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Strategies to mitigate the emission of methane in pastures: enteric methane: A review

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Abstract

The global population reached 7.9 billion in 2021, which represents a 160% increase in the number of people to be fed since 1960. Agricultural systems must sustainably meet food demand for this growing population while minimizing or mitigating potential environmental impacts, which are of growing concern to both consumers and the scientific community. High protein animal products (meat and milk) play a crucial part in human nutrition and pastures represent ~20% of the planet's surface. Pastoral areas have a great influence on both ecological balance and human subsistence. Ruminant livestock production systems are hotly debated because of the emission of methane, which is produced during enteric fermentation of ingested food within the rumen. Methanogenesis is a naturally occurring process in the digestive system of ruminant animals and ingesting a high-quality diet has been shown to reduce methane production. An additional function of pastoral grasslands is the capacity of the soils to operate as carbon sinks. Well managed pastures absorb carbon from the atmosphere where it can add to soil organic matter directly, through residue decomposition or excrement returns. However, in Brazil and globally, the efficiency of animal productivity tends to be lower in extensively grazed farming systems. Changes to pasture and grazing management in combination with the adoption of technology is necessary to improve the quality of pastures, increase animal productivity, and consequently reduce methane emissions from ruminant livestock. This review will discuss how to improve the conversion efficiency using pasture management to reduce or mitigate enteric methane production.

Keywords: Forage quality; greenhouse gases; pasture management.
Abbreviations: GHG_greenhouse gas; N_2_nitrogen; CO_2_carbon dioxide; CH_4_methane; N_2O_nitrous oxide; H_2_hydrogen; NH_3_ammonia; O_2_oxygen; SC_structural carbohydrates; NSC_non-structural carbohydrates; ADF_acid detergent fiber; NDF_neutral detergent fiber; C_carbon; C_4_grasses plants, C_3_grasses plants.

Introduction

In 2020 Brazil had in excess of 214M total head of cattle (Abiec, 2021). This is the largest national commercial herd and accounts for 20% of international beef exports (Abiec, 2021). In order to meet the demands of an increasing global population Brazil is uniquely placed to supply cost-effective high-quality protein due to predominantly pastoral based grazing systems. However, these systems are not operating at potential and often have poor conversion efficiency so there is significant capacity to increase the production of meat and dairy products. With a population of 211M in 2019 (World Bank, 05/19/2021), Fontaneli et al. (2019) reported Brazil currently produces enough food to feed ~1.2 billion people and has the resources to expand production by a further 40%.
With the advent of the Green Revolution production agriculture initially focused on maximizing yields, animal production and financial returns. More recently, the impact of these systems on the environment has been recognized. This has led to criticism from scientists and end consumers who want sustainable production from systems that minimize or mitigate damage to the environment. Although there is criticism from the media, pastoral-based production of animal products is primarily based on converting "human inedible-food" products (cellulose and hemicellulose) into meat and milk, without competing with human food (Tedeschi et al., 2015). The concept of sustainable development must encompass economic prosperity, environmental quality and social equity equally (Dick, 2013). Thus, the challenge is to intensify livestock farming sustainably to increase food production while minimizing the environmental impacts to land, water, ecological systems and the atmosphere.

To this end, the Kyoto protocol and Copenhagen agreements aim to reduce pollution by nutrients and greenhouse gas (GHG) emissions. Of the total anthropogenic GHG emissions produced globally ~11% are from the agricultural sector (Smith et al., 2007). The main pollutants of concern from ruminant production systems are nitrogen (N), GHGs (carbon dioxide (CO_2); methane (CH_4); and nitrous oxide (N_2O)) and volatile organic compounds (Kebreab et al., 2010). Much of the debate surrounding ruminant production systems focuses on CH_4 emissions, via eructation, because its heating potential is 25 times that of CO_2 (Zubieta et al., 2021). Ideally, quantification of agricultural GHG emissions should be based on optimizing resource use.

This review aims to discuss methodologies to improve the efficiency of pasture management, prioritizing the mitigation of enteric methane. We review research which has evaluated simple solutions (changes in grazing management and diet) to increase the efficiency of pasture conversion into ruminant animal product at moderate grazing intensities, in temperate and tropical pastures, to mitigate methane production and emission to the atmosphere.

