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REVIEW ARTICLE

Methane mitigating options with forages fed to ruminants

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Abstract

Nutritional strategies, including feed management measures, are promising methods for CH_4 and overall GHG reduction. Evidence from literature is reviewed in this article in relation to the effects of forage quality (digestible organic matter, DOM) and forage type (grasses vs. legumes, and maize). The major determinants of forage quality are botanical composition and phenological stage, i.e., at advanced growth stages of plants, the fibre content increases while DOM decreases. Methane yield (g/kg DMI) decreases with increased digestibility of forages in both dairy cattle and sheep, and also CH_4 intensity (g/kg milk) decreases with increased digestibility of forages for dairy cattle. Using forage legumes in ruminant feeding systems can reduce overall GHG emissions due to decreased N fertilizer use and related emissions. Recommended dietary mitigation measures are often related to a reduction in N excretion such as better matching of dietary protein to animal needs, shifting N excretion from urine to faeces (by tannin inclusion at low levels) and reducing the amount of excreted fermentable organic matter. Methane decreases with increasing intake of forage legumes rich in tannins and there is a shift of N partition from urinary N towards faecal N. Reduced CH_4 emissions from ruminants fed on forage-based diets will decrease the carbon footprint of livestock and agriculture and improve the efficiency of productive ruminants in both developing and developed countries. Likewise, estimations of net CH_4 output should account for enteric CH_4 emissions and soil carbon (C) sequestration of land used for feed production (i.e., grasslands and croplands).

KEYWORDS
C sequestration, forage, methane, mitigation

1 | INTRODUCTION

Livestock production is responsible for environmental burdens participating in around 14.5% of global greenhouse gas emissions (GHG; Gerber et al., 2013). Among those GHG, enteric methane (CH_4) emission contributes up to 40% of livestock's GHG (Gerber et al., 2013). Consequently, several nutritional strategies to mitigate enteric CH_4 have been studied and developed (Hristov et al., 2013). Among the different

options, feed and feed management measures, such as enhanced forage quality (increased digestibility by feed processing [i.e., drying, grinding]) and livestock precision feeding are the most promising strategies to reduce enteric CH_4 (Gerber et al., 2013). Animal performance is related to efficient forage use associated with good nutrition management allowing to combine increased animal production with CH_4 reduction measures (Pereira et al., 2015). In the last decades, a large number of studies have been conducted related to the effects of forages

(grass, legumes, or mixture) on N excretion and N_2O emissions, and to the effects of grassland management on C fluxes. Grass-based diet has gained interest, as bringing together pasture ecosystem services and livestock production. Among pasture ecosystem services beneficial for livestock production and emissions are biodiversity, which relates to forage quality and subsequent product quantity and quality but also to the environment, e.g., legumes reduce the need for mineral N fertilisation and related N_2O emissions, and finally C sequestration of pastures.

However, the different options diverge in terms of viability, costs, and acceptance by the producers. To be adopted, these strategies should provide similar or increased animal performance and economic viability while reducing CH_4 intensity (emission per unit of milk or meat), but also other sources of GHG, such as N_2O from crop fertilizers/manure and CO_2 from feed production and C sequestration (Gerber et al., 2013; Pereira et al., 2015).

This article aims to review the forage GHG mitigating options from individual studies and review articles from the literature that are the most documented and promising. It summarises both qualitative and quantitative effects of those mitigating options (i.e., forage quality, type, and conservation modes, grassland management, biodiversity) mostly on enteric CH_4, N excretion and related N_2O (along with CH_4) and C sequestration. Moreover, it provides insights into statistical models that consider the effects of diet composition, such as the chemical composition or digestibility of forages on GHG emissions. Their ability to capture the GHG abatement options is crucial nowadays in order to be implemented into GHG accounting tools or national GHG inventories.

2 | ENTERIC METHANE MITIGATION

2.1 | Forage quality

Increasing forage digestibility and digestible forage intake seems to be one of the main CH_4 mitigation practices, recommended worldwide (Hristov et al., 2013). The effect of forage organic matter (OM) digestibility on CH_4 emission intensity has been studied for forages with different nature (i.e., fresh herbage and silage) and for different forage types, such as grass, legume or maize, and for different animal categories (cattle and sheep; Phelan et al., 2015; Van Gastelen et al., 2019). Though large efforts have been made, the response in CH_4 emission is not consistent and depends on the unit as well as the animal category considered (Van Gastelen et al., 2019). Increased forage digestibility resulted in increased dry-matter intake (DMI, kg/day) and consequently increased CH_4 emission (g/day) for dairy and beef cattle, but not for sheep. When intake or production is considered, both CH_4 yield (g/kg DMI) and CH_4 intensity (g/kg milk) are decreased with increased digestibility for dairy cattle, but no difference in CH_4 yield (g/kg DMI) was observed for beef cattle. For sheep, CH_4 yield decreased with increased forage digestibility (Van Gastelen et al., 2019).

It is important to include forage quality into GHG accounting tools or GHG inventory methodology. A number of equations have been developed during the last years for different animals fed forages or on pasture to predict CH_4 emission (e.g., Archimède et al., 2011;

Ellis et al., 2007; Escobar-Bahamondes et al., 2017; Van Lingen et al., 2019; Niu et al., 2018; Rico et al., 2016). To be more general, Sauvant et al. (2018) have developed an equation using "Methafour" database (104 publications, 211 experiments, 592 treatments; see Nozière et al., 2018), comprising CH_4 emissions measured under currently applicable measurement techniques, in ruminants only fed with forages, used for GHG inventory methodology and in INRA's feeding system. Briefly, the equation estimated the CH_4 production per kg of digestible OM (g/kg DOM; 34.7 ± 9.1, min = 10.9, max = 69.1) and was based on the combination of feeding level (FL, DMI % of body weight (BW)) and NDF content of forage (proposed by Eugène et al., 2014), and the DOM content of the forage (Equation 1 in Table 1). There are only a few direct comparisons in in vivo trials, and consequently, the specific effect of type of forage and species cannot be assessed. There is a marginal increase of the slope for forages with low quality as compared to mean CH_4 production (i.e., 60 vs. 40 g/kg DOM, respectively) whereas for forages with high quality, there is a marginal decrease of the slope as compared to mean CH_4 production (36 vs. 40 g/kg DOM, respectively). Comparisons of relationships including CH_4/DMI (Equation 2) or CH_4/DOM (Equation 1) indicate that DOM is an important explanatory variable that needs to be considered (Table 1). Consequently, equations with CH_4/DOM are recommended as DOM considers both quantity and quality of forage. For animals fed with forages, there is a close positive relationship between $CH_4\%$ of gross energy (GE) and the acetate to propionate ratio in the rumen (C_2/C_3; Moss et al., 2000), as illustrated in Figure 1. The fermentation of cell wall carbohydrates in forages generally produces a higher C_2/C_3 ratio in the rumen and consequently a higher amount of CH_4 as compared to non-fibre carbohydrate fermentation (Hegarty, 1999; Moss et al., 2000). Indeed, propionate production favours competitive pathways for H_2 use in the rumen, whereas acetate production favours H_2 production in the rumen (Moss et al., 2000).

