Review

Intensification: A Key Strategy to Achieve Great Animal and Environmental Beef Cattle Production Sustainability in *Brachiaria* Grasslands

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Abstract: Intensification of tropical grassland can be a strategy to increase beef production, but methods for achieving this should maintain or reduce its environmental impact and should not compromise future food-producing capacity. The objective of this review was to discuss the aspects of grassland management, animal supplementation, the environment, and the socioeconomics of grassland intensification. Reducing environmental impact in the form of, for example, greenhouse gas (GHG) emissions is particularly important in Brazil, which is the second-largest beef producer in the world. Most Brazilian pastures, however, are degraded, representing a considerable opportunity for the mitigation and increase of beef-cattle production, and consequently increasing global protein supply. Moreover, in Brazil, forage production is necessary for seasonal feeding strategies that maintain animal performance during periods of forage scarcity. There are many options to achieve this objective that can be adopted alone or in association. These options include improving grassland management, pasture fertilization, and animal supplementation. Improving grazing management has the potential to mitigate GHG emissions through the reduction of the intensity of CO_2 emissions, as well as the preservation of natural areas by reducing the need for expanding pastureland. Limitations to farmers adopting intensification strategies include cultural aspects and the lack of financial resources and technical assistance.

Keywords: animal supplementation; beef cattle; grazing management; pasture fertilization; sustainable intensification

1. Introduction

The global importance of grasslands is indicated by their extent; they comprise some 26% of total land area and 80% of agriculturally productive land. Most grasslands are in tropical developing countries, where they are particularly important to the livelihoods of some one billion poor people. Grasslands clearly provide the feed base for grazing livestock and, thus, numerous high-quality foods, but such livestock also provide products such as fertilizer, transport, traction, fiber, and leather [1].

Intensification of tropical grasslands is an important strategy of land utilization in developing countries. In the scientific literature, this means "increased production" and "minimized environmental impact" through the "best management of inputs, outputs, environmental services, and natural resources/capital" [2].

The adoption of intensification strategies in livestock production in tropical grassland areas depends on famers' knowledge on soil, water resources, plant and animal management, and the beef market. Accordingly, it has sometimes proven difficult to quantify the overall effectiveness of particular intensification strategies because they involve several strategies, are implemented in a wide range of conditions, and are assessed according to a wide range of criteria [3]. In addition, grasslands provide important services and roles, including serving as water catchments, for biodiversity preservation, for cultural and recreational needs, and as potential carbon sinks to alleviate greenhouse gas emissions. Inevitably, such functions may conflict with management for livestock production [1].

Strategies like modifying the duration and frequency of grazing, changing the stage of plant regrowth, adjusting stocking rate according to forage allowance, fertilizer application, and using supplements or legumes would improve animal performance [1,4–6].

Forage utilization associated with inedible byproduct supplements can increase the efficiency of nutrient utilization, reduce the proportion of food to be consumed by humans, increase animal performance and gains per area, and reduce slaughter age. Competition between feed and food does, in fact, concern those proteins of plant origin that are consumable by humans but are consumed by animals [7].

Ruminants are often blamed for methane emissions, and it is often proposed to shift from ruminant to monogastric production in order to reduce the carbon footprint of our diet [8,9]. However, this evolution can, to a certain extent, increase feed–food competition. All available data show that, contrary to what is often said, ruminants are very efficient animals in producing proteins, provided they are fed with forage and inedible byproducts. Moreover, higher animal production can be obtained by increasing the concentrate level in the diets of cattle, thus lowering the greenhouse gas emissions in terms of product unit (e.g., kg meat or milk) [9].

We must consider better management strategies for forage production as well as the conservation and utilization of more appropriate genetics adapted to the environment to maximize forage use efficiency, and limit the appearance of livestock inefficiencies, such as drops in fertility or rearing mortality [7].

An increased use of grassland for ruminant production could also bring positive responses to societal demand for more natural practices, and could contribute to the provision of various ecosystem services [9]. In addition, several studies demonstrated that the economic performance of grassland-based systems is similar and sometimes higher than that observed in more intensive systems [8]. The intensification using irrigation, reseeding, and feedlots requires investments in infrastructure and machinery that reduce net profitability compared to that of grassland-based systems [9]. However, grassland utilization remains dependent on the willingness of farmers who are often reluctant, as well as on the attitudes of the other actors of marketing chains [10].

In most of Brazil, there are two well-defined climatic seasons: The rainy season (spring and summer) and the dry season (autumn and winter). During the rainy season, optimal environmental conditions, such as sunlight, temperature, and precipitation, favor the growth of forage plants, which are limited during the dry season [11]. Despite the vast area of the country, forage exploitation in Brazil is based primarily on *Brachiaria* (*Urochloa*) in most regions, but also *Panicum* (*Megathyrsus*), *Cynodon,* and *Pennisetum,* or temperate grasses, such as *Lolium multiflorum*, *Avena strigose*, and *Avena sativa* in the southern regions [12].

