BIOSCIENCE JOURNAL

PASTURE MANAGEMENT AND GREENHOUSE GASES EMISSIONS

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How to cite: CARDOSO, A.S., et al. Pasture management and greenhouse gases emissions. *Bioscience Journal*. 2022, **38**, e38099. https://doi.org/10.14393/BJ-v38n0a2022-60614

Abstract
Pastures are important environments worldwide because they offer many ecosystem services and sustain meat and milk production. However, pastures ecosystems are responsible for greenhouse gas (GHG) emission. The major GHGs include CO_2, CH_4, and N_2O. The present review summarizes GHG emission from pasture ecosystems and discusses strategies to mitigate this problem. In pastures, emissions originate from animal excretion, fertilization, and organic matter decomposition. Emissions of specific gases can be measured based on certain factors that were recently updated by the United Nation's Intergovernmental Panel on Climate Change in 2019. Urine is the main source of N_2O emission. Forage structure is an important factor driving GHG transport. Forage fiber content and animal intake are the key drivers of enteric CH_4 emission, and the introduction of forage legumes in pasture systems is one of the most promising strategy to mitigate GHG emission.

Keywords: Carbon Dioxide. Grazing Management. Methane. Nitrous Oxide.

1. Introduction

Since 2001, we have experienced 15 of the 16 warmest years ever recorded in the history. The global mean temperature in 2016 was the highest since 1880, when recording of the earth's surface temperature began (Ruggieri et al. 2020). These increasing temperatures are melting the polar ice caps, causing desertification, damaging biodiversity, and impeding food production.

The earth's temperature is regulated through a mechanism known as the greenhouse effect. Part of the solar energy in the form of radiation passes through the atmosphere and reaches the earth's surface, where it is absorbed or reflected. A fraction of the radiation reflected by the earth's surface is absorbed by the layer of greenhouse gases (GHG), leading to atmospheric warming (IPCC 2019; Cardoso et al. 2020a; Ruggieri et al. 2020). Therefore, increase in the amount of radiation reaching the earth or that being absorbed by the GHG layer can lead to further warming of the atmosphere. Increase in atmospheric warming (global warming) as a result of increase in GHG levels is a widely accepted hypothesis by the scientific community.

The major GHGs include CO_2, CH_4, and N_2O. Burning of fossil fuels and biomass and deforestation are the main factors responsible for increasing atmospheric CO_2 levels. Enteric CH_4 emissions by ruminants, followed by CH_4 production in flooded or swamp areas and termite emissions, are the key contributors to increased CH_4 emissions. Meanwhile, nitrogen fertilization and emissions from animal excretion are the major sources of increased atmospheric N_2O levels (IPCC 2019).

According to Gerber et al. (2013), the agricultural, forest, and other land use sectors produced 10 billion Mg CO_2 eq in 2010. Of this, approximately 50% CO_2 came from food production and 38% from deforestation. Of the total CO_2 emitted by agriculture, 40% comes from enteric fermentation, 16% from animal excretion in pastures, 13% from synthetic fertilization, 10% from flooded paddy fields, 7% from waste management, and 5% from savanna burning. Global GHG emissions from agricultural activities grew by 196% between 1961 and 2011. Moreover, given the increasing human population and the consequent increase in demand for food, GHG emissions are expected to continue to rise.

In the context of Brazil, deforestation accounted for 41% of total CO_2 emissions in 2015, with a drastic reduction in the total emission of the country. Compared to the statistic in 2005, emissions due to deforestation dropped by 80% in 2015. Agriculture accounted for 73% of total CH_4 emitted by the country, of which approximately 85% came from enteric fermentation. In addition, the agricultural sector was responsible for 80% of the total N_2O emission of the country, of which respectively 55% and 45% came from direct and indirect emissions, respectively. Overall, of the total GHG emissions from agriculture, 27% came from animal excretion in pastures and 9% from synthetic nitrogen fertilization. Therefore, pastoral systems play a fundamental role in CH_4 and N_2O emission (MCTI 2020).