General aspects related to the emission of greenhouse gases in livestock

The greenhouse effect is a natural process related to the concentration of GHGs in the atmosphere, and is essential for the existence of life on the planet. Without its presence the average global temperature would be 18 ºC, which would make the planet uninhabitable (Carvalho et al., 2010).

The main GHGs are: carbon dioxide (CO_2), nitrous oxide (N_2O) which has a heating potential 298 times that of CO_2, and methane (CH_4), with a heating potential 25 times more than CO_2 (Zubieta et al., 2021). The concentrations of these gases in the atmosphere have already increased ~2.5 times from pre-industrial levels, due to human activities (Wmo, 2019). The intensification of land use, combined with the consumption of fossil fuels in the manufacture of equipment, fertilizers, agrichemicals, and the harvest and transport of crops (Figure 1) contributes significantly to increases in GHG emissions from the agricultural sector (Johnson et al., 2007).

Brazil is ranked in the ten countries with the highest total GHG emissions globally (Brasil, 2015) and has made several voluntary commitments to reduce emissions. The country is committed to reducing GHG emissions by 43%, compared with levels in 2005, by 2030 (Brasil, 2015). Emission reduction targets, such as those proposed by Brazil, are directly linked to improving the efficiency of production processes in different economic sectors (Soares and Cunha, 2019).

Opio et al. (2013) reported enteric CH_4 emissions differed among ruminant species (Figure 2). In addition, the level of system intensification also had an impact on GHG emissions for the production systems. Evaluating different levels intensification from extensive to intensive (with legumes) in beef cattle systems in Brazil had carbon footprints of 58.3 to 29.4 kg CO_2 equivalent (eq.), respectively, for each kg of carcass produced (Cardoso et al., 2016). This confirmed the existence of differences in production system efficiencies.

Thoma et al. (2013) reported 72% of GHG emissions in the United States occurred before milk left the farmgate. Of this the dairy herd contributed 25% of emissions (in the form of CH_4) with a further 24% from manure (as CH_4 and N_2O). The remainder of dairy farm emissions came from field areas (19% in the form of N_2O and CO_2) and agricultural energy (4% in the form of CO_2). In Canada, Beauchemin et al. (2010) used a Life Cycle Analysis tool to estimate GHG emissions (CO_2 eq., % of total emissions) from a beef cattle farm. They estimated enteric fermentation (CH_4) was responsible for 63% of gas emissions, followed by manure (N_2O and CH_4; 28%), energy (CO_2; 5%) and soil (N_2O; 4%). For traditional low productivity, extensive beef cattle systems in southern Brazil it was shown that 84% of total GHG emissions came from animals (19.0 kg CO_2 eq. kg live weight gain^{-1}). The majority of this (97% or 18.5 kg CO_2 eq. kg live weight gain^{-1}) was from enteric fermentation (Silva et al., 2014).

It is evident that there is a need to improve the efficiency of productive processes within grazed agricultural production systems. However, gas emissions by animals alone cannot be considered a complete measure of the impact of livestock on the environment (Reisinger et al., 2012). Ultimately a carbon footprint should include greenhouse gas emissions over the entire life cycle of a product or system. It is usually expressed as kg of CO_2 equivalent per unit of a product (De Vries and De Boer, 2010) or kg of CO_2 equivalent per unit area of the production system (Reisinger and Ledgard, 2013). Appropriate estimates and analyzes of the carbon footprint are crucial to identify opportunities to reduce GHG emissions, and allow inferences about the efficiency of the animal and the production system.

Ruminal methanogenesis

Ruminant animals convert low quality fibre into high quality protein for human consumption. The rumen is a complex ecosystem, with numerous characteristics that ferment the feed consumed. This process is mediated by ruminal microorganisms (bacteria, fungi and protozoa), which transform the ingested product into short-chain volatile fatty acids (acetic, propionic and butyric). These products provide energy to the animal in addition to protein synthesis, which is mediated by the ruminal microbial mass (Kozloski, 2012). During this process CO_2, H_2, NH_3 and CH_4 are released. Methane production is essential during the fermentation process to generate energy and microbial protein. Thus, it does not represent an inefficiency to the ruminant.