The intensification of pasture-based beef-production systems aims to intensify, reinforce, and increase productivity. There are studies in the literature exhibiting that the Brazilian potential for cattle production is beyond current indices without expanding agricultural areas by adopting technologies (pasture management, fertilization, supplementation, and animal breeding) and

intensifying production systems based on *Brachiaria* grass [4,13–15]. The technologies used in Brazil have the potential to be adopted in other countries of South America and many countries of Africa. In many trials in Asia, Africa, and the Americas, the hybrid brachiaria cultivars have consistently produced significantly more dry-season forage than other tropical grasses and other brachiaria grasses [16]. The aspects reviewed here can be applied to global areas where *Brachiaria* occurs (Figure 1).
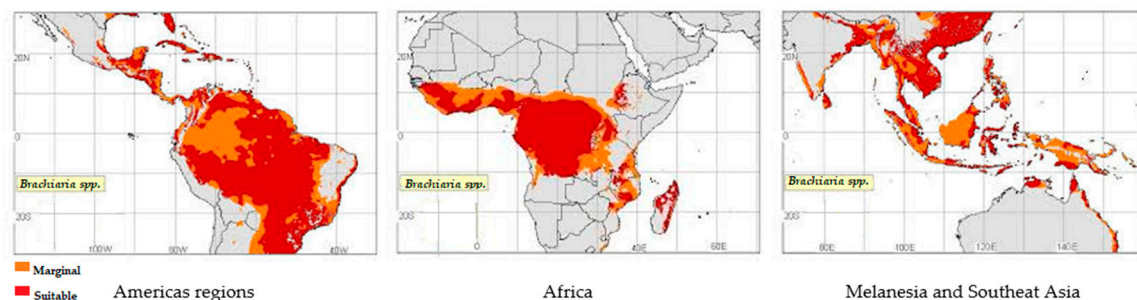

Figure 1. Global *Brachiaria* distribution (reproduced from [17]).

The aim of the present review is to discuss the productive and environmental aspects of beef-cattle production intensification in *Brachiaria* grass-based systems and to suggest future studies to better understand the aspects of intensification.

2. Concepts in Sustainable Intensification

2.1. Role of Forage in Intensification Systems

Intensification of grassland systems may lead to increases in grazing pressure or intensity. Grazing pressure, independent of stocking method, is a determining factor of the productive potential of perennial pasture [16]. Grazing intensity is defined by the height of residue or stocking rate (which affect sward height and forage mass), and leads to changes in morphogenic and structural characteristics [18].

Low grazing pressure increases sward height, leads to greater amounts of senescent material, increase shoot mass (kg ha^{-1}), decreases nutritive value, and, consequently, lowers animal gains per unit area. High-intensity grazing reduces stem elongation, which is important for maintaining a leaf–stem ratio that is adequate in supporting higher stocking rates and forage mass [19]. Therefore, the challenge is managing the plant–herbivore relationship to achieve sustainable grazing intensity that optimizes both plant and animal production.

To achieve sustainable intensification, it is necessary to understand morphogenesis and structural canopy characteristics. Plant morphogenesis can be described by three main characteristics: Leaf appearance rate, leaf elongation rate, and leaf lifespan. The combination of these morphogenic variables determines the three main structural characteristics: Leaf size, tiller density, and number of green leaves per tiller, which determine the leaf area index. Sward height is an easily measured structural variable that is one of the most useful measures of forage production [20]. The Forage Laboratory of São Paulo State University, Jaboticabal campus, studied different canopy heights (15, 25, and 35 cm) in Marandu grass (*Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster cv. Marandu) management under continuous and variable stocking rates over the course of 10 years. In these studies, an individual animal performance three times greater than the Brazilian national average during the rearing phase (0.9 kg animal^{-1} day^{-1}) and greater stocking rates (5–6 AU ha^{-1}) were observed. The data of animal performance, herbage production, structure, and chemical composition from these experiments allowed researchers to determine which treatment resulted in a sustainable livestock intensification, allowing for animal production without compromising forage production or pasture persistence and avoiding increases in greenhouse gas emissions. This system comprises the central region of Brazil.

The sward height of 25 cm was the best for this grass management when subjected to continuous grazing because desirable tillering characteristics, forage mass, and animal performance were achieved. When compared to the sward height of 25 cm, there was less animal gain per area for the 35 cm height, and at 15 cm, forage mass was limited and decreased animal production [21].

After confirming that a sward height at 25 cm was optimal for Marandu (under continuous stocking), another challenge for sustainable intensification was increasing the usage of input technologies, such as nitrogen (*n*) fertilization. Nitrogen is considered an essential nutrient for productive and persistent grass maintenance [22]. Nitrogen fertilization influences foliar elongation rate. Leaf expansion rate is the main factor responsible for greater average leaf length, which contributes to the reconstitution of the leaf area after defoliation [23,24].

