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Review

Ruminant Grazing Lands in the Tropics: Silvopastoral Systems and *Tithonia diversifolia* as Tools with Potential to Promote Sustainability

Ana Maria Krüger [1], Paulo de Mello Tavares Lima [1,2,*], Vagner Ovani [1], Simón Pérez-Marquéz [1,3], Helder Louvandini [1] and Adibe Luiz Abdalla [1]

1 Centro de Energia Nuclear na Agricultura, Universidade de São Paulo Av. Centenário, 303, Piracicaba 13400-970, SP, Brazil; anakruger@usp.br (A.M.K.); vagnerovani@usp.br (V.O.); simon.perez-marquez@rothamsted.ac.uk (S.P.-M.); louvandini@cena.usp.br (H.L.); abdalla@cena.usp.br (A.L.A.)
2 Department of Animal Science, University of Wyoming, 1000 East University Avenue, Laramie, WY 82071, USA
3 Rothamsted Research, North Wyke, Okehampton EX20 2SB, UK
* Correspondence: pdemello@uwyo.edu

Abstract: Food security, sustainability of food production, and greenhouse gas (GHG) production of ruminant livestock are topics that generate scrutiny and debates worldwide. In a scenario of increasing human population and concerns with climate change, it is necessary to increase animal-derived food in sustainable operations. Grazing systems are crucial for ruminant production worldwide, and in the tropics, well-managed grasslands can provide sustainable intensification of this activity. In these regions, production often relies on grass monoculture managed extensively, a practice that commonly has led to the occurrence of degraded soils, limited animal productivity, and increased intensity of GHG emissions. Silvopastoralism is a practice that promotes several ecosystem services, showing potential to maintain soil quality while reducing the environmental impacts of ruminant production. These systems also have the potential to improve animal productive performance and reduce GHG emissions. The review was guided by a search in the Web of Science database using population terms and refined by document type (Article) and language (English OR Portuguese) following PRISMA protocol. Infographics were created using the Bibliometrix package in R software (version 4.3.2), and a specific topic on *Tithonia diversifolia* (Hemsl.) A. Gray was explored to demonstrate the importance of this forage resource for tropical silvopastoral systems and its potential contribution to food security. The *T. diversifolia* shrub is widely distributed in Latin America and tropical regions and presents several characteristics that make it a good option for silvopastoral systems. Focusing on the tropics, our objectives were to present one literature review addressing the role of grazing ruminant production towards the current climate change and food security challenges. Additionally, we aimed to explore the state of knowledge on silvopastoral systems and the use of *T. diversifolia*, presenting their potential to cope with this scenario of increased concerns with the sustainability of human activities.

Keywords: food security; grasslands; greenhouse gases; methane; shrubs

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Citation: Krüger, A.M.; Lima, P.d.M.T.; Ovani, V.; Pérez-Marquéz, S.; Louvandini, H.; Abdalla, A.L. Ruminant Grazing Lands in the Tropics: Silvopastoral Systems and *Tithonia diversifolia* as Tools with Potential to Promote Sustainability. *Agronomy* **2024**, *14*, 1386. https://doi.org/10.3390/agronomy14071386

Academic Editors: Renata La Guardia Nave and Martin Gierus

Received: 16 April 2024
Revised: 23 May 2024
Accepted: 25 June 2024
Published: 27 June 2024

1. Introduction

Grasslands are among the largest and most crucial ecosystems globally, serving as a primary pillar for human population development, particularly by supporting grazing ruminants' production [1]. Increased demand for animal food products, including milk and meat, is expected in the next few years due to a growing global population and changing dietary habits in many countries worldwide. Consequently, this trend will likely result in a greater demand for limited resources, such as land, fuel, water, and minerals [2]. Considering these factors, enhancing the production levels of animal food products is necessary to meet these higher demands. However, at the same time, greenhouse gas (GHG) emissions from livestock production are identified as primary anthropogenic sources contributing to climate change. Enteric methane (CH_4) accounts for about 40% of emissions from the sector [3], with a global warming potential 25 times greater than that of CO_2 [4]. In addition to its environmental impacts, CH_4 production may be equivalent to a 2–12% loss of dietary gross energy [5], representing a limiting factor to animal productive performance. Therefore, achieving higher production should involve using sustainable practices, commonly referred to as sustainable intensification, to ensure that ruminant livestock production remains a feasible activity for both population and the planet [6,7].