The difference between animals (bovine vs. ovine) could also be linked to mean retention time differences and fractional degradation rates of feeds in the rumen (Poppi et al., 1981; Siddons & Paradine, 1983). Poppi et al. (1981) reported a longer mean retention time and lower fractional degradation rates in beef and dairy cattle than in sheep.

TABLE 1 Methane prediction for animal fed forages

CH_4 (g/kg DOM) = 34.95 − 4.05 × FL + 0.027 × NDF − 0.010 × DOM. (Equation 1) (n of data points = 412, number of trials = 153, RMSE = 3.1 g/kg DOM). Sauvant et al. (2018)
CH_4 (g/kg DMI) = −22.4 − 2.25 × FL + 0.137 × DOM (g/kg DM) − 0.00009 × DOM^2 (g/kg DM). (Equation 2) (n = 283, n trials = 53, RMSE = 1.6 g/kg DMI). Sauvant et al. (2011)
CH_4 (g/kg DOM) = 34.26 − 3.96 × FL + 0.027 × NDF − 0.008 × DOM − 1.72 × Log_{10} (1 + TAN). (Equation 3) (n = 398, n trials = 147, RMSE = 3.1 g/kg DOM) Eugène, Sauvant, et al. (2019)

Note: FL is the feeding level (DMI%BW), NDF content, digestible OM (DOM) content and TAN is the tannin content (g/kg DM) of the forages. Methane yield is expressed as g/kg DMI or g/kg DOM.
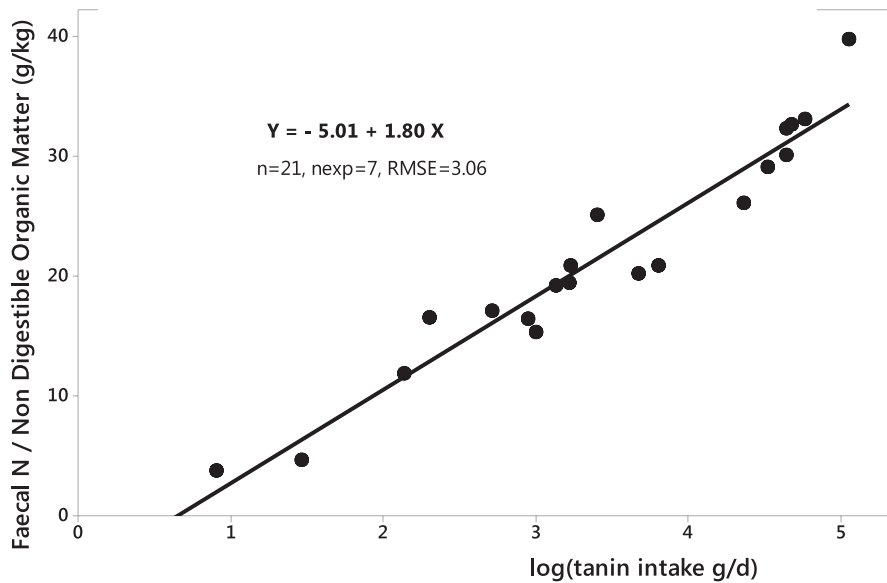
$$Y = -5.01 + 1.80\,X$$

n=21, nexp=7, RMSE=3.06

FIGURE 1 Intra-experiment relationships between energy from CH_4 in % of gross energy (ECH_4%GE) and the acetate/propionate (C_2/C_3) ratio in the rumen, for ruminant fed-forages, in different studies (from Methafour database)

According to the analysis of the "Methafour" database (Nozière et al., 2018) for this present review, the main factor of forage quality is the stage of growth (i.e., phenology of vegetation, Baumont et al., 2018); when the growth stages advance (i.e., the vegetation becomes older as moving from vegetative to generative cycle), we observed an increase in the crude fibre (3.72 ± 3.28 g/kg DM) and NDF contents (4.78 ± 3.54 g/kg DM) for every 10 days of grass growth, which explains the decrease in the quality. Most of the studies used in this analysis were conducted during spring and not in autumn where a delayed harvest time also results in older vegetation but then without generative grass stems. However, there is also a decline in the level of DMI/BW (-0.15 ± 0.08 g/kg BW for every 10 days). This last parameter has a dominant effect on CH_4 production which increases per unit of DMI (0.145 ± 0.106 g/kg DM for 10 days) but not per kg BW, leading to a mean decrease equal to 0.51 ± 0.06 g/kg DM.

2.2 | Forage type and conservation methods

2.2.1 | Legumes versus grass

Feeding forages, especially forage legume species, represents an interesting strategy to both provide nitrogen to the animal and decrease CH_4 emissions, thus enhancing animal productivity (growth, milk, and wool production) and mitigating climate change (CH_4, N_2O, and ammonia emissions; Makkar, 2003; Reed, 1995). However, several authors have stressed the importance to conduct diet improvements in a holistic multi-criteria approach (Kebreab et al., 2006; Van den Pol et al., 2018) in order to integrate diet management to all aspects of a farm (field operations, supply chain, socio-economics, environment, etc.). For instance, one important factor of diet is the ability of forages to prevent gastrointestinal parasitic nematodes (Makkar, 2003; Mueller-Harvey et al., 2019). Forage legumes containing condensed tannins (e.g., sainfoin (*Onobrychis viciifolia* Scop.), birdsfoot trefoil (*Lotus corniculatus* L.), and sulla (*Hedysarum coronarium* L.))

or polyphenol oxidase enzymes (e.g., red clover (*Trifolium pratense* L.)) have been shown to reduce rumen protein degradation in vitro (Makkar, 2003) and ruminants seem to capture these proteins more efficiently into meat and milk. However, more evidence is required using in vivo production experiments. To assess the quantitative effects of tannins on CH_4 emissions, Eugène, Doreau, et al. (2019) conducted a meta-analysis. Although several reviews have been published on that topic (Jayanegara et al., 2012), only a few general equations, mostly derived from in vitro trials, have been published because of the diversity in methods and types of tannins. Using the "Methafour" database (Nozière et al., 2018), it was possible to significantly complete Equation 1 by integrating tannin content (TAN, g/kg DM, Equation 3). In Equation 3 (see Table 1), CH_4 (g/kg DOM; 34.7 ± 9.1, min = 10.9, max = 69.1 g/kg DOM) is expressed by the log-transformed TAN (Eugène, Sauvant, et al., 2019). In spite of this, the coefficients of regression of other variables remained fairly stable between Equations 1 and 3. Consequently, we recommend using the TAN coefficient in Equation 3 to evaluate the average quantitative effect of tannins in all types of diets. Nevertheless, more data are needed to fully assess the differential effects of the wide variety of tannins in different diets, concerning the structure/activity relationships of tannins (condensed or hydrolysable), and the long-term effects of such diets.