Relatively lower *n* rates (90 kg N ha^{-1}) applied to Marandu can intensify the *Brachiaria* system, increasing stocking rate and animal productivity fourfold [25]. Warm-season C4 grass is more efficient in nitrogen utilization at the leaf level compared to legumes; however, legumes usually have a competitive advantage in low-N environments due to biological nitrogen fixation [25,26]. However, the high cost of nitrogen fertilizers and increased awareness of the need for alternative sustainable nutrient sources have increased the strategic importance of biological nutrient fixation [27,28]. The productivity of pastoral ecosystems is highly dependent on the availability of soil nitrogen and/or the biological fixation of the atmosphere.

Two studies of Marandu grass intercropped with forage peanut (*Arachis pintoi* BRS Mandobi) under four management strategies with a 42-day fixed defoliation period and three light interceptions of 90%, 95%, and 100% were conducted. Both studies indicated that the management of an intercropping system must be in the range of 90% to 95% of light interception to be able to use the canopy height, which varied between 24 and 30 cm, and residual height of 15 cm was used as a practical measure [29,30]. In continuous stocking, a higher percentage of nitrogen was observed, which was derived from the atmosphere, and a greater amount of nitrogen from the biological fixation process of the peanut (*Arachis pintoi* cv. Belmonte) was obtained when pastures were grazed leniently/sustainably (heights of 15 and 20 cm [28]).

2.2. Role of Animals in Intensification Systems

Animal production systems are evaluated in terms of animal performance. Sustainable intensification in beef-cattle production can be evaluated in terms of determined results, such as animal slaughter age and carcass yield, which can be influenced by feeding behavior, animal performance, and animal adaptation to environmental conditions.

In Brazil, most animals reared in pasture systems are *Bos taurus indicus*, but some crossbred steers are also used [31]. Crossbred animals obtained higher overall animal performance than that of the purebred Nellore. These results demonstrated differences among breeds, but it should be considered that even inside a breed (e.g., Nellore), differing animal performance can be achieved (Table 1) [32]. Aiming for sustainable intensification by increased productivity [33], breed definition can improve beef-cattle productivity.

Growth in the Brazilian beef-cattle production industry that occurred after 1970 was mainly caused by the adoption of the Nellore–Cerrado–*Brachiaria* system [31]. In systems developed with this triple bottom, or in those just using Nellore cattle and *Brachiaria* pastures, forage intake is fundamental in maintaining daily weight gains. Animal intake is, in part, controlled by feeding behavior, and, therefore, understanding it in a grazing system could help cattle producers decide upon the management strategy to improve animal production. Adjustment of stocking rate is essential in the management of pastures to keep optimal grazing pressure and, consequently, higher animal gains [14]. Forage intake by animal grazing is restricted by forage availability. It was reported that ruminants tend to change their behavior to be more selective on pastures with a lower leaf–stem ratio, but this was compensated by increasing grazing times [37]. This behavior occurs with some boundaries; thus, the right stocking rate

adjustments are crucial in allowing sward structures with greater leaf–stem ratios for both short-term and total forage intake rates.

Table 1. Performances (average daily gain (ADG), kg BW d^{-1}) of Nellore cattle (purebred or crossbred) in different experiments during the rearing phase in systems developed with sustainable intensification and using a sward height of 25 cm on Unesp–Jaboticabal, SP, Brazil.

Sex	Suppl. Level [1]	Animal Breed [2]	ADG [3]	Author
Female	-	PB	0.731	[34]
Female	MM [4]	CB	0.490	[27]
Female	0.3	CB	0.665	[27]
Male	-	PB	0.600	[4]
Male	0.3	PB	1.150	[4]
Male	0.1	PB	0.844	[35]
Male	0.3	PB	0.940	[35]
Male	MM [4]	PB	0.854	[36]
Male	0.3E [5]	PB	0.920	[36]
Male	0.3EP [5]	PB	0.959	[36]
Male	0.3$_{DDG}$ [5]	PB	0.930	[36]

[1] % body weight (% BW), subscripts refer to experiment treatments; [2] PB—purebred, CB—crossbreed; [3] average daily gain (kg day^{-1}); [4] mineral mixture; [5] E—energetic, EP—energetic–protein, and DDG—dried distiller grains replacing traditional protein source.

Another important consideration in sustainable intensification systems is the use of supplemental cattle diets. The authors in [34] reported that supplementation reduced animal grazing activity and that it should be supplied during the hottest day to minimize pasture substitution effects. Supplementation can be used to optimize pasture use and maximize animal performance [38]. Thus, identifying the best day to supply extra feed can produce better results for all system variables (canopy structure, herbage allowance, and animal performance).

