bacteria, fungi and nematodes) suggested that co-grazing not only benefits biodiversity but that it would also provide higher levels of ecosystem services (Wang et al., 2019). Other livestock combinations can also benefit pasture biodiversity. The ability of horses to feed on coarse vegetation can reduce the rate of encroachment by shrubs, phragmites and competitive grass species (Menard et al., 2002). Thus, co-grazing cattle and horses limited the development of shrubs on upland pastures (Loiseau and Martin-Rosset, 1988) – with a significant impact of horse trampling on *Vaccinium myrtillus* – and of tall patches of highly competitive and non-palatable grasses on coastal pastures (Loucougaray et al., 2004). In this last study, the benefits of co-grazing resulted not only from horse high intake capacity and ability to feed on coarse forages, but also from cattle grazing on horse latrine areas and thus limiting strongly competitive *Elymus repens* and *Agrostis stolonifera*. Consequently, co-grazing cattle and horse produced more species-rich and structurally diverse swards than cattle or horse grazing alone (Loucougaray et al., 2004). Although it was not reported in the reviewed literature, co-grazing or sequential grazing with a too high stocking rate may erode pasture biodiversity over the long run.

## 2.2. Technical and economic sustainability

### 2.2.1. Productivity

Co-grazing systems tend to have higher productivity per unit area than single-species grazing systems (Table 1). Compiling results of 14 experiments conducted across the world, Walker (1994) showed that co-grazing (cattle, sheep and/or goat) always increased productivity per unit area compared to cattle-only grazing (by 24%, on average on a weight gain (g/day) per ha basis) and usually increased productivity per unit area compared to sheep-only grazing (by 9%, on average on a weight gain (g/day) per ha basis). A more recent meta-analysis confirmed the benefits of cattle-sheep co-grazing systems, which had higher productivity (g/day) per ha than cattle- or sheep-only systems (D'Alexis et al., 2014). Co-grazing of ruminants and monogastrics has seldomly been investigated, but a similar increase in productivity (g/day) was observed when co-grazing heifers and sows (Sehested et al., 2004). Total animal weight gain per ha was higher in co-grazing systems (by 140–250 g/day for heifers and 42–61 g/day for sows, either simultaneous or sequential) than in single-species grazing systems.

Usually, only one of the species involved benefits from co-grazing (Table 1). Compared to single-species grazing systems, simultaneous or sequential grazing of cattle and sheep increased average daily weight gain by 14.5 g per animal for sheep but did not change it for cattle (D'Alexis et al., 2014). This confirms earlier findings (Abaye et al., 1994; Fraser et al., 2007; Fraser et al., 2014; Jordan et al., 1988; Wright et al., 2006). Similarly, 20 years of research in Texas (USA) revealed that co-grazing of cattle, sheep, and goats increased performance of sheep (weight gain and wool production) but did not affect cattle or goat performance (weight gain and mohair production) (Taylor Jr, 1985). Olson et al. (1999) even found a decrease in average daily weight gain for calves co-grazed with sheep, and only one study reported increased liveweight gain for cattle co-grazed with sheep (Nolan and Connolly, 1989). Several reasons have been suggested to explain this trend, including higher competitive ability of sheep during grazing (Walker, 1994), fewer helminths in co-grazed sheep (Jordan et al., 1988), higher relative growth rate of lambs than calves and higher prolificacy of ewes than cows (Matthews et al., 1986; Wilson and Graetz, 1980).

The variability observed in these studies of the productivity of co-grazing systems is related to the type of grazing management, stocking rates and the relative proportions of each species. Kitessa and Nicol (2001) observed that cattle simultaneously co-grazed with sheep had lower average daily weight gain than those sequentially grazed with sheep (804 and 706 vs. 1039 and 1028 g/day in two trials, respectively), while sheep were nearly unaffected by grazing management (150 and 155 vs. 138 and 147 g/day in two trials, respectively). The authors suggested that the disadvantage for cattle co-grazing with sheep in simultaneous grazing systems was related to the latter's more competitive use of herbage compared to that in sequential grazing systems. It may be compensated by management decisions on which species grazes first, which very much depends on farmers' priorities. Competition for feed may also depend on the stocking rate during grazing. For example, decreasing the space allowance (from 267 to 67 $m^2$ per animal) decreased average daily weight gain of red deer hinds and ewes more under co-grazing (211 vs. 141 g/day for hinds, 202 vs. 170 g/day for ewes, respectively) than under single-species grazing (225 vs. 185 g/day for hinds, 185 vs. 175 g/day for ewes, respectively) (Blanc et al., 1999). Thus, decreasing the space allowance by increasing the stocking rate increased competition for herbage and decreased productivity in the multi-species groups. The meta-analysis of D'Alexis et al. (2014) further revealed that overall productivity of sheep-cattle grazing systems peaks when the proportion of sheep liveweight in total (cattle + sheep) liveweight equals 0.4.