The use of forage legumes such as lucerne (*Medicago sativa* L.), red clover or white clover (*Trifolium repens* L.) that contain high concentrations of degradable proteins may increase the risk of bloat (Phelan et al., 2015). Because these legumes are associated with high voluntary intake and fast rates of particle breakdown in the rumen, they tend to be associated with higher bloat risks. Sainfoin, birdsfoot trefoil or sulla contain tannins or saponins, which may explain their low risk of bloat. However, when compared to grass- or cereal-based ruminant production systems using high amounts of N fertilizer, forage legume-based production systems (i.e., farms) tend to have a less negative environmental impact on plant species biodiversity, N losses via leaching and GHG emissions (Phelan et al., 2015). Although these forage legumes generally have lower yields and persistence,

genetic modification would allow the insertion of these traits into more widely cultivated forages (Broderick, 2018).

The soluble carbohydrate content of forage legumes is low as compared to forage grasses, so that the use of supplements rich in starch (cereals) are required (Ruckle et al., 2017).

Forages rich in secondary plant compounds, such as tannins, have been studied both for their nutritional effects on animal productivity (Reed, 1995) and for their anti-methanogenic properties, as thoroughly described by Jayanegara et al. (2012) and Jayanegara et al. (2015). Condensed tannins (CTs) can account for up to 20% of the dry matter in forage legumes rich in tannins used as ruminant feeds. Compared to temperate forages, tropical forages have a lower digestibility and differ in their chemical and structural composition (Leng, 1990). Ruminants fed tropical grasses seemed to have increased CH_4 emissions as compared to when fed tropical leguminous forages (Archimède et al., 2011; Eugène et al., 2014; Table 2).

However, the mitigating effect of tannins on CH_4 is inconsistent (Beauchemin et al., 2008; Makkar, 2003). The discrepancies of responses of animals to tannins among different studies are attributed to the different tannin concentrations in the diet, chemical structures of tannins, and types of diets. Recent research has highlighted the importance of the molecular structure of tannins (Mueller-Harvey et al., 2019). An establishment of a structure-activity relationship would be required to explain differences among studies and obtain consistent analyses of the beneficial effects related to tannins (Patra & Saxena, 2011). Likewise, multi-criteria analysis of the "Methafour" database indicated that the use of tannin-rich diets shifted the N partition from urinary N towards faecal N (Figure 2a). Consequently, as urinary N is a source of N_2O, a shift towards faecal N will decrease N_2O emissions. This shift is explained by the positive relation between faecal N excretion/non-digestible OM (g/kg) and tannin contents (log-transformed) of forages fed (Figure 2b), in other words, the correlation between TAN and N/C ratio of faecal excretions (i.e., Mueller-Harvey et al., 2019).

Other possible diets becoming more interesting in the view of the environment are legume silage (red clover; Dewhurst, 2012; Hristov et al., 2013) or mixtures of grass and legumes (such as white or red clover, birdsfoot trefoil, sainfoin; Phelan et al., 2015) and the use of legumes as an intercropping culture (such as *Stylosanthes guianensis* (Aubl.) Sw., *Lablab purpureus* (L.) Sweet, and *Vigna unguiculata* (L.) Walp.) (Hassen et al., 2017). Indeed, intercropped legumes could increase the forage productivity at the system level and help to preserve biodiversity, while reducing N losses via leaching and gas emissions.

2.2.2 | Silages

Maize silage

Although responses vary, CH_4 emissions can be reduced when maize silage replaces grass silage in the diet (Hristov et al., 2013). Van Gastelen et al. (2019) have summarised different studies comparing the CH_4 emission of ruminants fed maize silage in the replacement of grass silage or legume silage.

Different responses in CH_4 emission and intake are observed between dairy, beef, and sheep. For sheep, there was a quadratic effect on CH_4 yield (Jonker et al., 2016) when maize silage gradually replaced lucerne silage fed at an intake level of 2% BW. In other words, methane yield (g/kg of DMI; % of GEI) increased when sainfoin, birdsfoot trefoil, sulla or red clover were used with up to 50% of the diet. When using higher proportions of feed supplements, methane yield decreased but the level did not fall below that of 100% lucerne silage. For dairy cattle, increased levels of maize silage resulted in an average decreased CH_4 yield (g/kg DMI; MJ/MJ GEI), while some studies reported quadratic relations (Arndt et al., 2015; Hassanat et al., 2013; Van Gastelen et al., 2019). Several factors may contribute to the responses observed. First, DMI and consequently intake level (DMI % BW), feed digestibility and retention time in the rumen may have an effect. Moreover, there might be a starch concentration threshold that shifts the fermentation in the rumen towards more propionate formation (Hassanat et al., 2013), but this was not evidenced in the work of Jonker et al. (2016), where sheep were fed increasing levels of maize silage in the replacement of lucerne silage.

Although maize silage decreases enteric CH_4 production, manure CH_4 could increase due to increased faecal output of fermentable OM. Especially soil CO_2 emissions are much greater for maize silage compared with grass silage, reducing C sequestration potential as a result of crop cultivation (Börjesson et al., 2018; Franzluebbers et al. 2014). Accordingly, there is a need to use a holistic approach to evaluate and reconcile animal production with GHG emissions for different feed production systems.