Total grazing time by ruminants is close to 8 h day^{-1} [39], but the forage digestion process and passage rate [40] are important factors that control its duration [35]. For example, total animal grazing time in a sustainable intensification system was decreased to around 6 h [35] due to forage nutritive value and allowance. Variation in short-term forage intake rate by grazing animals is more closely correlated with sward height than forage mass, and there is a stronger relationship between sward height and plant structure; however, optimal sward height does not necessarily give greater intake or higher individual animal performance [41].

Optimal sward height results in greater daily herbage intake and higher animal performance. Maximal short-term intake rate per unit of grazing time occurs at approximately 30% grazing efficiency, measured by the animals' total forage intake during a determined grazing time and correlated with forage accumulation [38,39].

As previously mentioned, systems are measured by animal performance, determined primarily by nutrient intake, which can be related to non-nutritional factors, including forage mass, sward height, herbage allowance, and nutritional value. The dry matter intake of grazing animals showed a curvilinear relationship controlled by non-nutritional and nutritional factors [40]. In the ascending part of the curve, the ability of the animal to harvest forage (non-nutritional factors) appears to be the most important in limiting intake. These factors include diet selection, grazing time, bite size, bite rate, and forage allowance. At the plateau or asymptotic section, nutritional factors such as digestibility, passage rate, and the concentration of metabolic products appear to be important in controlling intake.

Forage mass, herbage allowance, and forage nutritive value could represent variation in average daily gain (ADG) between 50% and 90%, dependent on specific conditions [38]. In order to ensure that forage quality and quantity are adequate for maintaining high ADG during the rainy season [4,14,35,41], good grazing management is necessary, and is a feature in sustainable intensification systems. Different beef-cattle intensification levels changed the animals' ADG (Table 1). Animals supplied

with just a mineral mixture during the wet season had an ADG of 0.490 and 0.854 kg day^{-1} for the previously mentioned studies, respectively. When supplemented at 0.3% body weight (BW), ADG reached 0.665 and 0.936 kg day^{-1} for Nellore heifers and young bulls, respectively (Figure 2) [10,14]. These intensification practices allow for achievement of ADG and gains per hectare in addition to decreasing methane emissions per unit of produced beef product [4,6].
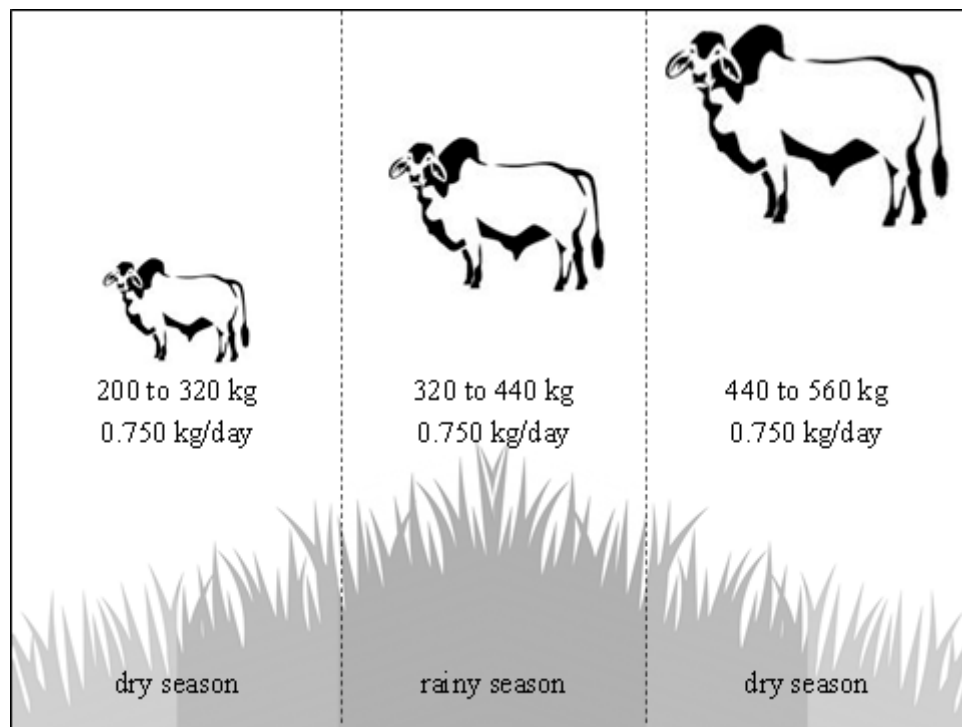

Figure 2. Illustration of production targets necessary to slaughter a young bull of 560 kg body weight and about 24 months of age. Source: Authors using public domain images (Google).

2.3. Role of Supplementation in Intensification Systems

Supplementation is used to intensify cattle production on grasslands to increase individual animal performance and productivity [4]. Productivity per area is the result of stocking rate and individual performance. Increasing stocking rate tends to increase productivity per area up to the point to which reduced available fodder limits forage intake and, consequently, reduces individual performance.