### 2.2.2. Profitability

The profitability of multi-species livestock farms has not been studied extensively. This may be because profitability can vary with the proportion of each livestock species, the operational costs of each production enterprise and the relative values of livestock products, which varies considerably among years, countries or even regions. As mentioned, multi-species livestock farms tend to have higher meat productivity per unit area as long as locally relevant management practices are implemented, in particular an appropriate stocking rate during grazing. In addition, co-grazing may use herbage more efficiently and reduce farm dependency on feed inputs. Umberger et al. (1983) also reported a 29% increase in farm net income when combining cattle and sheep compared to that of a cattle farm, as long as steer prices were ca. 20% higher than lamb prices (Table 1).

Economies of scope apply when producing two or more products simultaneously costs less than producing each product separately (Chavas and Kim, 2007). Thus multi-species livestock farms can obtain economies of scope when inputs that can be shared among production enterprises lower the total cost of producing two or more products. The machines and equipment to produce, store and distribute feed can be common to different species. Walker (1994) suggested that a 20% increase in stocking rate allowed by multi-species livestock grazing would decrease fixed costs per head by 17%, assuming no capital improvements were needed for the second species. Fencing requirements are similar for some co-grazed livestock species (e.g. sheep and goats) but not for others (e.g. sheep and cattle) (Animut and Goetsch, 2008). Fences that will contain sheep and goats will also contain cattle, but the opposite is not true (Walker, 1994). Sheep can also be housed in the fodder shed after cattle have consumed some forage, since sheep generally graze later in winter. In spring, ewes can be housed in the cattle barn for lambing while cattle have returned to pasture; however, this approach requires some time to adapt the barn. Another way to generate economies of scope is to use by-products from one enterprise as an input for another enterprise (e.g. feeding piglets whey from milk processed into cheese).

Although economies of scope may be possible, multi-species livestock farmers need to manage more groups and types of animals. Overall, more skills and time to train and market products are needed. Farmers may perform less well when managing more complex systems such as multi-species livestock farms, and some time-saving technologies that are profitable only above a given scale cannot be adopted (de Roest et al. Almeida et al., 2018). Moreover, one species is usually less profitable than the other (Meyer and Harvey, 1985), thereby reducing the efficiency of resource allocation to the enterprises. This reduces economies of scale, which are defined as a decrease in the cost per unit of output of the farm as output increases. As Chavas (2008) highlighted, trade-offs exist between (i) economic gains due to complementarity (economies of scope) between enterprises and risk-reducing effects and (ii) economic losses due to lower economies of scale and allocation of some farm resources to a less profitable enterprise (at least in the short term). As Bell and Moore (2012) highlighted, empirical evidence from a farm sample is lacking to identify the conditions under which multi-species livestock farms are profitable.

Other economic advantages of multi-species livestock farming are similar to those of any diversified farming system (Bowman and Zilberman, 2013; van Keulen and Schiere, 2004). Since different species have different sensitivities to risks (e.g. markets, prices, climate, workforce, public policies), a good outcome for one enterprise can offset a poor outcome for the other one in a given year. It may also allow farmers to easily adjust herd sizes or adapt the type of livestock products sold (e.g. lean or fattened animals) to the conditions of a given year (Nozières et al., 2011). This strengthens the farm's ability to cope with unexpected events, thereby promoting stability in the farmer's income (Esmail, 1991; Darnhofer et al., 2010). Thus, multi-species livestock farming is a way to mitigate risks (Bowman and Zilberman, 2013) that can both increase mean profit and decrease profit variability.

Diversified farms such as multi-species livestock farms tend to sell their products through multiple marketing channels that often focus on distinctive food products and increase economic viability (de Roest et al., 2018). Marketing products from more than one livestock species increases farm income by enabling farmers to market products throughout the year. Diversifying production enterprises can be an asset for short supply channels and, conversely, developing short supply channels to add value to products can lead to diversification of types of production, including potential processing of raw products to increase added value. This way of marketing, however, is an activity in itself and can obscure the technical performance and profitability of the enterprises providing raw materials. Further studies are needed to refine these inter-relationships between enterprise practices and technical performances, processing methods and sales practices, and workload and work organization that determine the overall profitability of diversified farms.