Due to the magnitude of the animal production sector and the diversity of climatic regions and production systems in Brazil, studies aimed at elucidating emission routes and organisms involved or GHG emission modeling are warranted, which represent a great opportunity for Brazilian researchers. The present review summarizes the major routes of GHG emission and discusses strategies to mitigate CO_2, CH_4, and N_2O emissions from pastures.

2. GHG emissions from animal excreta

The type of excreta can influence N_2O production (van der Weerden et al. 2016). After animal urination, urinary urea is promptly hydrolyzed to ammonium in the soil, boosting the soil pH and stimulating the release of water-soluble carbon available as the substrate for denitrifying bacteria (Cardoso et al. 2019a). Under favorable soil conditions, ammonium can be rapidly nitrified to nitrate and then further denitrified to N_2O and N_2. In contrast to urine, dung contains significantly less mineral N. Therefore, the activity of nitrogen changes in soil beneath dung patches is lower. According to Van der Weerden et al. (2016), the interactions between microbial communities in the dung patches and soil can be restricted because of the high dry matter content of dung. This can also inhibit the infiltration of dung nitrogen into the soil, reducing the availability of nitrogen to be emitted as N_2O.

CH_4 emission occurs as a result of microbial degradation of proteins, organic acids, carbohydrates, and soluble lipids present in excreta (Khan et al. 1997). According to the United Nation's Intergovernmental Panel on Climate Change (IPCC 2019), the emission factor (EF) for CH_4 of beef cattle dung in Latin America is 1 kg CH_4 head^{-1} year^{-1}. According to Cardoso et al. (2019a), EF of dung was 0.54 head^{-1} year^{-1}; this value is nearly half of that reported by the IPCC but greater than the values reported in subtropical and tropical regions [0.02 (winter) and 0.05 (summer) kg CH_4 head^{-1} year^{-1} in São Paulo and 0.06 (winter) and 0.10 (summer) kg CH_4 head^{-1} year^{-1} in Rondônia] (Mazzetto et al. 2014). Finally, this value is also lower than that reported by Cardoso et al. (2018) (0.95 kg head^{-1} year^{-1}) for dairy cattle dung in a tropical pastureland in Rio de Janeiro.

Few studies have calculated the EFs for N_2O and CH_4 in tropical soils. Simon et al. (2018) reported that the EF for N_2O from urine was 0.34% and that from feces was 0.11% of nitrogen applied. Cardoso et al. (2019a) reported EFs of 0.79 and 0.18 kg CH_4 animal^{-1} year^{-1} from Ferralsols in the wet and dry season, respectively. These EF values are lower than that recommended by the IPCC (2019), calculated based on default data from GHG inventories in Brazil. Therefore, the EFs for N_2O, CH_4, and CO_2 from soil, feces, urine, and nitrogen fertilizers should be established in tropical regions.

3. Effect of pasture management on GHG emission

Appropriate management of forage plants in pastoral ecosystems requires the understanding of the canopy structure to efficiently produce meat, milk, wool, and chicks. The canopy structure constitutes the tillers density, number of leaves per tillers, leaf size, forage mass, and canopy height. Based on these components, the critical leaf area index can be determined. When the canopy reaches the 95% light interception there is the maximization of leaf production and minimization of forage accumulation via pseudostem and senescent material formation (Da Silva et al. 2020). Considering that the measurement of light interception in the field conditions is difficult, the canopy height is managed, as this parameter strongly correlated with the other variables mentioned above. Thus, numerous studies have explored the average canopy height for continuous stocking as well as the height of entry and exit for intermittent stocking.

Cardoso et al. (2017) studied the effect of pastures heights on GHGs emissions in marandu grassland. They found that fluxes of N_2O, CH_4, and CO_2 varied among seasons and between years. The magnitude of fluxes observed were explained by seasonal variations in temperature, precipitation, % WFPS, and inorganic N content. Indeed, climate variation influenced more the GHG fluxes than pasture management. When the authors evaluated the effect of pasture management on the total of GHG emitted pasture heights had a negative linear effect on annual, summer, and autumn cumulative N_2O emissions/consumption and a positive linear effect on annual cumulative CO_2 emissions. Raposo et al. (2020) measured the effect of N fertilization on GHGs emissions in marandu grassland. Nitrous oxide increased linearly with augmentation of N doses and CH_4 oxidation was increased. This means that N fertilization can mitigate CH_4 emissions from grassland soils.