Methanogenesis occurs naturally in the digestive system of ruminant animals in the complete absence of oxygen (O_2), due to the fermentation of structural carbohydrates (SC) and non-structural carbohydrates (NSC). This is possible through the symbiosis process between ruminal microorganisms and the ruminant animal (Akin, 1993). Up to 92% of the total CH_4 is produced in the rumen (Torrent and Johnson, 1994). The remainder is produced at the intestinal level. As such, 98% of emissions occur via eructation and expiration and only 2% through flatulence (Murray et al., 1976). The consumption of dry matter and efficiency of feed conversion affects enteric production of CH_4 (Wattiaux et al., 2019). Thus, the composition of the diet offered to the animals can increase or reduce CH_4 production.

Studies to understand the cause of differences in methanogenesis have focused on animal nutrition. They focus mainly on intensive temperate systems and use animals with high conversion efficiency to demonstrate mitigation of GHG emissions (Knapp et al., 2014). However, their applicability to extensive low-productivity grazing systems is a challenge due to technical, economic and animal welfare aspects (Gerssen-Gondelach et al., 2017). Extensive pastoral grazing systems often have both low dry matter production and low nutritional value. Consequently, CH_4 emissions are greater compared to animals that have high grain intake in intensive feedlot systems (Herrero et al., 2016). However, research has shown a reduction in CH_4 emissions per unit of product when feed quality is increased for a range of ruminant species in tropical, temperate, native pastures and under integrated agricultural production systems (Savian et al., 2018; Souza Filho et al., 2019; Cezimbra et al., 2021; Zubieta et al., 2021).

Hydrogen is the main limiting substrate for methanogenesis (Janssen, 2010). The profile of short-chain volatile fatty acids produced during the carbohydrate fermentation influences the availability of H_2. Digestion of feeds high in structural carbohydrates stimulate the production of acetic and butyric acids, which increases the availability of H_2 in the rumen. The higher H_2 concentrations result in increased CH_4 production. In contrast, feeds high in non structural carbohydrates stimulate the production of propionic acid, which consumes H_2 and, reduces its concentration in the rumen. Thus, the greater the proportion of propionic acid the less CH_4 is produced (Ramin and Huhtanen, 2013). High quality tropical or temperate forages generally reduce CH_4 production, which has been correlated with dry matter digestibility (Shibata and Terada, 2010). Moraes et al. (2014) revealed a positive relationship between CH_4 production and neutral detergent fibre (NDF) in the diet of dairy cows. However, it is worth noting that the formation of CH_4 from SC is associated with other factors that involve the nutritional value of food. Sejian et al. (2011) reported several factors that influence CH_4 emissions by ruminant animals (Figure 3). GHG emissions, in particular CH_4, decrease as animal performance increases. Management strategies to increase animal performance include: the efficient management of pasture areas, the introduction of new plant species and the genetic improvement of animals (Zubieta et al., 2021).

Management of pastoral systems and their effects on GHG mitigation

Most of the arable areas in the world are occupied by pastures, whether natural or cultivated (annual and perennial) (Damian et al., 2021). In Brazil the use of tropical C_4 forage species from the genus Brachiaria (*Urochloa*), Panicum (*Megathyrsus*), *Cynodon* and *Pennisetum*, dominate pastures in the Central Brazil. However, the southern region has a subtropical climate, allowing the use of temperate grasses such as *Lolium multiflorum*, *Avena strigosa* and *Avena sativa* (De Moraes et al., 2014) in cultivated pastures. These supplement native species belonging to the Pampa Biome.

Brazil has approximately 162.3M hectares of pastures (Ibge, 2019). They feed beef and dairy cattle, buffalo, goat and sheep but technology levels differ substantially. Most pastures are exploited in an extractive manner and degrade over time. Pastures are sown in low fertility soils and often nutrients removed in product are not replaced. Approximately 150.5M hectares are used exclusively for pastoral grazing and ~11.8 million hectares of pasture in integrated (mixed cropping) systems with soybean or corn (Ibge, 2019). It is estimated that 50 - 70% of pastures are degraded (Ibge, 2017). The degradation occurs due to establishment of monospecific developed pastures, overgrazing and excessive trampling (Figure 4). This reduces soil fertility, reduces vegetation cover and subsequently increases soil erosion (Machado et al., 2017).