### 2.3. Social sustainability

#### 2.3.1. Animal health and welfare

Combining different livestock species on the same pasture, simultaneously or sequentially, takes advantage of the host specificity of most gastrointestinal nematodes (Table 1). For example, since sheep and goats host the same species of nematodes (Deplazes et al., 2013), co-grazing them will not decrease nematode infections. However, lambs frequently have fewer gastrointestinal nematodes or excrete fewer nematode eggs when co-grazed with cattle than when sheep alone are grazed (Arundel and Hamilton, 1975; Brito et al., 2013; Jordan et al., 1988; Marley et al., 2006). Rotational grazing of tropical pastures by goats and heifers reduced faecal egg excretion and mortality in kids; the kids also grew faster while heifers were not significantly affected by gastrointestinal nematodes and grew normally (Mahieu, 2013). Similar benefits were recently observed in saddle horses; young horses grazed with cattle excreted twice less strongyle eggs than those grazed alone in specialized horse farms (Forteau et al., 2020). Surveys made in the same farm network revealed that only one third of the mixed farmers were aware that co-grazing of horses with cattle could be used as part of their strongyle control strategy. Beyond these benefits, some inter-species transmission have, however, also been reported, e.g. bovine-specific *Haemonchus placei* can infest sheep, and ovine-adapted *Haemonchus contortus* can infest cattle (Riggs, 2001; Almeida et al., 2018) with harmful effects on animal health and welfare. These two nematode species have even hybridized (Chaudhry et al., 2015).

Beside the risk for parasitic cross-infection, multi-species livestock farming systems also face the challenge of cross-species transmission of bacterial and viral diseases (Rogdo et al., 2012; Table 1). Managing these risks requires knowledge of (i) how long a specific pathogen remains infectious under given circumstances and (ii) which animals can serve as an intermediate host of a pathogen to which another species is clinically susceptible. Knowledge in this area of research is incomplete, however, and requires further investigation. Examples of such diseases include malignant catarrhal fever (Syrjälä et al., 2006), ovine herpesvirus 2, ovine Johne's disease (Moloney and Whittington, 2008) and chronic wasting disease (Raymond et al., 2000; Belay et al., 2004). For some diseases, such as malignant catarrhal fever and ovine herpesvirus 2, sheep are asymptomatic carriers that infect clinically susceptible species such as cattle. For other diseases, such as ovine Johne's disease and chronic wasting disease, cattle are carriers and thus pose a risk to clinically susceptible species such as small ruminants.

Certain pathogens can clinically affect several species and therefore pose a greater threat to multi-species livestock farming; examples include anthrax (Beyer and Turnbull, 2009; Owen et al., 2015) and brucellosis (Taleski et al., 2002). Diseases with high mutation rates, such as small-ruminant lentiviruses, commonly transmitted horizontally in sheep and goats via bodily fluids (Nettleton et al., 1998), also threaten multi-species livestock farming. Generally, RNA viruses (e.g. small-ruminant lentiviruses) have high mutation rates and are therefore more likely to transcend the species boundary (Minguijón et al., 2015; de Pablo-Maiso et al., 2018). For example, avian influenza recently spread from birds to humans and swine (Forrest and Webster, 2010; Bourret et al., 2017). Similarly, a close relationship among different strains of a virus or bacteria genus could lead to cross-species transmission or indicate recent transcendence of the species boundary. The viruses that cause bovine viral diarrhea, border disease and classical swine fever are all pestiviruses in the family Flaviviridae and hence closely related (Braun et al., 2014; Göktuna et al., 2017). Passler and Walz (2010) suggested that all three strains can be transmitted between species, and Braun et al. (2014) confirmed it experimentally for sheep and calves.

Although simultaneous grazing of livestock species may also modify behavior, interspecific behavior of livestock species sharing a pasture has received little attention. Most co-grazing studies focus on sheep kept with goats (Hulet et al., 1989; Animut and Goetsch, 2008), cattle (Cuchillo-Hilario et al., 2018) or horses (Patkowski et al., 2018), but these studies mainly cover issues such as bonding management or nutrient requirements. To our knowledge, only one study addressed changes in behavior: cattle ruminated and rested longer when simultaneously grazed with sheep, while sheep covered more distance than those in single-species systems, which may have been due to cattle pushing sheep from preferred grazing spots (Cuchillo-Hilario et al., 2017).