Grass silage

Some studies and literature reviews indicate that the improvement of digestibility of grass silage could lead to reduced methanogenesis (Van Gastelen et al., 2019). This can be explained by the stage of maturity at which grass has been harvested, as grass silage can have lower fibre concentration, higher fibre digestibility and higher nitrogen content depending on mowing date, climate and species mixture of the sward (Elgersma & Søegaard, 2018). Accordingly,

TABLE 2 Effect of forage type on CH_4 emission, in L/kg dry matter intake (DMI), L/kg organic matter intake (OMI), L/kg digested OM (DOM), from Archimède et al. (2011)

	CH_4 (L/kg DMI)	CH_4 (L/kg OMI)	CH_4 (L/kg DOM)
Grasses			
C3 type	30.0[b]	33.1[b]	52.1[b]
C4 type	33.7[c]	38.8[c]	57.7[b]
Legumes			
Cool	30.1[bc]	33.7[bc]	52.4[b]
Warm	25.9[a]	27.2[a]	40.7[a]
SEM	1.8	1.8	2.9
p	.001	.001	.001

[a,b,c]Superscripts: Mean values within columns carrying no common letters are significantly different at $p < .05$.

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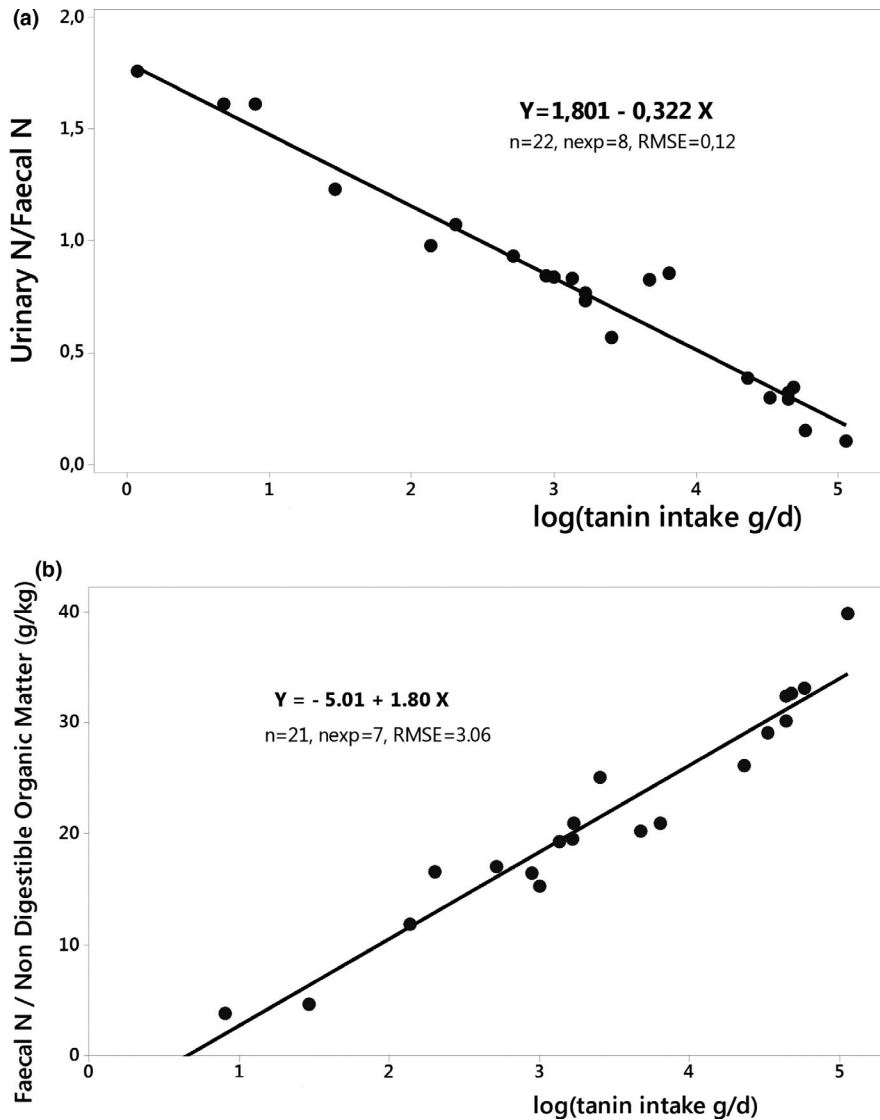
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FIGURE 2 Intra-experiment relationships between tannin contents and the Urinary N/Faecal N ratio (a) and faecal N excretions/non-digestible OM (g/kg) (b), for ruminant fed-forages, in different studies (from Methafour database)

the phenological stage and subsequent optimal timing for mowing may help to achieve high animal performance and reduced retention time in the rumen (Dewhurst et al., 2009). These strategies are most effective for dairy cattle, and also for beef cattle to a certain extent, but seem to have minor or no effects for sheep (Van Gastelen et al., 2019).

3 | C SEQUESTRATION

3.1 | Mitigation through the C sequestration of grazed grasslands

GHG balance studies with growing ruminants show a mean partition of ingested C between faeces (29%), CH_4 (4%), urine (4.5%), CO_2 (58%) and 4.5% for the C balance (i.e., calorimetric studies "Rumener" database, Sauvant & Giger-Reverdin, 2009). In lactating ruminants, the corresponding values are 29% (faeces); 3.5% (CH_4); 3.5% (urine); 42% (CO_2), 3% retained and 21% in milk. The majority

of ingested C is thus partitioned into CO_2 and emitted into the air (around 50% in cattle), and faecal C (around 30%, that returns to grasslands), followed by milk, urine, CH_4 and C balance (Sauvant & Giger-Reverdin, 2009).

There is evidence that the GHG balance of ruminants can be improved by grass-based systems and the capacity of grasslands to sequester C in soil. In general, grasslands have a higher soil organic matter content and soil C has longer residence time than croplands, because there is less soil disturbance (i.e., grassland ploughing, mowing and renovation) and a greater proportion of the input from root turnover is physically protected as chemically stabilized particulate organic matter (Six et al., 2004).

In grasslands, the degree of sequestered C is primarily influenced by plant productivity and the frequency and extent of disturbance (i.e., grazing; grassland ploughing and renovation). In view of that, grazing has a direct impact on grassland productivity, plant community structure and biogeochemical cycling. In grazed grasslands, much of the primary production is ingested by animals, where about 50% are emitted in the air (i.e., cow respiration), and returned to the soil in the

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form of faecal OM (non-digestible carbon; 25% to 40% of the intake, depending directly on its digestibility); the remainder is returned to the soil in the form of plant litter (ungrazed biomass) or root exudates. Accordingly, effects of grazing are driven by plant tissue removal (defoliation, intake), excretion (dung and urine deposits; with a C urine/C faecal ratio of 12.2 ± 6.0%, Sauvant & Giger-Reverdin, 2009), but also by trampling, which exerts mechanical pressure and causes physical damage to the vegetation where animals pass repeatedly. Due to uneven patterns of defoliation and animal returns, grazing animals promote spatial heterogeneity in C-N-P pools and fluxes, which add to a mosaic of patches of variable vegetation height and feed quality, and C storage potential (Bloor & Pottier, 2014).