The main challenge for agricultural production systems is to increase the efficiency with which natural resources are used, to promote greater productivity and increase sustainability (Machado et al., 2019). For ruminant production systems this means improved pastoral management to increase the quantity and quality of feed for animal consumption to maximize animal production (Savian et al., 2018; Vasconcelos et al., 2018; Cezimbra et al., 2021). Further, pastures are important sinks for GHGs, through so-called temporary carbon stocks. Grazing livestock act as renewers of pasture, as grazing stimulates regrowth and CO_2 is removed by the plants from the atmosphere (Dick, 2013).

To minimize environmental impacts, short, medium and long-term actions are required. For Brazil, the recovery of degraded pastoral areas is a priority. This can be facilitated by expansion of Integrated Agricultural Production Systems, with emphasis on the intensification of the use of Crop-Livestock Integration (Souza Filho et al., 2019). This will also reduce the need to graze degraded areas and stimulate natural regeneration through reduced grazing pressure. Additionally, there should be further work to promote no-till agriculture and encourage the use of biological nitrogen fixation. This would reduce the need for inorganic nitrogen fertilizers, reduce soil disturbance and increase the quality of feed available. Further improvements can be made through the use of technologies for the treatment of animal feces and urine (Figure 4) (Machado et al., 2017).

In the C_4 grassland ecosystems of Central Brazil, enteric methane emissions were less than those reported by the IPCC (2007). The IPCC reports that a bovine emits between 55 and 58 kg of CH_4 per year. Barbero et al. (2015) managed tropical Marandu grass with different heights (15, 25 and 35 cm), and reported the average CH_4 emission was 47 kg of CH_4 per year. The cattle were supplemented with a protein-energy supplement at 0.3% of live weight, which improves the digestibility of the forage consumed and thus, reduces CH_4 production (Van Lingen et al., 2019).

Lower CH_4 emissions, due to better digestibility of forage, was also reported by Neto et al. (2015) for Xaraés grass pasture for cattle supplemented with two levels of starch (high or low), either alone or combined with oil. They reported an average emission of 43 kg of CH_4 year^{-1} head^{-1}. Similar results were reported by San Vito et al. (2016) under the same experimental conditions. In this experiment the cattle were supplemented with increasing doses of crude glycerin, and on average emitted 48 kg of CH_4 year^{-1} head^{-1}. Thus, in all three cases, it is evident that inventories overestimated the actual emission of enteric methane and that supplementation can reduce enteric CH_4 emissions.

Intercropping grasses and legumes can also improve the digestibility of forage and decrease the emission of CH_4. Berça et al. (2019) compared Marandu grass fertilized with 150 kg of N ha^{-1} year^{-1} versus Marandu grass intercropped with forage peanut (*Arachis pintoi*). Methane emissions from grazing cattle were 51 and 48 kg of CH_4 per year, respectively, cross breeding of cattle races specialized in meat production can also reduce emissions (Berça et al., 2019). For all cases of emissions from C_4 grasses reviewed here, pastures were grazed when they reached 95% light interception.

Table 1. Comparison of CO_2 in beef production.

Production system	Feeding	kg of CO_2	Country	Reference
Complete cycle	Native pasture	14.1	Brazil	Vasconcelos et al. (2018)
	Improved native pasture	10.4		
	Fertilized native pasture	10.0		
Complete cycle	Native pasture	16.7	Uruguay	Modernel et al. (2013)
	Improved native pasture	9.5		
Cow/calf	Improved native pasture	20.8	Uruguay	Becoña et al. (2014)
Complete cycle	Native pasture	42.6	Brazil	Ruviaro et al. (2015)
	Improved native pasture	20.2		
Complete cycle	Native pasture	22.5	Brazil	Dick et al. (2015)
	Improved native pasture	9.1		