The productivity (in terms of quality and quantity) of tropical grasses, the primary nutrient source for ruminants in the tropics, is often reduced during severe climatic conditions, leading to fluctuations in animal performance throughout the year. Various approaches to overcome this situation and maximize productivity in these grazing systems have been documented in the literature [1,8]. More recently, the use of trees or shrubs in grazing systems, an agroforestry practice named silvopastoralism, is gaining attention as a practice capable of providing benefits to forage production, animal performance, and the environment. Therefore, it represents a tool with the potential to enhance sustainability in tropical grazing systems [9,10].

Tithonia diversifolia (Hemsl.) A. Gray is a shrub species native to Central America but widespread in tropical and subtropical regions across the globe, showing promising potential for use in silvopastoral systems [11,12]. Compared to other tropical forages, *T. diversifolia* demonstrates greater crude protein (CP) and phosphorus content, maintaining a relatively stable nutritional value even during dry seasons while exhibiting tolerance to acidic soils and moderate to low water and fertilization demands [11,13,14]. Indigenous populations have traditionally used this plant for treating various diseases due to the presence of bioactive secondary compounds [15]. These compounds also influence ruminal fermentation, potentially reducing CH_4 emissions [11,16].

Given the characteristics of silvopastoral systems and *T. diversifolia*, as well as the relative novelty of both topics, it is evident that more comprehensive assessments of these in ruminant production, along with accurate analyses of the available data, are needed for the consolidation and elucidation of silvopastoralism and the use of this forage as a viable option for farmers in tropical regions to improve system productivity sustainably. Therefore, the objectives of the present review were to provide an overview of the role of grazing ruminant production towards the scenario of climate change and food security challenges as well as fundamental key aspects of the existing knowledge and potential impacts associated with the utilization of silvopastoralism in this context, with a specific focus on tropical systems and the utilization of the tropical shrub *T. diversifolia.*

2. Ruminant Production and Food Security—A Brief Overview

The food production sector is facing a challenging moment worldwide due to the increased number of people with inadequate access to nutritious diets, presenting insufficient daily intake of nutrients such as carbohydrates, proteins, and fats, leading to vitamin and mineral deficiencies. Simultaneously, issues like obesity and type two diabetes, which pose significant risks to human health, are increasingly prevalent in society [17,18]. Concurrently, there is a growing concern regarding the environmental impact of human activities. The livestock production sector is particularly noteworthy in this aspect, often cited as one of the primary contributors to these harmful effects on the environment [19,20]. Animal husbandry is identified as responsible for 14.5% of total anthropogenic GHG emissions in the atmosphere, with a very significant portion of these emissions, as mentioned earlier, being represented by the enteric CH_4 that arises from the fermentative process in the gastrointestinal tract of ruminants, serving as a byproduct from their feed digestion, especially structural carbohydrates [3,21]. However, products such as meat and milk obtained from ruminants can be part of well-balanced diets for humans, providing essential macro and micronutrients, including proteins, fatty acids, vitamins A, B12, calcium, iron, zinc, and others, contributing significantly to promoting health in the population and reducing the occurrence of several illnesses [18,22,23].

The world's population growth, coupled with changes in the profile of societies such as increased average income and more widespread dissemination of the western lifestyle, leads to the estimation that the demand for animal food products will be 70% higher in 2050 relative to 2010 [2,24]. Ruminant production stands out in this scenario, as these animals can be reared on non-arable lands, consuming fibrous feedstuff to produce high-quality protein food, contributing significantly to achieving food security without relying on grains and other cereals that could be used in the human diet [6,25,26]. According to the Food and Agriculture Organization of the United Nations (FAO), food security entails "access to sufficient, safe, nutritious food to maintain a healthy and active life". Therefore, sustainable ruminant production should be crucial in meeting the increasing demand for food in human society while simultaneously achieving the targeted reductions of anthropogenic GHG emissions, frequently a focal point of discussion in climate-related scientific conferences [18,21,25,27].