At low grazing intensities, it seems that the animal excretion favours the N cycle in the soil and the net primary productivity of vegetation cover (via a reduction in above-ground standing biomass), as well as litter production and plant nutrient status. Similarly, if there is much dead plant material in the sward, shading the live leaves (e.g., extensive low-productive swards), grazing events can allow light to penetrate into the plant canopy and encourage new tillers, leading to an increase in the storage of C (Zhou et al., 2017). Conversely, if grazing is too intense or the period between successive grazing periods is too short, the biomass and soil cover (e.g., amount of live leaves) can be reduced so that light interception falls, and growth and C capture are reduced as well as litter and root production. In these cases, intense grazing can lead to a reduction in soil C storage (Derner & Schuman, 2007; Zhou et al., 2017). There exists, therefore, a compromise between promoting animal production and promoting carbon sequestration (see Soussana & Lemaire, 2014), which is the compromise between biomass production (and intensity of use), and C inputs to soil (via litter, animal wastes and roots). In the relation between C storage and herbage use (i.e., ratio between produced biomass and biomass removal by grazing), we observed an increase of both, until an optimum beyond which the storage of C decreased (threshold of ~0.5 to 0.7) with further increase in herbage use (Klumpp & Graux, 2020). The C sequestration potential of European grazed grasslands (on average 0.21 ± 0.6 Mg C ha^{-1} year^{-1}) showed large variability, related to on site-effects such as climate, soil type, grazing intensity and vegetation cover (Klumpp & Graux, 2020).

3.2 | Indirect effects of forage quality C sequestration

In productive systems, biomass production is associated with forage quality given there is sufficient N available. Grasslands adapted to low grazing levels are generally characterized by slow-growing plant species and lower aboveground net primary productivity and quality, a microbial community dominated by fungi, as well as greater N retention and C storage (see also Eugène et al., 2014). In these latter pastures, grazing has long-term effects on litter quality and quantity, which are driven by changes in plant community composition and defoliation-tolerant species or unpalatable species (Wardle et al., 2004). Under medium to high grazing pressure, fast-growing, palatable species

typical of nutrient-rich, managed grasslands show high above-ground productivity and quality (lower C: N), promoting higher C inputs to soil and rapid degradation by bacteria (Cotrufo et al., 2013).

3.3 | Effects of plant biodiversity on C sequestration

Grazing has the capacity to change the vegetation by modifying plant botanical composition (presence of legumes in particular; Bagchi & Ritchie, 2010; Zhou et al., 2017), which affects the supply of soil with aerial and root plant biomass. Those in turn can affect not only grassland productivity, but also soil organic matter decomposition. Then again, in agricultural settings, plant diversity is often associated with low biomass yield and low forage quality. Recent studies underline that increased plant diversity is an important production factor being independent of management intensity, as it enhances quality-adjusted yield (Schaub et al., 2020). Besides, it appears that grasslands with complex flora (with high species number) allow higher C storage (Hungate et al., 2017; Lange et al., 2015). This storage increases in fact with the specific richness of the sward and with the presence of legumes (Cong et al., 2014; Rutledge et al., 2017). The latter is probably linked to a diversity of root systems (more or less dense and deep), as well as to an increase in the availability of N in the presence of urine, dung and legumes and thus, variation in primary productivity.

Most grasslands are subject to the marked seasonality of biomass production. Annual cycles of temperature or rainfall impose cycles of plant growth and phenology that result in cycles of biomass abundance and quality. For instance, factors that affect forage quality are leaf-to-stem ratio, phenological stage, diseases and pests. Forage digestibility declines with an increased stem proportion; it declines as plants develop from the vegetative into the generative stage. For that reason, information on the nutritive value of forage quality by the use of phenological stages may help to choose suitable grazing/harvesting times and stocking rates. This, in turn, may help to achieve higher animal performance without damage to the vegetation and related decline in C sequestration potential, increase in soil N_2O and enteric CH_4 (see Van den Pol et al., 2018). Poor forage quality is often related to lower intake and digestibility and thus increases the CH_4 yield of ruminants (Archimède et al., 2011; Rossignol et al., 2014). Although effects on CH_4 yield seem to be variable, CH_4 intensity increases with reduced forage quality (Van Gastelen et al., 2019). Accordingly, there are a number of trade-offs that need to be considered when intensifying grazed systems (see Soussana & Lemaire, 2014, Figure 3): (a) an increase in productivity (and subsequent biomass removal) leads to a decline in the amounts of organic carbon returned to the soil, (b) maximization of forage quality (low C/N ratio) and the related increased digestibility (i.e., improved animal production) leads to a decline in mean residence time of soil organic C (i.e., increase of root and shoot litter decomposability), and (c) increasing net primary productivity through fertilizer supply and legumes (biological N fixation) leads to an increase in N_2O emissions (from fertilizer and urine) and CH_4 emissions from enteric fermentation due to increased forage quality.
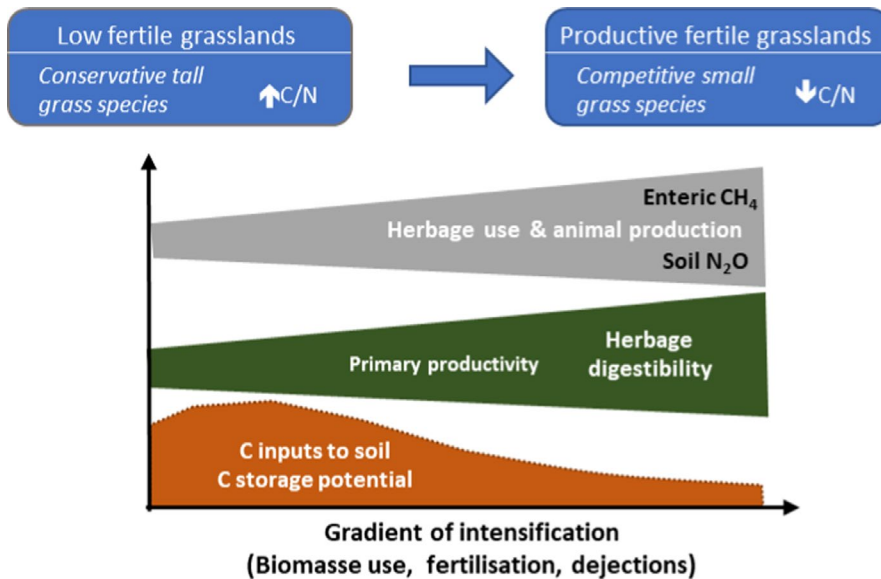
FIGURE 3 Estimated range and directions of effects of grassland intensification by grazing (x-axis) and fertilisation (y-axis; adapted from Soussana & Lemaire, 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSIONS

Feeding systems of ruminants based on high-quality forages can decrease the contribution of livestock and agriculture to GHG. The major determinant of forage quality is the stage of growth at harvest and species mixture. With the advanced stage of growth, the fibre contents increase resulting in higher methane production. Forage legumes used in ruminant systems can decrease GHG emissions due to lower N fertilizer use and fertilizer production, enhancement of biodiversity and decreased parasitism in ruminants. Therefore, they are environmentally and economically beneficial for some systems, for which there is no overload of N supply. Moreover, with regard to manure, dietary measures reducing the amount of N excreted (e.g., better matching of dietary protein to animal requirements), shifting N excretion from urine to faeces (e.g., tannin inclusion at low levels) and reducing the amount of fermentable organic matter excreted are recommended. Ruminants will retain their niches because of their ability to produce valuable human food from low-value feedstuffs. Employing these emerging strategies will allow improved productive efficiency of ruminants in both developing and developed countries. Net CH_4 output is required to consider the enteric CH_4 emissions and soil C sequestration potential of fields having served for feed (e.g., grasslands and croplands management). The next step could be a multicriteria assessment of GHG mitigations based on forages, such as life cycle analysis or process-based modelling, to consider the interactions and trade-off/synergy between GHG.

AUTHOR CONTRIBUTION

Maguy Eugene: Formal analysis (equal); Writing - review & editing (lead). **Katja Klumpp**: Formal analysis (equal); Writing - review (equal). **Daniel Sauvant**: Formal analysis (lead); review (equal).

DATA AVAILABILITY STATEMENT

Data available on request.

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REFERENCES

Archimède, H., Eugène, M., Magdeleine, C. M., Boval, M., Martin, C., Morgavi, D. P., Lecomte, P., & Doreau, M. (2011). Comparison of methane production between C3 and C4 grasses and legumes. *Animal Feed Science and Technology*, *166–167*, 59–64. https://doi.org/10.1016/j.anifeedsci.2011.04.003

Arndt, C., Powell, J. M., Aguerre, M. J., & Wattiaux, M. A. (2015). Performance, digestion, nitrogen balance, and emission of manure ammonia, enteric methane, and carbon dioxide in lactating cows fed diets with varying alfalfa silage-to-corn silage ratios. *Journal of Dairy Science*, *98*(1), 418–430. https://doi.org/10.3168/jds.2014-8298

Bagchi, S., & Ritchie, M. E. (2010). Introduced grazers can restrict potential soil carbon sequestration through impacts on plant community composition. *Ecology Letters*, *13*(8), 959–968. https://doi.org/10.1111/j.1461-0248.2010.01486.x

Baumont, R., Sauvant, D., Maxin, G., Chapoutot, P., Tran, G., Boudon, A., Lemosquet-Simon, S., & Nozière, P. (2018). Calculation of feed values in INRA system: Feed tables and prediction equations. In *INRA Feeding System for Ruminants* (p. 411–439). Wageningen Academic Publishers. 640 p. https://doi.org/10.3920/978-90-8686-292-4

Beauchemin, K. A., Kreuzer, M., O'Mara, F., & McAllister, T. A. (2008). Nutritional management for enteric methane abatement: A review. *Australian Journal of Experimental Agriculture.*, *48*(2), 21–27. https://doi.org/10.1071/EA07199

Bloor, J., & Pottier, J. (2014). Grazing and spatial heterogeneity: Implications for grassland structure and function. In P. Mariotte & P. Kardol (Eds.), *Grassland biodiversity and conservation in a changing world* (pp 135–162). Nova Science Publishers Inc.

Börjesson, G., Bolinder, M. A., Kichmann, H., & Kätterer, T. (2018). Organic carbon stocks in topsoil and subsoil in long-term ley and cereal monoculture rotations. *Biology and Fertility of Soils.*, *54*, 549–558. https://doi.org/10.1007/s00374-018-1281-x

Broderick, G. A. (2018). Review: Optimizing ruminant conversion of feed protein to human food protein. *Animal*, *12*(8), 1722–1734. https://doi.org/10.1017/S1751731117002592

Cong, W.-F., van Ruijven, J., Mommer, L., De Deyn, G. B., Berendse, F., & Hoffland, E. (2014). Plant species richness promotes soil carbon

and nitrogen stocks in grasslands without legumes. *Journal of Ecology*, *102*(5), 1163–1170. https://doi.org/10.1111/1365-2745.12280

Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology*, *19*(4), 988–995. https://doi.org/10.1111/gcb.12113

Derner, J., & Schuman, G. (2007). Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation*, *62*(2), 77–85.

Dewhurst, R. J. (2012). Milk production from silage: Comparison of grass, legume and maize silages and their mixtures. In K. Kuoppala, M. Rinne, & A. Vanhatalo (Eds.), *Proceedings of the XVI International Silage Conference*. MTT Agrifood Research Finland, University of Helsinki. p. 134–135.

Dewhurst, R. J., Delaby, L., Moloney, A., Boland, T., & Lewis, E. (2009). Nutritive value of forage legumes used for grazing and silage. *Irish Journal of Agricultural and Food Research*, *48*(2), 167–187. https://www.jstor.org/stable/20720367

Elgersma, A., & Søegaard, K. (2018). Changes in nutritive value and herbage yield during extended growth intervals in grass-legume mixtures: Effects of species, maturity at harvest, and relationships between productivity and components of feed quality. *Grass and Forage Science*, *73*(1), 78–93. https://doi.org/10.1111/gfs.12287

Ellis, J. L., Kebreab, E., Odongo, N. E., McBride, B. W., Okine, E. K., & France, J. (2007). Prediction of methane production from dairy and beef cattle. *Journal of Dairy Science*, *90*(7), 3456–3466. https://doi.org/10.3168/jds.2006-675

Escobar-Bahamondes, P., Oba, M., & Beauchemin, K. A. (2017). An evaluation of the accuracy and precision of methane prediction equations for beef cattle fed high-forage and high-grain diets. *Animal*, *11*(1), 68–77. https://doi.org/10.1017/S175173111600121x

Eugène, M., Archimède, H., Giger Reverdin, S., Doreau, M., & Sauvant, D. (2014). Effect of feeding forages on enteric methane emissions from ruminants: A meta-analysis. In *Harnessing the Ecology and Physiology of Herbivores*. Paper presented at the (30) 2014; Joint ISNH/ISRP International Conference 2014, Canberra, AUS, pp. 223.