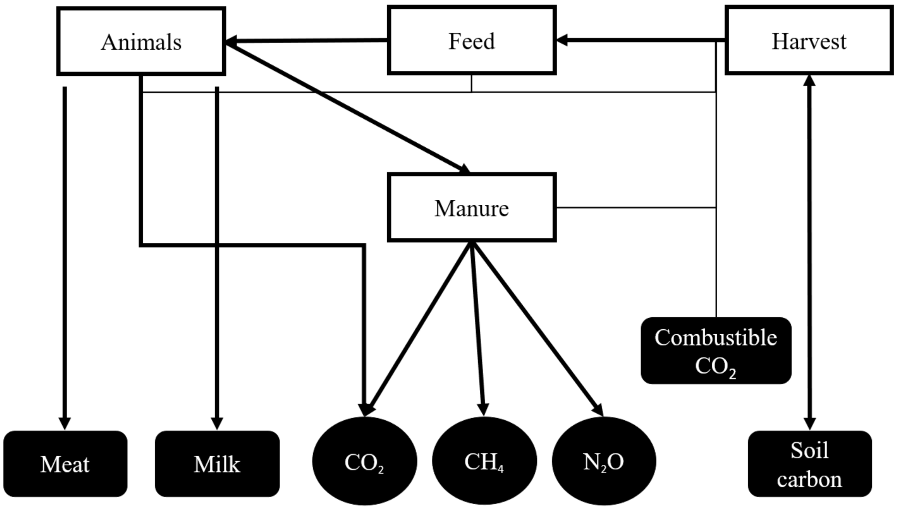

Figure 1. Diagram of products and GHGs from cattle production. Source: adapted from Machado et al. (2017).

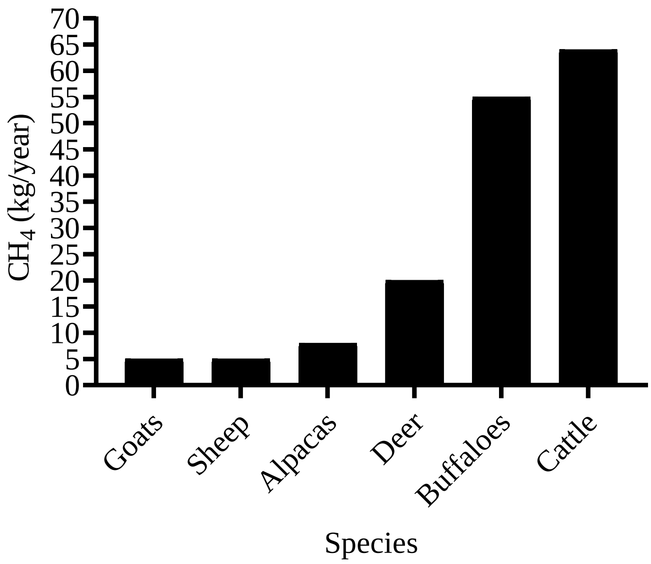

Figure 2. Average CH_4 emissions by different species of ruminant animals. Source: adapted from the IPCC, 2007.

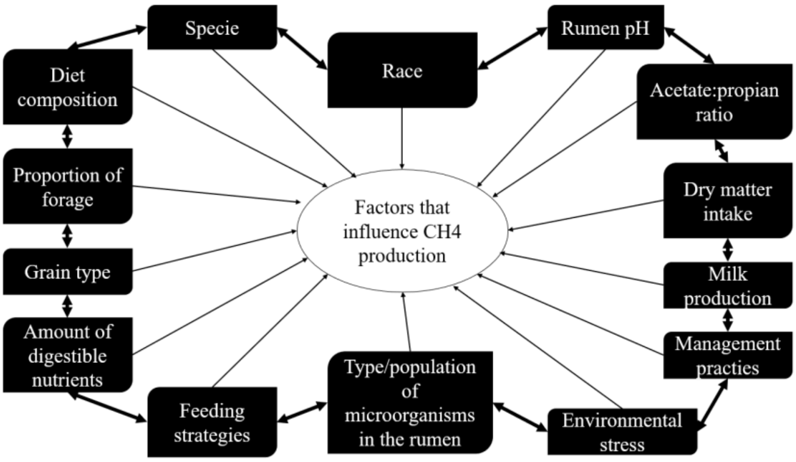

Figure 3. Production of CH_4 by ruminants from enteric fermentation. Source: Adapted from Sejian et al., 2011.