Under low-stocking-rate conditions resulting in high herbage allowance, animals can reach their maximal potential intakes and, consequently, their maximal individual animal performance, but a low stocking rate limits productivity per area. In the model of production proposed by [42], maximal productivity per area and maximal individual animal performance do not occur at the same stocking rate. In this way, the use of supplements provides production intensification by increasing dry matter and nutrient intake, and results in greater weight gain, even with a high stocking rate (Table 1).

In an increasingly competitive scenario with variations on inputs and prices of supplement formulations, such as maize, as well as the narrowing of the profit margin in livestock, the economic viability of adopting supplementation demands that its use results in additional gains. To do this, decisions on the formulation and the amount of supplement should consider aspects such as the chemical composition and availability of the basal diet, i.e., the forage [34]. Supplement composition should supply what is missing from the diet or add to feed intake [4]. Therefore, successful supplementation strategies require the following information:

(a)   What is the predicted performance (average daily weight gain)?
(b)   What is the nutritional requirement for the predicted performance?

(c)　　What is the estimated nutrient intake from the forage?
(d)　　What is the deficiency (what is lacking) in relation to the requirements?

The use of antimicrobial additives was developed to improve feed efficiency, and it is an option to intensify the systems. The most commonly used antimicrobial additives for grazing animals are ionophore antibiotics, such as monensin, lasalocid, and salinomycin, which result in the reduction of methane production [43]. The effects of ionophore monensin on rumen protein metabolism are mainly observed when true protein, peptides, and amino acids are used in supplements [44]. The reduction in rumen amino acid deamination caused by ionophores is more pronounced when the diet consists of forage with a high soluble protein fraction [45]. Thus, the effectiveness of ionophores depends on several factors, and may differ depending on the used doses.

Nonionophore antibiotics used for grassfed animals, such as virginiamycin and flavomycin, have been the focus of few studies; e.g., [46]. Like ionophore antibiotics, the results are controversial and depend on factors related to the consumed fodder and supplements. Despite occurring via a different mechanism from that of ionophore antibiotics, virginiamycin also inhibits the growth of Gram-positive bacteria [47].

The possible effect caused by the addition of live yeast is the removal of O_2 from the rumen environment, resulting from the consumption of water and feed and improving environmental conditions for the growth of strictly anaerobic bacteria. This may provide growth factors, such as B vitamins, for ruminal micro-organisms [33].

Natural additives, such as essential oils and tannins, also act to modulate the rumen environment and reduce risks to food safety. Essential oils are volatile lipophilic compounds derived from secondary plant metabolites, extracted by steam treatment or solvents [48]. These natural products appear to have greater effects on Gram-positive bacteria than on Gram-negative bacteria [49]. However, the interaction between compounds such as carvacrol and the cell membranes of Gram-negative bacteria can cause the loss of cell contents and cell lysis [50].

The effects of essential oils include a reduction in the proportion of acetate, an increase in propionate [51], and a reduction in rumen ammonia concentration [52], suggesting that they reduce amino acid fermentation. The inclusion of essential oils from cinnamon bark and oregano leaves in in vitro experiments resulted in reduced methane production and ruminal ammonia concentration [53].

Like essential oils, tannins are found in plants and have the potential to modulate ruminal fermentation. When consumed in high concentrations, and dependent on plant species, these compounds can cause negative responses in the acceptability of legume forages to grazers, but rarely browsers, and in the availability and utilization of nutrients [54]. Condensed tannins are water-soluble polyphenolic compounds with high molecular weights that may affect ruminal fermentation by reducing rumen protein degradation and methane production, and may improve weight gain [55].

However, hydrolyzable tannins have potential for use in the diet of ruminants in high-forage diets. The inclusion of 0.25% hydrolyzable tannins, 1.5% hydrolyzable tannins, the combination of 0.125% hydrolyzable tannins and 0.125% condensed tannins, and the combination of 0.75% hydrolyzable tannins and 0.75% condensed tannins resulted in the reduction of ruminal ammonia concentration, regardless of type or dose, without causing a reduction in animal performance [56].

Condensed tannin supplementation alters the *n* excretion pathway, increases fecal *n* excretion, and reduces urinary *n* excretion [57]. This process may reduce the environmental impact of ammonia volatilization, nitrous oxide (N_2O) emissions, and nitrate leaching (NO_3^-) because of the increased consumption of soluble protein [58].

Tropical forage legumes may be an alternative for improving protein intake in the rumen and for supplying condensed tannins to ruminants. *Stylosanthes capitate* and *Stylosanthes macrocephala* have condensed tannins that could be beneficial to cattle [59]. However, there are difficulties in the handling, logistics, and the high cost of forages or plants rich in these compounds that can be fed to the animals in a trough or administered in consortium with grass. In conclusion, costs should be accounted for to

assess whether tropical–forage–legume supply or condensed tannin supplementation is the best option to reduce environmental impact and increase n utilization efficiency in beef-cattle production systems.