In Brazil, *Urochloa* species, specifically *Urochloa brizantha* ‘Marandu’, are the most commonly used fodder grasses in beef cattle production systems in the tropical regions. In this context, Santana et al. (2017) tested different heights for the management of Marandu grass and recommended a target height of 25 cm for continuous stocking, based on the tillering dynamics of the species and forage mass. Subsequently, Delevatti et al. (2019) used a target height of 25 cm for the management of Marandu grass supplied with different nitrogen doses and showed that this target height and nitrogen fertilization increased the stocking rate (3.3 animal unit [UA]/ha to 6.5 AU/ha) and the average daily gain (±950 g) as well as improved the digestibility of the forage consumed. However, high doses of nitrogen, particularly in the form of urea, are marked lost through volatilization. Corrêa et al. (2021) showed that nitrogen loss due to ammonia volatilization was 27.6%, 4.3%, and 3.5% for urea, ammonium nitrate, and ammonium sulfate, respectively.

Unlike in industrialized countries, the largest share of CO_2, N_2O, and CH_4 emissions comes from agriculture in Brazil (Cardoso et al. 2016). As a result, ruminant production in pastoral systems has been subject to wide criticism. CO_2 is present at high concentrations in the atmosphere; therefore, emissions are expressed in the form of CO_2 equivalent (CO_2 eq). The atmospheric concentration of N_2O and CH_4 is lower than that of CO_2; however, their global warming potential is respectively265 and 28 times higher than that of CO_2 (Liebig et al. 2012; MCTI 2020); therefore, the dynamics of these gases in the pastoral ecosystem must be clarified to successfully mitigate their emissions.

The fundamental processes in all conventional food production systems include the use of solar energy and supply of nutrients to crops (via soil solutions) for the production of plant organs such as leaves, grains, and roots (Hodgson, 1990). In pastoral ecosystems, forage accumulation occurs as mesophyll cells with chloroplasts, which contain specialized pigments for light absorption, mainly the chlorophylls. CO_2 entering the cells from the substomatal chamber is captured by a highly specialized enzymatic complex called ribulose-1,5-bisphosphate carboxylase-oxygenase (in all plants) and phosphoenolpyruvate carboxylase (in the CAM and C4 plants) (Taiz et al. 2017).

During photosynthesis, the plants use solar energy to oxidize water, consequently releasing oxygen and reducing CO_2 and thus forming carbonated compounds, specifically sugars. Thus, plants continuously capture and mitigate CO_2 in the presence of light for the formation and functioning of plant tissues. Therefore, pastures that are appropriately fertilized and managed act as a GHG sink because they have increased photosynthetic potential (i.e., they consume more CO_2); such pastures produce more biomass and can therefore deposit a greater amount of organic matter (dead material, litter, and roots) in the ecosystems (Godde et al. 2020; Oliveira et al. 2020). Regarding pasture management effect on soil organic carbon (SOC) stocks in grasslands, Maia et al. (2009) studied three levels of intensification: Degraded without inputs such as fertilizers, weed controls, and soil erosion. The nominal grasslands received the same management, but maintained reasonable productivity, presumably due to more appropriate grazing regimes and improved grasslands that received management (stocking rate adjustment, fertilization, weed control). Compared to SOC stocks in native vegetation, degraded grassland management decreased SOC by a factor of 0.91 and nominal grassland management reduced SOC in Latossols by a factor of 0.99, whereas SOC storage increased by a factor of 1.24 with nominal management in other soil types. In Latossols, the study observed that improved grasslands increased SOC storage by a factor of 1.19, but in other types of soil, there was no evidence of SOC increase. An average C emission of 280 kg C ha^{-1} $year^{-1}$ was reported.

CH_4 is a GHG produced in the soil by the anaerobic decomposition of organic matter, such as proteins, organic acids, carbohydrates, and soluble lipids, in animal excreta via the action of methanogens (Yuan et al. 2018). Pasture soils serve as a significant sink for CH_4 via oxidation by methanotrophic bacteria (Saggar et al. 2007; Wang et al. 2009).

