Methane mitigating options with forages fed to ruminants
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**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 N2O 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 N2O 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 CH4 intensity (emission per unit of milk or meat), but also other sources of GHG, such as N2O from crop fertilizers/manure and CO2 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 CH4, N excretion and related N2O (along with CH4) 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 CH4 mitigation practices, recommended worldwide (Hristov et al., 2013). The effect of forage organic matter (OM) digestibility on CH4 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 CH4 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 CH4 emission (g/day) for dairy and beef cattle, but not for sheep. When intake or production is considered, both CH4 yield (g/kg DMI) and CH4 intensity (g/kg milk) are decreased with increased digestibility for dairy cattle, but no difference in CH4 yield (g/kg DMI) was observed for beef cattle. For sheep, CH4 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 CH4 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 CH4 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 CH4 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 CH4 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 CH4 production (36 vs. 40 g/kg DOM, respectively). Comparisons of relationships including CH4/DMI (Equation 2) or CH4/DOM (Equation 1) indicate that DOM is an important explanatory variable that needs to be considered (Table 1). Consequently, equations with CH4/DOM are recommended as DOM considers both quantity and quality of forage. For animals fed with forages, there is a close positive relationship between CH4% of gross energy (GE) and the acetate to propionate ratio in the rumen (C2/C3; Moss et al., 2000), as illustrated in Figure 1. The fermentation of cell wall carbohydrates in forages generally produces a higher C2/C3 ratio in the rumen and consequently a higher amount of CH4 as compared to non-fibre carbohydrate fermentation (Hegarty, 1999; Moss et al., 2000). Indeed, propionate production favours competitive pathways for H2 use in the rumen, whereas acetate production favours H2 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

| CH4 (g/kg DOM) | FL = 4.05 × NDF − 0.010 × DOM (Equation 1) |
|---------------|------------------------------------------|
| CH4 (g/kg DMI) | = -22.4 − 2.25 × FL + 0.137 × DOM (g/kg DMI) − 0.000009 × DOM2 (g/kg DMI) (Equation 2) |
| CH4 (g/kg DOM) | = 34.26 − 3.96 × FL + 0.027 × NDF − 0.008 × DOM − 1.72 × Log10 (1 + TAN) (Equation 3) |

**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.
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 CH₄ 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 CH₄ emissions, thus enhancing animal productivity (growth, milk, and wool production) and mitigating climate change (CH₄, N₂O, and ammonia emissions; Makkar, 2003; Reed, 1995). However, several authors have stressed the importance to conduct diet improvements in a holistic multi-criteria approach (Kebrab 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 vicifolia 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 CH₄ 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), CH₄ (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,
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 thoroughlly 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 rumi-nant 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\textsubscript{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\textsubscript{4} is inconsistent (Beauchemin et al., 2008; Makk, 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\textsubscript{2}O, a shift towards faecal N will decrease N\textsubscript{2}O 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\textsubscript{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\textsubscript{4} emission of ruminants fed maize silage in the replacement of grass silage or legume silage.

Different responses in CH\textsubscript{4} emission and intake are observed between dairy, beef, and sheep. For sheep, there was a quadratic effect on CH\textsubscript{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, sullia 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\textsubscript{4} yield (g/kg DMI; MJ/MJ GEI), while some studies reported quadratic relations (Arndt et al., 2015; Hassanet 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 (Hassanet 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\textsubscript{4} production, manure CH\textsubscript{4} could increase due to increased faecal output of fermentable OM. Especially soil CO\textsubscript{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\textsubscript{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)

| Forage Type  | CH\textsubscript{4} (L/kg DMI) | CH\textsubscript{4} (L/kg OMI) | CH\textsubscript{4} (L/kg DOM) |
|-------------|-------------------------------|-------------------------------|-------------------------------|
| Grasses     |                               |                               |                               |
| C3 type     | 30.0\textsuperscript{b}       | 33.1\textsuperscript{b}       | 52.1\textsuperscript{b}       |
| C4 type     | 33.7\textsuperscript{c}       | 38.8\textsuperscript{c}       | 57.7\textsuperscript{a}       |
| Legumes     |                               |                               |                               |
| Cool        | 30.1\textsuperscript{bc}      | 33.7\textsuperscript{bc}      | 52.4\textsuperscript{b}       |
| Warm        | 25.9\textsuperscript{a}       | 27.2\textsuperscript{a}       | 40.7\textsuperscript{a}       |
| SEM         | 1.8                           | 1.8                           | 2.9                           |
| p           | 0.001                         | 0.001                         | 0.001                         |

\textsuperscript{a,b,c}Superscripts: Mean values within columns carrying no common letters are significantly different at p < 0.05.
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%), CH₄ (4%), urine (4.5%), CO₂ (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% (CH₄); 3.5% (urine); 42% (CO₂); 3% retained and 21% in milk. The majority of ingested C is thus partitioned into CO₂ and emitted into the air (around 50% in cattle), and faecal C (around 30%, that returns to grasslands), followed by milk, urine, CH₄ 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

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)
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 (de-
foliation, 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 un-
even patterns of defoliation and animal returns, grazing animals pro-
mote 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 fa-
vours the N cycle in the soil and the net primary productivity of veg-
etation 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).

3.3 | 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 under-
line 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 leg-
umes (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 bio-
mass production. Annual cycles of temperature or rainfall impose
cycles of plant growth and phenology that result in cycles of bio-
mass abundance and quality. For instance, factors that affect for-
age quality are leaf-to-stem ratio, phenological stage, diseases and
pests. Forage digestibility declines with an increased stem propor-
tion; it declines as plants develop from the vegetative into the gener-
ative 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\(_2\)O 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 decom-
position), and (c) increasing net primary productivity through fer-
tilizer supply and legumes (biological N fixation) leads to an increase
in N\(_2\)O emissions (from fertilizer and urine) and CH\(_4\) emissions from
enteric fermentation due to increased forage quality.

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 spe-
cies and lower aboveground net primary productivity and quality, a mi-
crobial 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).
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 fertiliser 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 CH₄ output is required to consider the enteric CH₄ 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 Eugène: 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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