One specific type of combination of livestock species is the use of guardian animals. Flocks of sheep are sometimes guarded by an individual animal (e.g. llama, donkey; see Smith et al. (2000) for an evaluation of several guardian species) or group of animals from a different species (e.g. cattle; Hulet et al., 1989; Anderson, 1998). Regarding the latter, in extensive farming systems, some species that do not naturally associate but rather create independently moving single-species groups can be forced to bond (e.g. goats and sheep: Gipson et al., 2003; cattle and sheep: Anderson, 1998; Anderson et al., 2012; Hulet et al., 1989). One way to force two groups of different species to bond is to increase proximity, which can create one cohesive group over time. After bonding, one species remains near the other species or seeks it out in times of danger (e.g. predators), even without fences (e.g. cattle and sheep: Anderson, 1998; Anderson et al., 2012; cattle, sheep and goats: Hulet et al., 1989; horses and sheep: Patkowski et al., 2018). Hulet et al. (1989) reported reduced stress in lambs at weaning when the flock had bonded with cattle.

### 2.3.2. Farmer welfare

Farmer welfare depends greatly on work organization, which has gained increasing interest in the agricultural science literature in recent years (Fiorelli et al., 2007; Hostiou and Dedieu, 2012; Cournut et al., 2018). To date, however, no empirical study has been published on work organization on multi-species livestock farms (Table 1). Ideally, farm work must be organized in a way that meets a farmer's expectations for working conditions, quality of life and income, while addressing livestock management issues, particularly animal welfare (Cournut et al., 2018). In practice, achieving these goals depends on social, cultural and structural conditions of the context; effectiveness of farm-management strategies; external constraints (e.g. economic) and the farmer's perception of the work (David et al., 2010; Cournut et al., 2018). These strategies and perceptions are driven by different motivations for being a farmer that tend to disconnect issues of workload and income to some extent. High workload and/or low income do not necessarily result in a low social satisfaction of the farmer (Fiorelli et al., 2007; Besser and Mann, 2015).

Production diversity increases the number of activities and thus the number of tasks on a farm. Even though it may imply a higher total workload and management complexity for the farmer (Kingwell, 2011), the actual workload per worker may not increase if diversification is accompanied by re-organization of work and/or by improved management of production processes (Darnhofer et al., 2010; Hostiou, 2013). Still, farmers may have difficulties identifying appropriate individual options to achieve these goals. Further, options such as the simplification of processes may conflict with other management goals, especially animal welfare. Delegation to employees is another option but it is only possible if a farm's economic performance allows for it. In a diversified farming context, this may imply concentrating on niche markets rather than increasing production of standard goods, a result also indicated by David et al. (2010).

Production diversity may promote flexibility in work organization. Allocation of the workforce can shift with changes in the production context (Bell and Moore, 2012). However, work flexibility may decrease as workload per worker increases. This situation arises when tasks are time-consuming (e.g. due to limited mechanization) and/or the size of the workforce (e.g. Carneiro dos Santos Filho et al., 2012). Again, the most obvious solutions to increase flexibility are to increase the workforce (e.g. by delegation) or work efficiency (e.g. by mechanization) (Hostiou et al., 2015). Increasing the workforce may be possible with diversification if the new activities generate additional income. In contrast, options for mechanization are limited in livestock farming systems, and investments may prevent economic viability in small management units (Bowman and Zilberman, 2013; Morel et al., 2017). Another option may be to re-design the structure and processes of the farming system, as indicated by studies of work organization patterns on organic suckler-sheep farms (Hostiou, 2013) and of development patterns of organic farms (David et al., 2010).

## 3. Research areas for multi-species livestock farming

### 3.1. Better characterize the management of multi-species livestock farms

Multi-species livestock farming could represent a promising option for improving sustainability of livestock farming systems; however, according to Animut and Goetsch (2008), this practice does not always improve the sustainability of multi-species farms. Among the reasons they identified, a key one is maladapted integration of livestock species, or of pasture and livestock enterprises, leading to inappropriate management of stocking density, sward diversity, etc. As illustrated in the previous section, management practices can either promote benefits or adverse effects of multi-species livestock farming. This highlights the key role of farmer management in the integration of agrobiodiversity components and farm enterprises in space and time (Hendrickson et al., 2008). As mentioned, however, the management dimension is often poorly understood beyond the effects of stocking rate and livestock species (Table 1). We claim that this is a central dimension for scaling-up multi-species livestock farming and that it thus requires further investigation to better characterize the management of multi-species livestock farms.