2.4. Role of Fertilizers in Intensification Systems

n fertilizer application has significantly contributed to forage productivity in tropical regions [60–62]. Nitrogen addition can increase plant growth rate, resulting in higher forage production, augmented green leaf mass, and increased crude protein concentration, as well as affecting energy and protein digestibility in ruminants and, consequently, impacting feeding value, animal nutrition, and n excretion from urine and feces [63,64].

Studies of the most used tropical grass in the world (*Urochloa brizantha* cv. Marandu) observed a linear relationship between amount of n fertilizer and forage mass until an n rate of 270 kg N ha^{-1}; this was also observed with herbage accumulation, which increases from 30 to 90 kg dry matter ha^{-1} day^{-1}, varying from zero to 270 kg N ha^{-1} [5]. However, the effect of n fertilization on Brachiaria grasses maybe depend on other factors. A quadratic response was observed where maximum forage mass production was reached at 200 kg N ha^{-1} [65].

Nitrogen application has a direct effect on the proportion of forage true protein content. Increasing n fertilization from 0 to 400 kg ha^{-1} year^{-1} decreases the proportion of true protein from 90% to 70% [66]. n fertilization increases the fraction of soluble n because plant n uptake increases rapidly with increasing levels of n, thereby leading to a build-up of nonprotein organic n [67]. The proportion of n bound to the cell wall decreases with increasing n fertilization. The effect of n fertilization on fractions of plant n implies variation in n feed efficiency utilization by ruminants. Ammonia is completely soluble and quickly degraded in the rumen, while the n bound in plant cell walls is used by only a few rumen micro-organisms that degrade potentially degraded neutral detergent fiber fraction and, consequently, is scarcely used by the animal itself.

Application of phosphor (p) in grasslands enhances the efficiency of n utilization by forage plants. An increase in forage mass production of 3% to 5% was found [68]. The maximal increase in mass produced per kg of n fertilizer was observed at 150 kg N ha^{-1}. Production increased from 39 to 51 kg DM kg^{-1} N ha^{-1} when p application was doubled.

The effect of potassium fertilization on *Brachiaria* grass is positive. In the Cerrado region, an increase in forage production up to 25% was observed. This positive effect on herbage accumulation is due to the potassium functions of enzymatic activation of the photosynthesis processes. Response to K application depends on the soil n availability. Soil p content can also limit the efficiency of potassium fertilization in forage production [69,70]. Once tropical soils are more limited by p content than by K content, fertilization with K should be used after resolving the p limitation [71,72].

3. Environmental Aspects of Pasture Intensification

The adoption of sustainable intensification in livestock production in tropical grassland areas depends on the correct knowledge of greenhouse gas (GHGs) emissions. In grassland ecosystems, the main GHGs are CO_2, CH_4, and N_2O. Increases in the concentrations of these gases are responsible for increases in global average atmospheric temperature [66]. Grasslands occupy 30% of useful land on Earth, and play important roles in the production and consumption of these gases. Grasslands are responsible for 9%, 37%, 65%, and 64% of human-induced emissions of CO_2, CH_4, N_2O, and NH_3, respectively [73].

Carbon dioxide is produced in the soil through the oxidation of soil organic matter and the decomposition of organic material during root and micro-organism respiration [74]. CO_2 production during respiration is not considered a source of CO_2 responsible for global warming. In grassland ecosystems, environmentally damaging CO_2 emissions occur when pasture degradation takes place and with land use changes [75]. Soil carbon sequestration in grazing systems is one strategy, with a global mitigation potential of 37–800 Mt CO_2 yr^{-1} [69]. However, it is time-limited and reversible.

Several studies in Brazil have shown that soil carbon stocks decrease with conversion of Brachiaria pastures to cropland. The magnitude depends on soil and crop type, varying from 0% to 30% [76–78].

Methane is emitted from the soil, especially in flooded areas, decomposing manure, and during the enteric fermentation of feeds by ruminants [79]. Methanogenic micro-organisms produce CH_4 in anaerobic grassland soils. Feces from animals contain fermentable carbohydrates that are used by microbes that produce CH_4 [80]. The main factors affecting CH_4 production in grassland soils and from animal feces are soil moisture, temperature, and compaction [80,81], while the amount of feces, n content, and soil pH have minor impact [21,82]. The amount of CH_4 derived from feces in *Brachiaria* grasslands has been estimated to vary from 0.15 to 0.95 kg animal^{-1} year^{-1} [83,84].

Tropical grasslands could be a big CH_4 sink [24]. CH_4 emissions were measured from tropical grassland soil managed under different canopy heights for two years. The authors observed CH_4 production and sequestration, but when the data were integrated over the period, grassland soil could not be considered a source or sink of CH_4 [85]. These results are in line with [18,86], which also found that grassland soil was not a source of CH_4.