Eugène, M., Doreau, M., Archimède, H., Giger-Reverdin, S., Sauvant, D. (Speaker) (2019). Modelling by meta-analysis enteric methane emissions from ruminants fed forages supplemented or not with tannins. Presented at the *9th Workshop on Modelling Nutrient Digestion and Utilization in Farm animals (MODNUT)*. Itamambuca Eco Resort, Brazil.

Eugène, M., Sauvant, D., Nozière, P., Viallard, D., Oueslati, K., Lherm, M., Mathias, E., & Doreau, M. (2019). A new Tier 3 method to calculate methane emission inventory for ruminants. *Journal of Environmental Management*, *231*, 982–988. https://doi.org/10.1016/j.jenvman.2018.10.086

Franzluebbers, A. J., Sawchik, J., & Taboda, M. A. (2014). Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. *Agriculture, Ecosystems and Environment*, *190*, 18–26. https://doi.org/10.1016/j.agee.2013.09.017

Gerber, P. J., Hristov, A. N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A. T., Yang, W. Z., Tricarico, J. M., Kebreab, E., Waghorn, G., Dijkstra, J., & Oosting, S. (2013). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: A review. *Animal*, *7*, 220–234. https://doi.org/10.1017/S1751731113000876

Hassanat, F., Gervais, R., Julien, C., Massé, D. I., Lettat, A., Chouinard, P. Y., Petit, H. V., & Benchaar, C. (2013). Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production. *Journal of Dairy Science*, *96*(7), 4553–4567. https://doi.org/10.3168/jds.2012-6480

Hassen, A., Talore, D. G., Tesfamariam, E. H., Friend, M. A., & Mpanza, T. D. E. (2017). Potential use of forage-legume intercropping technologies to adapt to climate-change impacts on mixed crop-livestock systems in Africa: A review. *Regional Environmental Change*, *17*(6), 1713–1724. https://doi.org/10.1007/s10113-017-1131-7

Hegarty, R. S. (1999). Reducing rumen methane emissions through elimination of rumen protozoa. *Journal of Agricultural Research*, *50*(8), 1321–1328. https://doi.org/10.1071/AR99008

Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H. P., Adesogan, A. T., Yang, W., Lee, C., Gerber, P. J., Henderson, B., & Tricarico, J. M. (2013). Special topics–Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *Journal of Animal Science*, *91*(11), 5045–5069. https://doi.org/10.2527/jas.2013-6583

Hungate, B. A., Barbier, E. B., Ando, A. W., Marks, S. P., Reich, P. B., Van Gestel, N., Tilman, D., Knops, J. M., Hooper, D. U., & Butterfield, B. J. (2017). The economic value of grassland species for carbon storage. *Science Advances*, *3*(4), e1601880. https://doi.org/10.1126/sciadv.1601880

Jayanegara, A., Goel, G., Makkar, H. P. S., & Becker, K. (2015). Divergence between purified hydrolysable and condensed tannin effects on methane emission, rumen fermentation and microbial population in vitro. *Animal Feed Science and Technology*, *209*, 60–68. https://doi.org/10.1016/j.anifeedsci.2015.08.002

Jayanegara, A., Leiber, F., & Kreuzer, M. (2012). Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. *Journal of Animal Physiology and Animal Nutrition*, *96*(3), 365–375. https://doi.org/10.1111/j.1439-0396.2011.01172.x

Jonker, A., Lowe, K., Kittelmann, S., Janssen, P. H., Ledgard, S., & Pacheco, D. (2016). Methane emissions changed nonlinearly with graded substitution of alfalfa silage with corn silage and corn grain in the diet of sheep and relation with rumen fermentation characteristics in vivo and in vitro. *Journal of Animal Science*, *94*(8), 3464–3475. https://doi.org/10.2527/jas2015-9912

Kebreab, E., Clark, K., Wagner-Riddle, C., & France, J. (2006). Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Canadian Journal of Animal Science*, *86*(2), 135–157. https://doi.org/10.4141/a05-010

Klumpp, K., Graux, A. I., (2020). Etat des connaissances sur les pratiques réputées « stockantes » en prairies permanentes. In Pellerin et al,. In Pellerin *Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût?*. Synthèse du rapport d'étude, INRA. 114 pp.

Lange, M., Eisenhauer, N., Sierra, C. A., Bessler, H., Engels, C., Griffiths, R. I., Mellado-Vázquez, P. G., Malik, A. A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B. C., Trumbore, S. E., & Gleixner, G. (2015). Plant diversity increases soil microbial activity and soil carbon storage. *Nature Communications*, *6*(1), 6707. https://doi.org/10.1038/ncomms7707

Leng, R. A. (1990). Factors affecting the utilization of 'Poor-Quality' forages by ruminants particularly under tropical conditions. *Nutrition Research Reviews*, *3*(1), 277–303. https://doi.org/10.1079/NRR19900016

Makkar, H. P. S. (2003). Effects and fate of tannins in ruminant animals, adaptation to tannins, and strategies to overcome detrimental effects of feeding tannin-rich feeds. *Small Ruminant Research*, *49*(3), 241–256. https://doi.org/10.1016/S0921-4488(03)00142-1

Moss, A. R., Jouany, J.-P., & Newbold, J. (2000). Methane production by ruminants: Its contribution to global warming. In: *Paper Presented at the Annales de Zootechnie*, pp. 231–253. https://doi.org/10.1051/animres:2000119

Mueller-Harvey, I., Bee, G., Dohme-Meier, F., Hoste, H., Karonen, M., Kölliker, R., Lüscher, A., Niderkorn, V., Pellikaan, W. F., Salminen, J. P., Skøt, L., Smith, L. M. J., Thamsborg, S. M., Totterdell, P., Wilkinson, I., Williams, A. R., Azuhnwi, B. N., Baert, N., Brinkhaus, A. G., … Waghorn, G. C. (2019). Benefits of condensed tannins in forage legumes fed to ruminants: Importance of structure, concentration,

and diet composition. *Crop Science*, *59*(3), 861–885. https://doi.org/10.2135/cropsci2017.06.0369

Niu, M., Kebreab, E., Hristov, A. N., Oh, J., Arndt, C., Bannink, A., Bayat, A. R., Brito, A. F., Boland, T., Casper, D., Crompton, L. A., Dijkstra, J., Eugene, M. A., Garnsworthy, P. C., Haque, M. N., Hellwing, A. L. F., Huhtanen, P., Kreuzer, M., Kuhla, B., … Yu, Z. T. (2018). Prediction of enteric methane production, yield, and intensity in dairy cattle using an intercontinental database. *Global Change Biology*, *24*(8), 3368–3389. https://doi.org/10.1111/gcb.14094

Nozière, P., Sauvant, D., & Delaby, L. (2018). *INRA feeding system for ruminants* (640-p). Wageningen Academic Publishers.