Several analytical frameworks have been developed to assess farm-level integration (Sumberg, 2003; Hendrickson et al., 2008; Bell and Moore, 2012). They rely on a vision centered on farming practices, (i.e. whether enterprises are co-located or segregated in space, simultaneous or sequential in time) and/or on nutrient fluxes (Stark et al., 2018) and resource exchanges (products and by-products such as straw and manure). However, interactions among farm enterprises go beyond technical aspects and can lead to innovations in work organization and in processing and marketing channels. Three perspectives could be considered to characterize overall farm management:

- Integration through farming practices results from simultaneous temporal or spatial interactions among enterprises (instead of managing system components separately). Integration of crops, pastures and livestock has been shown to increase nutrient cycling (Soussana and Lemaire, 2014), reduce pest and disease pressure (Marley et al., 2006) and adapt the range of products (e.g. selling lean or fattened animals) to feed availability (Nozières et al., 2011).
- Integration through work organization (i.e. versatility of workers across enterprises vs. their specialization) in either a simultaneous (working together) or sequential (working one after the other) mode may help avoid work peaks and distribute workload better. Integration also allows risks to be managed at the farm scale and among workers by making collective production decisions (Martin et al., 2016) and offers greater management flexibility to cope with unexpected events (Nozières et al., 2011).
- Integration through sales (i.e. sales channels similar among enterprises vs. specific to each enterprise), either at similar or different times of the year, may increase economic efficiency (by decreasing sales costs), promote economies of scope (Veysset et al., 2014), ease access to short supply channels with a wider range of products, and reduce economic vulnerability of farming systems (Esmail, 1991; Russelle et al., 2007; Sneessens et al., 2019) Fig. 2.

Accordingly, a farm can have integrated farming practices but not have integrated work organization and/or sales management. That is, it may have specialized workers and/or specific sales channels per enterprise. In contrast, a farm can have versatile workers without integration in farming practices, with two enterprises segregated in space. For example, a farm with poultry and dairy-cattle enterprises managed by the same farmer can use different fields to produce the feed required

**Fig. 2.** Suggested perspectives to better characterize the management of multi-species livestock farms.

for each enterprise and different marketing channels for each one. Limited integration, however, may decrease most of these potential benefits of multi-species livestock farming.

By considering these three perspectives on multi-species livestock farming, one may explore the diversity of management options and their impacts on farm sustainability more easily.

### 3.2. *Further explore the complementarity of livestock species in multi-species settings*

To explain the lack of consistent improvements in sustainability performances of multi-species livestock farms, Animut and Goetsch (2008) highlighted the maladaptiveness of some species combinations, which increases dietary overlap, parasite susceptibility or disease transfer among species. As shown by the literature reviewed, resource-use efficiency, productivity and animal health of some combinations (e.g. cattle and sheep) have been extensively studied. However, systems analysis of these combinations considering management practices and related sustainability benefits at the farm level are lacking. Other species combinations remain largely ignored (Table 1), mainly those combining ruminants and monogastrics (e.g. cattle and poultry), although they may have some potential due to their complementary diet compositions and resource-acquisition strategies. For example, co-grazing of cattle and poultry may offer several benefits: cattle protect poultry from birds of prey and provide them with another protein source, since insectivorous birds forage in dung pads of pastured cattle and feed on beetles and fly larvae (Valiela, 1969). Dung pads pecked and scratched apart by birds degrade up to one year faster than intact pads (Anderson and Merritt, 1977), contributing to rapid dung removal, which is desired (Wall and Beynon, 2012). While simultaneous co-grazing of ruminants and poultry might contradict efforts to control zoonotic microorganisms in the food chain, (e.g. *Salmonella* spp.), it may reduce parasite pressure for at least one of the species involved.