The intensity and frequency of grazing affects both the absorption of CH_4 in the soil and its enteric emission (Soussana et al. 2007) after forage intake and digestion (Berça et al. 2019). To increase forage digestibility, nitrogen is supplemented to the canopy, which increases the crude protein content of forage consume by cattle (Delevatti et al. 2019).

Plants absorb nitrogen as NH_4^+ (ammonium) or NO_3^- ions. Legumes have established symbiotic relationships with nitrogen-fixing bacteria to convert molecular nitrogen (N_2) into ammonia (NH_3). Grasses have a low atmospheric nitrogen use efficiency, because of the limited availability of this element during the development of forage plants; therefore, it is more advantageous to supply nitrogen via soil solution in the form of urea, ammonium nitrate, or ammonium sulfate.

N_2O is produced through nitrification and denitrification, which are the processes dependent on oxygen availability, but in the opposite redox conditions (Pinheiro et al. 2018). The production of N_2O in soils, particularly those fertilized with nitrogen sources, and in urine patches occurs through microbial processes in which the reactive forms of nitrogen in the soil are reduced, depending on soil conditions, such as temperature, humidity, oxidizable carbon, available oxygen, and CO_2 concentration (Butterbach-Bahl et al. 2013).

Proper management of nitrogen to crops [each unit of nitrogen fixed in the soil in organic and stable form (humus)] can allow the mitigation of approximately 10 units of carbon in the soil (Guenet et al. 2020). However, considering that synthetic nitrogen fertilizers produce GHGs, biological nitrogen fixation is increasingly being preferred as the source of nitrogen, which offers the best prospects and should therefore be optimized (Côrrea et al. 2021). Alternatively, controlled release fertilizers, nitrification inhibitors, protected fertilizers, urease inhibitors, and fertilizers with the precise amount of nitrogen required by the forage crops can be used (Cardoso et al. 2020a).

4. Effect of fertilization on GHG emission

N_2O and CH_4 are the main GHGs contributing to global warming in the agricultural sector (IPCC, 2019). N_2O is released into the atmosphere via nitrification and denitrification, where the action of microorganisms promotes the oxidation (nitrification) of ammonium (NH_4^+) into nitrate (NO_3^-) and subsequent reduction (denitrification) into diazoate (N_2) and N_2O (Saggar et al. 2013).

In pastures, CH_4 can be both produced and consumed. CH_4 is produced exclusively by methanogenic archaea under anaerobiosis conditions from final fermentation products (acetate, CO_2, and $H_{2)}$. Under aerobiosis conditions, methanotrophic bacteria may oxidize CH_4 to O_2 (Hallet al. 2013). The global warming potential of CH_4 is 28 times greater than that of CO_2, and its atmosphere lifetime is 9 to 15 years (IPCC 2019).

Nitrogen fertilization increases productivity, improves in the chemical and morphological characteristics of forage (Marques et al. 2017; Carvalho et al. 2019), and promotes weight gain per animal and per unit area (Delevatti et al. 2019). However, inadequate use of nitrogen fertilizers can increase GHG emission (Raposo et al. 2020; Grassmann et al. 2020; Smith et al. 2020).

GHG emission from nitrogen fertilization is closely linked to fertilizer type, application dose, application method, and climatic conditions (e.g., temperature and humidity) (Gerber et al. 2013; Van der Weerden et al. 2016; Luo et al. 2016; Cardoso et al. 2019b; Chen et al. 2019; Raposo et al. 2020).

Plants can absorb nitrogen only when it is available in the form of NH_4^+ and NO_3; however, nitrogen fertilizers in the form of $CO(NH_2)$, NH_4^+, and NO_3^- are available. In the absence of absorption by plants, excess available nitrogen can promote GHG emissions (Raposo et al. 2020). For instance, urea is available in the ammoniacal form. Ammonium sulfate makes nitrogen available in the ammoniacal form and ammonium nitrate in both ammoniacal and nitric forms. Other types of formulated fertilizers that contain other compounds in addition to nitrogen source as well as slow-release nitrogen fertilizers are available.