Despite these facts, some scientists still propose a drastic reduction in the number of ruminants as a solution to avoid a climatic disaster [28]. However, the feasibility of this option must be analyzed in a broader context, considering the previously highlighted benefits that ruminant livestock production generates and the fact that livestock grasslands ecosystems support the livelihood of millions of people worldwide, providing economic goods and social-cultural services to these populations. Additionally, grasslands offer ecosystem services such as soil protection, maintenance of groundwaters quality, and climate regulation through carbon (C) sequestration, representing 25% of global soil sequestration potential [1,29–31].

Aiming for sustainability, ruminant production in pastoral systems should prioritize society's economic, environmental, social, and cultural demands. Productivity and the mitigation of GHG should serve as guiding principles to prevent ecological issues such as increased emissions and soil C loss, as well as shortage or unaffordable prices of animal food products [30]. Tropical grasslands are renowned as biodiversity hotspots, hosting several endangered species and serving as a pillar for environmental preservation [32]. As previously mentioned, tropical grasses are frequently susceptible to quality oscillations due to climatic factors, especially during dry seasons, when the plant may exhibit reduced CP content and increased structural carbohydrates, resulting in diminished productivity and increased GHG emissions per unit of generated product (i.e., GHG emissions' intensity) [33,34]. The use of silvopastoral systems by intercropping tropical forage grass species with native C_3 trees and shrubs is considered a management practice with potential to address the variation in forage productivity, as the presence of these trees and shrubs can enhance the system's resilience to extreme climate conditions, particularly during dry seasons, and contribute to increased biomass production, enhancing nutritive value of forages in such pastures, potentially resulting in a reduced intensity of CH_4 emissions [10,35].

3. Silvopastoralism in Ruminant Production

Due to increasing demand for animal products, especially in developing countries (which are mostly located in the world's tropical regions, particularly in Latin America), deforestation has occurred in order to expand pasture areas to support the growing requirements for higher animal production, since deforestation costs are usually lower than those associated with production intensification [36]. Approximately 70% of agricultural land is used for livestock production in the tropics. Pastures on these farms are commonly based on grass species cultivated in monocultural extensive systems, in which inadequate management practices often lead to issues like overgrazing and reduced soil productive potential, affecting animal performance and eventually leading to increased environmental impacts of the activity. Additionally, modest stocking rates are often observed, reducing productivity per land area [37,38]. Furthermore, the intensive use of inorganic fertilizers and biocides has diminished soil surface cover and destroyed crucial microbial communities responsible for soil ecosystem functions, contributing substantially to the deterioration of the physical, chemical, and biological properties of the soil [30]. Recognizing such factors has accelerated efforts towards sustainable intensification, which aims at increasing product generation per unit of area while simultaneously reverting soil degradation and enhancing ecosystem services [36].

The conscientious management of ruminants in agroforestry systems, particularly in silvopastoral systems which involve utilizing land for both forest products and animal production through the browsing of shrubs and trees and/or grazing of co-existing forage crops can significantly mitigate the ecological challenges posed by ruminant production systems [9]. Several tropical regions have implemented silvopastoral systems, reporting numerous benefits. To enhance our understanding of the current scenario regarding the utilization of these systems and the primary effects of their adoption, we conducted a brief systematic review following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) [39] guidelines. The Web of Science electronic database platforms were utilized to find papers using search population terms (i.e., TS = (silvopastoral OR silvipastoril OR silvopasture OR silvopastoralism)), refined by document type (i.e., Article) and language (i.e., "English" OR "Portuguese"). Intervention, comparison, and outcome terms were not used since the objective was to obtain an overview of the silvopastoral systems-related aspects being researched. The timeframe was extended until 5 March 2024.

This search yielded 1603 documents exported to BibTeX for evaluation through the Bibliometrix package [40] using R version 4.3.2 [41]. Over the last 8 years, we observed an exponential increase in published works on silvopastoral systems, reaching the highest number of documents published per year in 2022 (Figure 1C).