The field of ecology has long studied complementarity processes in ecosystems, particularly in pastureland ecosystems (Hooper et al., 2005; Fargione et al., 2007), and constitutes a promising source of inspiration to extend its concepts and analytical frameworks to the field of animal science. In ecology, niche differences among species are used to explain coexistence of large numbers of species and the increase in the provision of ecosystem services allowed by greater species diversity. In an ecosystem, species may compete for the same limited resources or be complementary by using different resources (Fig. 3; Hinsinger et al., 2011). Facilitation is a third relationship, with some species helping others benefit from a resource. The dietary overlap concept (Section 2.1) is an initial step toward characterizing niche differences and thus complementarity among livestock species. However, it needs to be implemented in a wider range of management situations (e.g. stocking rates, pasture types) and extended beyond the focus on grazing. At the farm level, competition, complementarity or facilitation should be determined for a wider range of resources, especially workforce, and a wider range of issues, especially animal health and welfare, depending on the transmissibility of parasites and diseases and the cohabitation ability of the species involved.

### 3.3. *Assess and better explain the sustainability of multi-species livestock farms*

The literature reviewed focused mainly on specific dimensions of farm sustainability rather than a comprehensive assessment. However, a comprehensive assessment is essential to develop consistent recommendations for improving existing multi-species livestock farms or introducing a new livestock species to a farm specialized in one livestock species. Previous analysis, assessment and modeling studies have focused mainly on single-species livestock farms, possibly due to the inherent complexity of multi-species livestock farms.

A range of sustainability assessment methods is already available in the literature (De Olde et al., 2016), such as SAFA (FAO, 2013), IDEA (Zahm et al., 2008, 2019) and RISE (HAFL, 2014). Most of these methods cover the three common dimensions of farm sustainability - economic, environmental and social - and were built on assumptions about farm sustainability and practices. For example, high agrobiodiversity on a farm is considered to be positive without considering threshold effects, interactions, or how crops, pastures and livestock are managed in space and over time. These assumptions need to be reconsidered, since it is currently unknown whether underlying assumptions and thus existing methods apply to multi-species farming systems. Moreover, certain dimensions of sustainability are more critical on multi-species livestock farms, such as work organization. Methods to assess work organization exist (e.g. Hostiou and Dedieu, 2012; Cournut et al., 2018) but have not yet been integrated into holistic sustainability assessments for farms. Two coefficients are usually calculated, one for workload and organization by relating workload to the available workforce, and another for the amount of flexible work time available. Adapting existing methods or developing new ones to assess sustainability of multi-species livestock farms is necessary (Table 1), especially to relate sustainability to the management practices implemented. It is a challenge to find simple and robust methods that can be extended to fit the complexity of multi-species livestock farms.

Another option to assess the sustainability of multi-species livestock

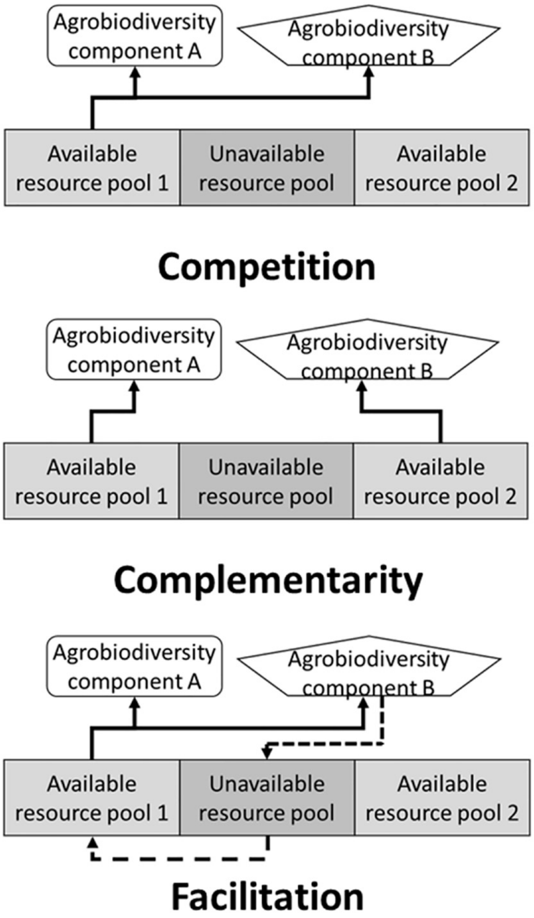

**Fig. 3.** Competition, complementarity (resource-use partitioning), and facilitation between two components of agrobiodiversity (A and B). Pools 1 and 2 represent different forms of a single resource (e.g. feed). Solid arrows indicate uptake of the resource, while dashed arrows indicate mechanisms by which component B can alter resource availability, increasing the size of the available pool at the expense of the unavailable pool, thereby increasing uptake of the resource by component A (facilitation). (Adapted from Hinsinger et al. (2011)).