In the rumen, CH_4 is produced during feed fermentation [87]. Fiber degradation by micro-organisms produces hydrogen ions that are used by methanogenic micro-organisms to produce CH_4. This mechanism is essential in sustaining digestion. If H^+ ions are not removed, ruminal pH decreases, and the occurrence of acidosis increases [87]. There are several studies on tropical grasslands investigating options to mitigate enteric CH_4 emissions using essential oils, supplements, and additives. Although enteric CH_4 is the most important greenhouse gas (GHG) to be considered in a project of grassland intensification, there are few studies that compare emissions from different grassland management techniques, plant species, and seasons of the year. One study that measured enteric CH_4 from bovines consuming only Marandu grass found that enteric CH_4 averaged 132 g day^{-1}, and 7.6% of gross energy intake was lost [11]. This is close to values reported by the Intergovernmental Panel on Climate Change (IPCC), with an emissions factor of 149 g day^{-1} and losses of 6.5% of gross energy intake [88].

Nitrous oxide is emitted from animal excretions and n fertilization. According to the Intergovernmental Panel on Climate Change (IPCC), default emission factors, i.e., the percentage of n applied, excreted, or emitted as N_2O, are 2.00% from excreta, from which n is emitted as N_2O, and 1.00% from n fertilizer [88]. However, these emission factors do not consider the types of excreta, climate, soil, grassland species, or other variables. Several studies on temperate grasslands, e.g., [89], and on tropical grasslands showed that urine is the main source of N_2O. Nevertheless, estimated emission factors hugely vary [63,83,84]. In subtropical pastures, a mean emission factor of 0.26% for urine and 0.15% for dung was reported [84]. In tropical savanna (Cerrado) regions, a mean emission factor of 0.70% for urine and 0.10% for feces was observed [90]. In addition, it was found that emission factors vary according to type of excretion; there is an interaction between feces and urine when they are excreted in the same patch, and emissions are much higher during the rainy season than the dry season [86]. The study found mean emission factors of 0.34%, 0.75%, and 0.59% for feces, urine, and interacting feces and urine, respectively. In both studies, the animals were grazing *Brachiaria* grass [65,86].

Few studies have been carried out on N_2O emissions caused by tropical grassland n fertilization. For synthetic fertilizer (urea), an emission factor of 0.85% from n applied in this form was found [90]. For organic fertilizer, N_2O emissions were measured from three sources of biofertilizer and compost applied to a grassland. The authors did not find differences in emissions in these organic fertilizers, and the average emission factor was 0.18%, five times lower than the value reported in [83,91,92].

Increasing grazing intensity results in strong elevation in grassland N_2O emissions. This occurs because artificially increased n is returned to the soil via excreta, and because soil compaction, which occurs due to increases in animal stocking rate, lowers n uptake by plants. Thus, heavy defoliation through high stocking rates can lower plant n uptake capacity, decoupling C and n [13]. The main variables driving N_2O emissions in tropical areas are n concentration in urine, soil moisture,

urine volume, and temperature [13,92–94]. Thus, the success of intensification in terms of mitigating N_2O emissions should diminish animal excretion via urine and consider using alternative *n* fertilizer sources, such as biofertilizers.

Ammonia (NH_3) volatilization is a major constraint on *n* fertilizer utilization in grasslands. When fertilizers are applied, substantial amounts of *n* can be lost. According to the IPCC, 20% of *n* fertilizer is lost as NH_3 to the atmosphere. Furthermore, 1.00% of this *n* is indirectly emitted as N_2O [88]. Ammonia losses from three nitrogen sources (urea, ammonium nitrate, and ammonium sulfate) at different levels of *n* fertilization (90, 180, and 270 kg N ha^{-1}) in *Brachiaria* pastures were measured in central Brazil [55,95]. For urea, the percentage of *n* lost varied from 11% to 47% of applied *n*; for ammonium nitrate, this ranged from 2% to 5%; and for ammonium sulfate, the amount of lost *n* was between 2% and 7%. Despite urea being the cheapest source of *n* in Brazil, it may be that *n* losses and the environmental impact justify the utilization of other *n* sources.

The carbon footprint of beef-cattle intensification was analyzed for central Brazil [96]. The authors calculated carbon footprints of 58.3, 40.9, 29.6, 32.4, and 29.4 kg COeq kg^{-1} carcass for extensive, semi-intensive, intensive with legumes, intensive, and intensive with finishing phase in feedlot systems, respectively. Increases in calving rate and reductions in slaughter age were the main reasons for reductions in carbon footprint. The cow-calf phase contributed more than 50% of emissions, and it is that phase that requires the most improvement in beef-cattle production systems to reduce their carbon footprint.