Patra, A. K., & Saxena, J. (2011). Exploitation of dietary tannins to improve rumen metabolism and ruminant nutrition. *Journal of the Science of Food and Agriculture*, *91*(1), 24–37. https://doi.org/10.1002/jsfa.4152

Pereira, L. G. R., Machado, F. S., Campos, M. M., Guimaraes, R., Tomich, T. R., Reis, L. G., & Coombs, C. (2015). Enteric methane mitigation strategies in ruminants: A review. *Revista Colombiana De Ciencias Pecuarias*, *28*(2), 124–143. https://doi.org/10.17533/udea.rccp.v28n2a02

Phelan, P., Moloney, A. P., McGeough, E. J., Humphreys, J., Bertilsson, J., O'Riordan, E. G., & O'Kiely, P. (2015). Forage legumes for grazing and conserving in ruminant production systems. *Critical Reviews in Plant Sciences*, *34*(1–3), 281–326. https://doi.org/10.1080/07352689.2014.898455

Poppi, D., Minson, D., & Ternouth, J. (1981). Studies of cattle and sheep eating leaf and stem fractions of grasses. 2. Factors controlling the retention of feed in the reticulo-rumen. *Australian Journal of Agricultural Research.*, *32*(1), 109–121. https://doi.org/10.1071/AR9810109

Reed, J. D. (1995). Nutritional toxicology of tannins and related polyphenols in forage legumes. *Journal of Animal Science*, *73*(5), 1516–1528. https://doi.org/10.2527/1995.7351516x

Rico, D. E., Chouinard, P. Y., Hassanat, F., Benchaar, C., & Gervais, R. (2016). Prediction of enteric methane emissions from Holstein dairy cows fed various forage sources. *Animal*, *10*(2), 203–211. https://doi.org/10.1017/S1751731115001949

Rossignol, N., Andueza, D., Carrère, P., Cruz, P., Duru, M., Fiorelli, J.-L., Michaud, A., Plantureux, S., Pottier, E., & Baumont, R. (2014). Assessing population maturity of three perennial grass species: Influence of phenology and tiller demography along latitudinal and altitudinal gradients. *Grass and Forage Science*, *69*(3), 534–548. https://doi.org/10.1111/gfs.12067

Ruckle, M. E., Meier, M. A., Frey, L., Eicke, S., Kolliker, R., Zeeman, S. C., & Studer, B. (2017). Diurnal leaf starch content: An orphan trait in forage legumes. *Agronomy-Basel*, *7*(1). Artn 16. https://doi.org/10.3390/Agronomy7010016

Rutledge, S., Wall, A., Mudge, P., Troughton, B., Campbell, D., Pronger, J., Joshi, C., & Schipper, L. (2017). The carbon balance of temperate grasslands part I: The impact of increased species diversity. *Agriculture, Ecosystems & Environment*, *239*, 310–323. https://doi.org/10.1016/j.agee.2017.01.039

Sauvant, D., & Giger-Reverdin, S. (2009). Modelling of digestive interactions and methane production in ruminants. *Productions Animales*, *22*(5), 375–384.

Sauvant, D., Giger-Reverdin, S., & Eugène, M. (2018). Enteric methane emissions. In P. Noziere, D. Sauvant, & L. Delaby (Eds.), *INRA feeding system for ruminants* (pp. 209–212). Wageningen Academic Publishers. 640 p. https://doi.org/10.3920/978-90-8686-292-4

Sauvant, D., Giger-Reverdin, S., Serment, A., & Broudiscou, L. (2011). Influences of diet and rumen fermentation on methane production by ruminants. *INRA Productions Animales*, *24*(5), 433–446.

Schaub, S., Finger, R., Leiber, F., Probst, S., Kreuzer, M., Weigelt, A., Buchmann, N., & Scherer-Lorenzen, M. (2020). Plant diversity effects on forage quality, yield and revenues of semi-natural grasslands. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-14541-4

Siddons, R. C., & Paradine, J. (1983). Protein degradation in the rumen of sheep and cattle. *Journal of the Science of Food and Agriculture.* *34*(7), 701–708. https://doi.org/10.1002/jsfa.2740340706

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Soussana, J.-F., & Lemaire, G. (2014). Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems & Environment*, *190*, 9–17. https://doi.org/10.1016/j.agee.2013.10.012

Van den Pol, A., Chabbi, A., de Vliegher, A., Hennessy, D., Hutchings, N., & Klumpp, K. (2018). *Grazing for carbon: End report. EIP-AGRI.*

Van Gastelen, S., Dijkstra, J., & Bannink, A. (2019). Are dietary strategies to mitigate enteric methane emission equally effective across dairy cattle, beef cattle, and sheep? *Journal of Dairy Science*, *102*(7), 6109–6130. https://doi.org/10.3168/jds.2018-15785

van Lingen, H. J., Niu, M., Kebreab, E., Valadares Filho, S. C., Rooke, J. A., Duthie, C.-A., Schwarm, A., Kreuzer, M., Hynd, P. I., & Caetano, M. (2019). Prediction of enteric methane production, yield and intensity of beef cattle using an intercontinental database. *Agriculture, Ecosystems & Environment*, *283*, 106575. https://doi.org/10.1016/j.agee.2019.106575

Wardle, D. A., Bardgett, R. D., Klironomos, J. N., Setälä, H., Van Der Putten, W. H., & Wall, D. H. (2004). Ecological linkages between aboveground and belowground biota. *Science*, *304*(5677), 1629–1633. https://doi.org/10.1126/science.1094875

Zhou, G., Zhou, X., He, Y., Shao, J., Hu, Z., Liu, R., Zhou, H., & Hosseinibai, S. (2017). Grazing intensity significantly affects belowground carbon and nitrogen cycling in grassland ecosystems: A meta-analysis. *Global Change Biology*, *23*(3), 1167–1179. https://doi.org/10.1111/gcb.13431