farms is simulation modeling, which allows the dynamic nature of the system to be related to variability in the production context. Like the sustainability assessment methods mentioned, however, available models were developed for farms with one livestock species (Rotz et al., 2005; Jouven and Baumont, 2008; Vayssières et al., 2009). Furthermore, existing models usually focus on, for example, trade-offs between productivity and biodiversity conservation (Jouven and Baumont, 2008), whereas a holistic and dynamic modeling approach is required to represent the complexity of multi-species livestock farming. Developments are needed to simulate different livestock species in one farming system, especially species previously overlooked (e.g. goats, broilers). Furthermore, the relationship between multiple livestock species and their impact on, for example, herbage-use efficiency or parasite load on pastures needs further investigation, because understanding these relationships is necessary to build models and ultimately assess sustainability. Based on these models, alternative scenarios of multi-species livestock farms, differing in, for example, the degree to which they integrate livestock production enterprises can be simulated to identify the minimum levels of integration required to take advantage of the benefits of livestock diversity. Moreover, models simulating a wider range of sustainability dimensions under a diversity of climatic and economic conditions should be developed.

### 3.4. *Characterize conditions for success of and obstacles for multi-species livestock farming*

The benefits of multi-species livestock farming have been mainly studied in semi-extensive (or free ranging) farms and areas but they remain under-explored in more intensive conditions. One reason may be that in intensive farms, multiple species of livestock are uncommon because of multiple lock-in effects such as those documented by Meynard et al. (2018) that hindered crop diversification in France. Crop diversification is a widely known mechanism to increase sustainability of cropping systems by, among other things, decreasing inputs, promoting ecosystem services, and stabilizing yields and income. Short-duration crop rotations with 1–3 crops remain dominant, however, in the French context described by the authors due to lock-ins that have developed in the sector. Lock-ins occur when relationships among environments, organizations, technologies, knowledge and values create strong interdependencies among stakeholders in a sector (Kallis and Norgaard, 2010). For crop diversification, several studies (Magrini et al., 2016, 2018; Meynard et al., 2018) have analyzed components of these lock-ins, which include low availability of well-suited cultivars and plant-protection solutions, scarcity of empirical data on best management options, lack of farmer knowledge and skills, logistical constraints on collection and storage of a diversity of grains, inability of value chains to process minor or emerging crops into food products and little demand by consumers for these products. Thus, lock-ins apply at all levels of agricultural products, from production to consumption.

Characterizing conditions for success of and obstacles for multi-species livestock farming is a precondition to its wider development (Table 1). This kind of socio-technical analysis will identify stakeholders active along the value chain from production to consumption, their respective objectives, work habits, and constraints. Increasing understanding should help prioritize actions (e.g. increasing genetic research focused on traits of relevance to multi-species livestock farming, inventing new forms of slaughterhouses able to process a diversity of animals, establishing empirical evidence of economic benefits of multi-species livestock farming) and organize them into pathways toward diversified livestock farms. These pathways will rely on a set of technological, organizational and institutional innovations (Magrini et al., 2016) and on simultaneous and coordinated mobilization of a wide range of stakeholders, from farmers to consumers (Meynard et al., 2018).

## 4. Conclusions

Multi-species livestock farms are a potential conduit to increase diversity in agriculture; however, they have not previously been studied or discussed in a comprehensive way. This review assessed the available literature concerning multi-species livestock, with a focus on farm sustainability. Many positive effects were identified, particularly in the areas of resource use efficiency, biodiversity conservation, productivity, profitability, and animal health and welfare. A limited number of negative interactions were identified, and these mainly involve the potential for inter-species transmission of parasites and pathogens.

The review also identifies four areas of needed research relating to multi-species livestock farming. These comprise better characterizing the management of multi-species livestock farms; further exploring complementarity of livestock species; developing methods for assessing farms designs in the context of sustainability, for example through the use of simulation models; and, socio-technical analysis of the conditions for success and obstacles for multi-species livestock farming. This review highlights the value and potential of multi-species livestock farms, and can assist researchers and policy makers in prioritizing efforts to promote them and improve their sustainability.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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