More complex management strategies (grassland intensification) also show promise in increasing soil C in tropical grasslands. Productive *Brachiaria* pastures have the potential to accumulate soil C in tropical climates [97,98]. The amount of soil organic C (SOC) is dependent on the deposition rate and decay rate of plant residues. In the case of grasslands and natural vegetation, soil stays largely physically undisturbed. Consequently, pasture residues derived from the aerial tissue are not incorporated into the soil bulk unless by action of soil fauna [99].

The effect of pasture management on SOC stocks in grasslands of the western Amazon was evaluated [76]. In this work, they 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 Oxisols by a factor of 0.99, whereas SOC storage increased by a factor of 1.24 with nominal management in other soil types. In Oxisols, 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 [76]. Therefore, the adoption of nominal or improved management practices could result in carbon sequestration in existing degraded pastures within the Amazon.

When evaluating soil C stocks in native Cerrado vegetation (Brazilian savannas), productive pastures, and degraded pastures, the study found that SOC stocks were greater in productive pastures than in native vegetation, and that C stocks in degraded pastures were intermediate or very similar to native vegetation stocks. The study confirmed that productive *Brachiaria* pastures increased soil C stocks compared to those present in native Cerrado vegetation [75].

Integrated crop–livestock systems are promising strategies for beef-cattle intensification [9]. Changes in soil organic carbon for over 22 years for pastures, cropping systems, and integrated crop–livestock systems in the Brazilian Cerrado were measured. It was found that pasture SOC stocks changed little during the study period. Continuous cropping without tillage preserved SOC, but when plow tillage was performed, there were significant reductions in SOC. In most of the studied integrated crop–livestock systems, SOC accumulation occurred. However, changes were modest; ^{13}C abundance analysis revealed that fertilizer inputs increased the decomposition rate of C derived from native vegetation in pastures [77].

The overall change in soil organic matter stocks was estimated 16 years after pristine forest vegetation in southern Bahia was removed and replaced with *Brachiaria brizantha* pastures. The authors observed gains in soil C of approximately 15 Mg C ha^{-1} to a depth of 30 cm, and 20 Mg C ha^{-1} to a depth of 100 cm. On the basis of ^{13}C abundance analysis, they concluded that the large gain in soil C was due to the slow decomposition of forest-derived C and the large accumulation of C derived from *Brachiaria* [98].

Potential increases in SOC can be optimized by introducing legumes into *Brachiaria* pastures. The inclusion of legumes supplies *n* to pastures via biologically fixed N$_2$, avoiding the economic constraints of *n* fertilizer application, and it could potentially increase SOC compared to pure grass pastures [99]. Indeed, soil C accumulation is enhanced by soil fertility and mainly by *n* fertilization [100]. Despite the works cited above, there is a lack of data on the potential of grassland soil to accumulate C from the most fertile soils of Brazil, which are found in the states of São Paulo and Paraná.

4. Conclusions

The intensification of *Brachiaria* grasslands is an important alternative for reducing GHGs and increasing the environmental, economic, and social benefits of grassland utilization. However, growing costs and environmental concerns regarding *n* losses challenge animal nutritionists and forage specialists to develop grazing systems that optimize *n* utilization.

Recent studies in tropical regions did not find any effects of grazing management or supplementation on enteric CH$_4$ [4,6,92], and energy losses are close to those stated by [88]. Further research should focus on reducing N$_2$O emissions and NH$_3$ volatilization. Urine was confirmed as the main source of N$_2$O. Therefore, nutritionists should seek strategies that reduce *n* excretion via urine or that shift the *n* excretion route. With regard to *n* fertilization, research should focus on quantifying emissions from different sources of *n*. It is necessary to measure the impact of sources, levels, time of application, and period of fertilizer application on N$_2$O emissions and NH$_3$ losses in tropical grasslands to better assess strategies to mitigate this impact.

Tropical grassland soils have higher potential to stock C than that of current levels, as is mentioned above. The effects of intensification, fertilization, grazing management techniques, different forage species, and soils on litter deposition and decomposition need to be measured. The introduction of legumes into forage systems has the potential to increase and sustain soil C stock. However, this needs to be confirmed in tropical grasslands, and technology needs to be developed for successful commercial establishment.

To achieve the benefits of sustainable intensification, one option that was investigated and proved to be viable is managing Marandu grass at a sward height of 25 cm in a continuous stocking system with a variable stocking rate (3–6 animal units of 450 kg BW). The best levels of *n* that resulted in the highest forage yield and animal performance and the lowest GHG emission intensities varied from 90 to 180 kg N ha^{-1} with split application during the growing season [4,5,13]. However, this review only considered urea as a source of *n*, and further studies should measure whether the same conclusion would be met for other sources of *n*.

Further studies should also focus on inedible byproduct use in the supplementation of beef cattle during the rearing and finishing phases, which appears to be an important strategy in sustainable livestock intensification. The supplementation of grazing animals increases weight gain per animal and area, reduces deforestation for pasture formation, and decreases competition for human food.

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