While testing various doses of ammonium nitrate fertilization in a temperate ryegrass pasture, Smit et al. (2020) observed that N_2O emission increased with increasing fertilization. In a 2-year study using increasing doses of urea fertilization (0, 90, 180, and 270 kg N $ha^{-1}year^{-1}$) in a Marandu pasture, Raposo et al. (2020) observed that the daily fluxes of N_2O were positively correlated with the dose of fertilization (-5.99, 36.14, 49.53, and 185.69 μg N_2O-N $m^{-2}h^{-1}$, respectively).

The doses and sources of nitrogen fertilization may alter CH_4 fluxes; however, this effect is more evident early after application, and CH_4 emission is closely related to climatic and soil conditions (Yue et al. 2016; Cardoso et al. 2019b; Raposo et al. 2020).

Pasture fertilizers are applied as top dressing, and fertilizers are not incorporated into the soil. Thus, the application of fertilizers in installments is a good alternative to minimize loss, since the availability of nitrogen in the soil decreases if fertilization is not split (Timilsena et al. 2015).

In a pasture-based study, Raposo et al. (2020) partitioned fertilization into three rounds and noted that both N_2O and CH_4 fluxes were higher early after each fertilization round. Similar observations were reported by Cardoso et al. (2019a) by applying organic fertilization with a high nutrient availability in a Marandu pasture. Raposo et al. (2020) found that the highest CH_4 fluxes occurred in the first two days after application. Mori and Hojito (2015) analyzed both N_2O and CH_4 fluxes and showed that the highest values were obtained immediately after application; subsequently, between 10 and 35 days after application, the fluxes became similar to those obtained without organic fertilization. Likewise, Bretas et al. (2020) analyzed the fluxes of N_2O and CH_4 from organic fertilization in a *Urochloa decumbens* 'Basilisk' pasture and reported similar findings.

Furthermore, climatic conditions affect GHG emissions, as they alter the filling of porous space in the soil with water, providing conditions of anaerobiosis or aerobiosis (Mazzetto et al. 2014). These effects are evident under tropical conditions, where CH_4 and N_2O are produced during rainy periods and consumed during drought periods (Chamberlain et al. 2016; Cardoso et al. 2019a; Cardoso et al. 2020a).

In a study in a Marandu grass pasture, Cardoso et al. (2020a) found that N_2O emission was mainly controlled by soil temperature and humidity; as such, the daily fluxes of N_2O were increased when the porous space filled with water was ≥52.5% and the temperature was ≥22.8°C. The same trend was observed for CH_4 fluxes, which were increased when the water-filled porous space was ≥66.0% and the temperature was ≥20.4°C.

5. Effects of mixed pastures on GHG emission

Legume inclusion in grassland ecosystems has been practiced since long. This can increase herbage biomass while reducing or substituting synthetic nitrogen fertilizers (Barneze et al. 2020), which are responsible for nitrogen loss to the environment through volatilization, leaching, runoff, and N_2 or N_2O emission (Uwizeye et al. 2020). This practice is possible because of the ability of legumes to fix atmosphere N_2 through symbiosis with soil bacteria within root nodules (Oldroyd et al. 2011). Nonetheless, slow establishment and low persistence hamper legume adaption to some regions, such as Brazil (Boddey et al. 2020).

The use of synthetic nitrogen fertilizers increases N_2O emissions (Nielsen et al. 2016; Niklaus et al. 2016). However, there carbon footprint of crop monoculture systems is low, which offsets the increased N_2O emissions from nitrogen-fertilized systems (Nielsen et al. 2016). Lower N_2O emissions after urine deposition were attributed the greater plant nitrogen uptake of legumes than of grasses and lower soil nitrification rate

(Bowatte et al. 2018). Alternatively, crops make a high amount of mineral N soil available to denitrification through faster nitrogen cycling via residual decomposition (Niklaus et al. 2016; Boddey et al. 2020), thereby increasing N_2O emission. Thus, legume inclusion in a grass system is a useful strategy to mitigate N_2O emission directly as a result of the uptake of available soil nitrogen by plants (Nyfeler et al. 2011) and indirectly as a result of increase in nitrogen use efficiency and no need for synthetic nitrogen fertilization, which reduces the carbon footprint of the mixed system (Schmeer et al. 2014). Additionally, legume inclusion in grass systems may enable soil carbon and nitrogen storage (Wu et al. 2017).