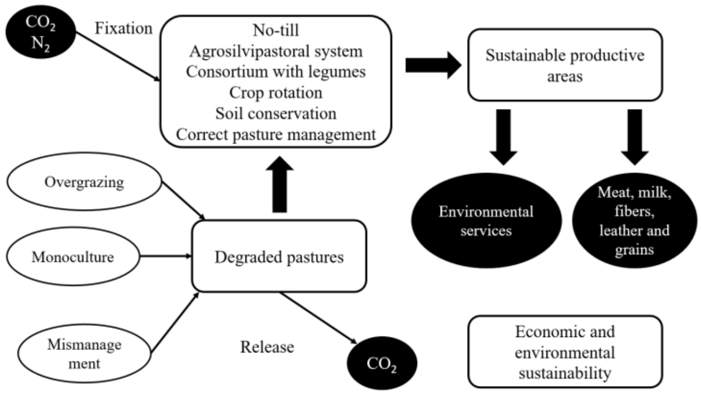

Figure 4. Overview of actions to optimize the sustainability of pastoral systems in Brazil. Source: Machado et al. 2017.

Thus, grazing heights of 25 cm for Marandu grass and 30 cm for Xaraés grass and Marandu mix and forage peanut, recommended to maximize daily live weight gain, gain per area and reduce CH_4 emission (Ruggieri et al., 2020).

For temperate pastures (C_3) in the southern region of Brazil, grazing sheep on annual ryegrass (*Lolium multiflorum*) pasture managed under fast rotational grazing, with pre- and post-grazing sward target heights of 18 and 11 cm was the best strategy to mitigate CH_4 emissions. Methane emissions decreased 64% per unit area and 170% less per unit of animal product compared with the traditional rotational grazing method (Savian et al., 2018). The reduction was influenced not only by the quantity of pasture ingested, but also by ADF and NDF content of the herbage. This indicates chemical composition (feed quality) becomes important from the moment when feed supply is no longer the main limiting factor to animal performance. The chemical composition of the feed begins to affect this performance to a greater extent and, consequently, affects the GHG gas emissions and the mitigation of the effects through the production of meat and/or milk.

Souza Filho et al. (2019) evaluated an integrated system of soybean and beef cattle in southern Brazil. There were different grazing intensities, defined by four grazing heights (10, 20, 30 and 40 cm) in a mixed black oat (*Avena sativa*)/annual ryegrass pasture. They reported CH_4 emissions were lower and animal performance higher when the height of the pasture was managed between 23 and 30 cm. They also pointed out that, due to the majority of rural producers adopting very low grazing heights, the use of target heights between 23-30 cm alone in southern Brazil have the potential to reduce GHG emissions by 13-14%. This is about half the goal of a 22-25% reduction in enteric fermentation from livestock from the agricultural sector promised by the Brazilian government in the Paris Agreement (Souza Filho et al., 2019).

Different tools have been used as indicators of sustainability, with emphasis on the Life Cycle Analysis (LCA) that helps in the alignment of activities with the principle of sustainability (Robert, 2000). The use of LCA has been adopted in order to draw panoramas that can be introduced into management practices. These can then take into account the measurement of environmental aspects associated with a product during its life cycle. A study with LCA confirmed that the increase in productivity and mitigation of GHGs was obtained from the supply through the year temperate species (grasses and/or legumes) in natural pasture areas of the Pampa Biome (Dick, 2013). When comparing the different production systems in Brazil and Uruguay, it was shown that the introduction of species reduced GHG emissions (Table 1). In complex pastoral environments found in native pastures, studies show that total dry matter consumption explained 55% of the CH_4 emitted by cattle (Cezimbra et al., 2021). The period of greatest CH_4 emissions occurs when the animal has the highest consumption of dry matter, and corresponds to the period of greatest animal production. Becoña et al. (2014) confirmed that the optimization of forage supply and grazing intensity are useful tools to increase pasture productivity, reproductive performance, beef productivity and, possibly, reduce GHG emissions in native improved pastures. In these areas, lower grazing intensities have enabled greater gains in live weight and reduced GHG emissions, as long as the forage supply is moderate (8% and 12% of DM kg^{-1} of live weight). Pastures managed with high grazing intensity and low forage supply, have had reduced live weight gains and increased GHG emissions per unit kg of carcass produced. Thus, in improved pastoral systems where intake is restricted by a low forage supply a better quality diet is not always the best strategy to mitigate CH_4 emissions, (Cezimbra et al., 2021). A reduction in grazing intensity provides a positive economic result. Rolf (2010) found to reduce CH_4 emissions per kg weight, there had to be an associated increase of 1.0 to 1.2 kg of production per head.