In a long-term field study, Schmeer et al. (2014) found reduced N_2O emission from a legume-based system compared with those from a nitrogen-fertilized grass-based systems, without compromising herbage biomass production. Similarly, in a short-term mesocosm study, Barneze et al. (2020) suggested that increasing the legume proportion in a grass system enhanced herbage biomass production without affecting the N_2O emission, and N_2O emission from the mixed system was reduced compared with than from the nitrogen-fertilized system.

Grasslands act as CH_4 sinks; however, pasture management plays an important role in GHG emission. In a global meta-analysis, Zhang et al. (2020) reported that N fertilization reduced CH_4 uptake in grasslands, while N+P fertilization showed little effect. In addition, the authors showed a fertilizer-associated increase in grass nitrogen uptake, which reduced the amount of available mineral N in soil and suppressed the activity of methane monooxygenase enzyme involved in CH_4 oxidation. Likewise, in a multi-species plant study, including grasses, vegetables, and small and tall non-leguminous herbs, neither N+P+K fertilization nor legume inclusion affected CH_4 uptake; however, CH_4 uptake decreased with increased species richness of the system (Niklaus et al. 2016). Remarkably, soil CH_4 emission or uptake depend on the presence of methanogenic and methanotrophic bacteria, respectively, in addition to environmental conditions (Plaza-Bonilla et al. 2020).

Overall, mixed pastures are beneficial in that they reduce GHG emissions and enhance agroecosystem functions (soil–plant–animal interactions). However, N_2O and CH_4 emissions from different plant communities remain largely unknown. Several factors such as climatic conditions, soil compaction (Schmeer et al. 2014), flooding (Oran et al. 2020), and excreta deposition (Bowatte et al. 2018; Cardoso et al. 2019a) have been considered the key drivers of these emissions.

6. Pasture management and enteric CH_4 emission

In Brazil, 87% of total cattle production depends exclusively on pastures (ABIEC 2020), with tropical forage representing the major source of protein, fiber, and energy required for proper ruminal function. In addition, this system incurs low production costs, can offer better conditions for animal health and comfort, and has a high capacity to sequester atmospheric carbon while reducing GHG emissions per kilogram of product (De Marchi et al. 2020). In this system, the greatest challenge related to ruminant nutrition is to increase animal performance and production while simultaneously reducing the environmental impact of the activity, particularly GHG emissions (Cardoso et al. 2020a).

The production of enteric CH_4 is, among other factors, directly affected by the quantity and quality of the diet offered and the conditions of ruminal fermentation (Ruggieri et al. 2020). Thus, dry matter content, roughage-to-concentrate ratio, chemical composition of the diet as well as the rate of degradation of feed fractions greatly affect methanogenesis (Min et al. 2020). In general, the greater the intake, the greater the CH_4 production per animal. However, CH_4 production in grams per kilogram of DM ingested can be reduced by increasing the passage of undigested feed to the small intestine (Wang et al. 2018).

Additionally, the type of fermented carbohydrate affects CH_4 production, as it directly affects the microbial composition and rumen pH as a function of the acetic-to-propionic acid ratio (Benaouda et al. 2019). According to Hatfield and Kalscheur (2020), structural carbohydrates present in the cell wall of forage, including pectin, hemicellulose, and cellulose, are the most important components determining the nutritional value of forage. The authors reported that fiber content is associated with low digestibility, and its amount and fractions affect the physical volume occupied in the rumen and, consequently, animal intake and performance.

Sauvant and Giger-Reverdin (2009) showed that ruminants fed forage rich in structural carbohydrates produced more CH_4 than those fed mixed diets with high levels of non-structural carbohydrates.