Genro et al. (2013) evaluated native pasture under three levels of intensification with moderate forage supply. They observed that there was no difference in the average CH_4 emission per animal. However, CH_4 emissions per kg of live weight ha^{-1} $year^{-1}$ was lowest for the most intensified systems (natural pasture improved by fertilization and/or improved species oversown). Specifically, the CH_4 emissions were 85.7 g CH_4 kg^{-1} live weight for the fertilized natural pasture system oversown with improved temperate species; 76.7g for the fertilized natural pasture system and 165 g for the control which had no management intervention. The results obtained by these authors, show the importance of obtaining pastoral systems capable of higher production rates, in order to mitigate CH_4 emissions. The authors also concluded that the implementation of adequate pasture management practices to improve the quality of pastures increased the productivity of the animals and had a significant effect in reducing enteric CH_4 emissions. This confirmed the importance of pasture management to allow greater forage intake, increase individual animal performance, and consequently reduce the emission per unit area. In addition, increasing animal performance can reduce slaughter age, which has a favorable effect on remediating native pastoral areas by producing more live weight from a reduced pastoral land area and decreasing emissions as evaluated by LCA.

Potentialities, challenges and opportunities for pastures

Pastures represent ~20% of the Earth's total land area and have a major influence on ecological balance and human livelihood (Damian et al., 2021). Traditional pasture management systems in Brazil need to change. Negative effects related to low yield and profitability must be addressed and continued degradation of native pastures to reduce the rate of soil erosion is crucial. There is mounting international pressure to implement alternative and sustainable agricultural production processes (Koyanagi et al., 2019) from scientists, media and consumers. It is essential to build mitigation systems that are easy to implement, produce feed of sufficient quantity and quality, and develop pasture management strategies farmers can understand and use for high animal performance. Conceição et al. (2007) measured carbon stocks in natural pasture areas in southern Brazil managed for several years with forage offerings of 4, 8 12 and 16% (kg of dry $matter^{-1}$ 100 kg of live $weight^{-1}$). They concluded that, with seasonal changes in stocking rate to match feed supply, there was a significant increase in soil carbon content in the soil with the highest forage allowance.

These results demonstrate that the adoption of an adequate forage allowence is possible not only to optimize animal performance, but also to maintain high levels of C in the soil. Increased rates of C sequestration have also been reported by Conant et al. (2001). The meta-analysis of 115 studies identified pasture management strategies to increase C sequestration included: stocking rate adjustment to match feed supply and animal demand, fertilization, oversowing of improved grasses and legumes, and the use of irrigation. According to the authors, the average rate of increase in soil C for all management improvements was 0.54 Mg C ha^{-1}. This was comparable to increases found in conservation programs and the adoption of no-till. Rates of C sequestration were primarily influenced by history and changes in management, climate and the type of vegetation. It was estimated that the accumulation of C in an area managed under a no-tillage system provided 0.48 Mg C ha^{-1} $year^{-1}$ in subtropical soils in southern Brazil (Bayer et al., 2006). These rates of C sequestration are similar, or higher, than the values found in temperate regions. For example, in the United States, values ranged from 0.24 to 0.40 Mg ha^{-1} $year^{-1}$ (average of 0.3 Mg ha^{-1} $year^{-1}$) (West and Marland, 2002).

The accumulation of C in the soil is strongly interconnected and controlled through chemical and biochemical processes, which affect the addition of organic matter to the soil and its' subsequent decomposition (Zhou et al., 2018). According to Damian et al. (2021), implementation of intensification and diversification management practices in areas with conventional management provided an 82% increase in soil fertility, altered the structure of the soil bacterial community and increased the accumulation of soil C. These techniques, combined with seasonal changes in stocking rates to match feed demand with supply can increase animal performance, thus creating mitigating systems, that have high animal production and allow the maintenance of high levels of C in the soil (Kunrath et al., 2020).

Final Considerations

The adoption of grazing and animal management technologies are necessary to improve the quality of pastures and increase animal productivity. These system modifications can, provide a significant reduction enteric methane production, particulary in low-input, extensive cattle systems which dominate in Brazil. Improved management of grazing and knowledge of residual pasture heights can create canopy structures suitable for animal consumption which favor sustainable grazing systems.

The greatest challenge for pastoral agriculture is to manage the soil-plant-animal relationship in a way that does not compromise the future capacity of food production. This should allow the production of protein from ingestion of "human inedible material" in manner which is ecologically, environmentally and socially aware.

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