In addition to fibers—analyzed and chemically classified as neutral detergent fiber (NDF) and acid detergent fiber (ADF)—other variables such as crude protein (CP) content and digestibility are also important in the qualitative analysis of forage, as they directly or indirectly affect the voluntary intake of DM and, consequently, animal productivity (Hatfield and Kalscheur 2020).

In tropical intensive production systems, enteric CH_4 production by cattle is affected by the morphological characteristics and chemical composition of forage plants as well as temperature. Temperature can affect methanogenesis either directly through changes in the animal's ingestive and digestive behavior or indirectly through interference with the chemical composition and digestibility of forage (Archimède et al. 2018). The composition of cell wall and proportions of its components are important in enteric CH_4 production, and tropical forage (C4) and temperate (C3) plants differ in terms of these parameters (Archimède et al. 2018).

Typically, C4 grasses contain a greater proportion of fibers than C3 grasses, since they have a higher rate and degree of lignin deposition in plant tissues (Liu et al. 2018); thus, in addition to altering plant intake and digestibility, this favors acetic fermentation, resulting in greater CH_4 production (Archimède et al. 2018). However, these plants provide low amounts of substrate for methanogens because of their low digestibility and low fermentation rate (Archimède et al. 2018).

Archimède et al. (2011) evaluated the effects of C3 and C4 grasses and vegetables in the temperate and tropical climates on enteric CH_4 production and found that ruminants fed with C4 grasses produce respectively 17% and 20% more CH_4 than those fed with C3 grasses and vegetables in tropical climates. Moreover, ruminants produced 14% less CH_4 in tropical climates than in temperate climates.

As enteric CH_4 mitigation strategies, the selection of forages with a high concentration of soluble carbohydrates, including vegetables producing secondary metabolites, such as condensed tannins, and the supply of forage with a high nutritive value may provide achieve animal performance and lower CH_4 production per unit of intake and product (Tedeschi and Fox 2018).

Condensed tannins are polyphenol complexes found in tropical vegetables and other C3 plants, such as Pinto peanut. At adequate doses (2%–4% on dry matter basis), these compounds can produce beneficial effects by reducing fiber fermentation in the rumen and consequently reducing hydrogen and acetate formation and inhibiting the growth of methanogens, ultimately decreasing enteric CH_4 production (Norris et al. 2020).

In this context, the use of mixed pastures of grass and vegetables may be an alternative to reduce the environmental impact of livestock (Berça et al. 2019). Owing to the contribution of nitrogen through biological fixation, the practice decreases the use of synthetic nitrogen fertilizers, thus reducing the emissions of CO_2 and N_2O into the atmosphere and minimizing the use of fossil fuels in food and fodder production (Stagnari et al. 2017). In addition, in mixed pastures increase forage quality because of the lower fiber content, higher CP content, higher passage rate, and in some cases, the presence of condensed tannins, resulting in reduced enteric CH_4 production by ruminants (Archimède et al. 2011; Tedeschi et al. 2014; Tedeschi and Fox 2018).

Authors' Contributions: CARDOSO, A.S.: conception and design, acquisition of data, analysis and interpretation of data and drafting the article; LONGHINI, V.Z.: conception and design, acquisition of data, analysis and interpretation of data and drafting the article; BERÇA, A.S.: conception and design, acquisition of data, analysis and interpretation of data and drafting the article; ONGARATTO, F.: conception and design, acquisition of data, analysis and interpretation of data and drafting the article; SINISCALCHI, D.: conception and design, acquisition of data, analysis and interpretation of data and drafting the article; REIS, R.A.: conception and design, acquisition of data, analysis and interpretation of data, drafting the article, and critical review of important intellectual content; RUGGIERI, A.C.: conception and design, acquisition of data, analysis and interpretation of data, drafting the article, and critical review of important intellectual content. All authors have read and approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics Approval: Not applicable.

Acknowledgments: The authors acknowledge the members of the Unesp for forage team for their insightful discussions. This research was funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), grant numbers 2015/16631-5, 2017/11274-5 and 2019/25997-4).

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Received: 22 April 2021 | **Accepted:** 26 January 2022 | **Published:** 09 December 2022