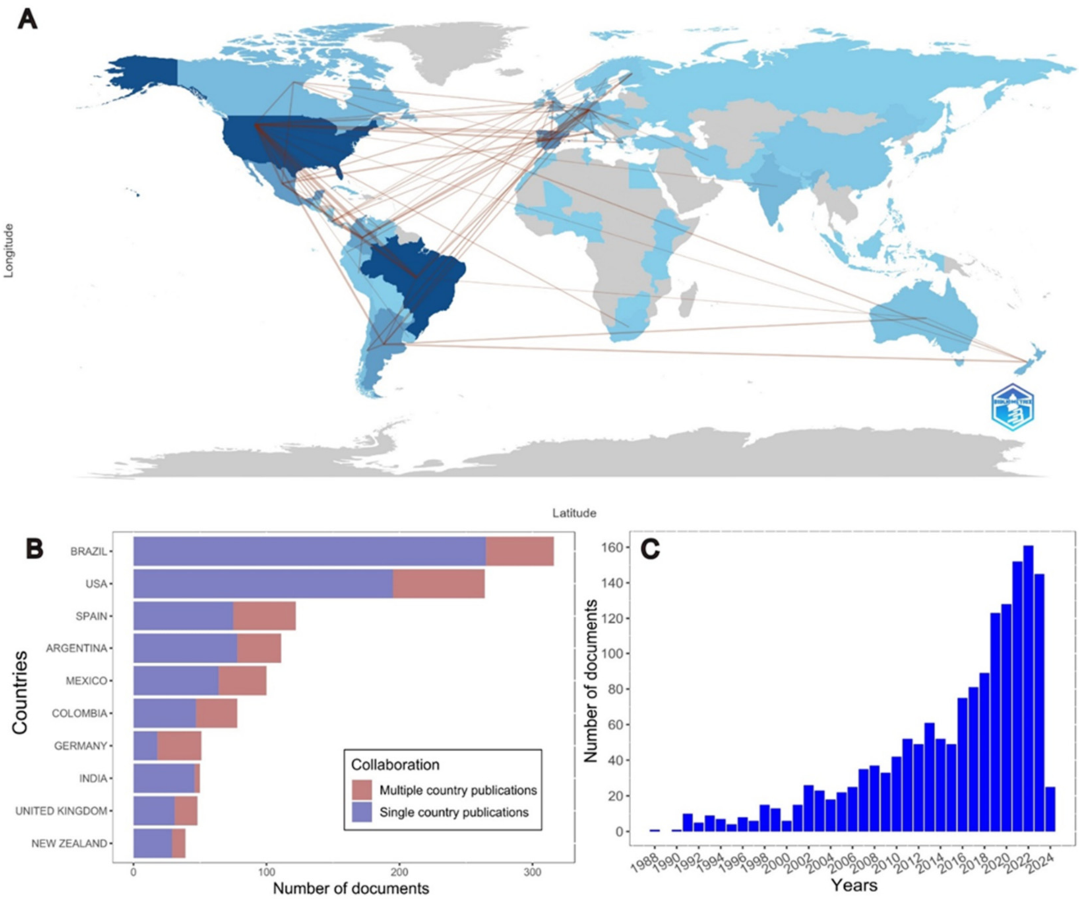

Figure 1. Country collaboration map (lines connecting countries indicate collaboration between themselves) (**A**), most relevant countries per corresponding's authors (**B**), and annual total scientific production (**C**).

When evaluating the corresponding authors' data, it is evident that Brazil and the United States of America (USA) are the two countries that contribute the most to research in this area, respectively (Figure 1B), followed by Spain, Argentina, Mexico, and Colombia. This pattern influences the collaboration map, revealing a solid connection between Brazil, the USA, and other countries in South America, Central America, and Europe (Figure 1A).

The substantial number of studies on silvopastoral systems in South, Central, and North American countries was expected, given that many of these nations widely adopt ruminant production practices in pastures, including extensive tropical regions. For example, Brazil, with approximately 239 million hectares of agricultural land, and the USA, with about 405 million hectares, feature extensive permanent meadows and pastures covering around 173 million and 245 million hectares, respectively. Similarly, Argentina, Mexico, and Colombia, with agricultural land areas of around 117 million, 97 million, and 42 million hectares, respectively, each have substantial coverage of permanent meadows and pastures, approximately 74 million, 74 million, and 38 million hectares, respectively [42].

To comprehend the benefits of adopting silvopastoral systems, we analyzed the first 40 most frequently used keywords from these 1603 articles in a word cloud (Figure 2). Among the prominently featured words, in addition to "silvopastoral system", are "forage production", "management", "pastures", "carbon (C) sequestration", and "nutritive value", along with terms related to climate change, biodiversity, and ecosystem services.

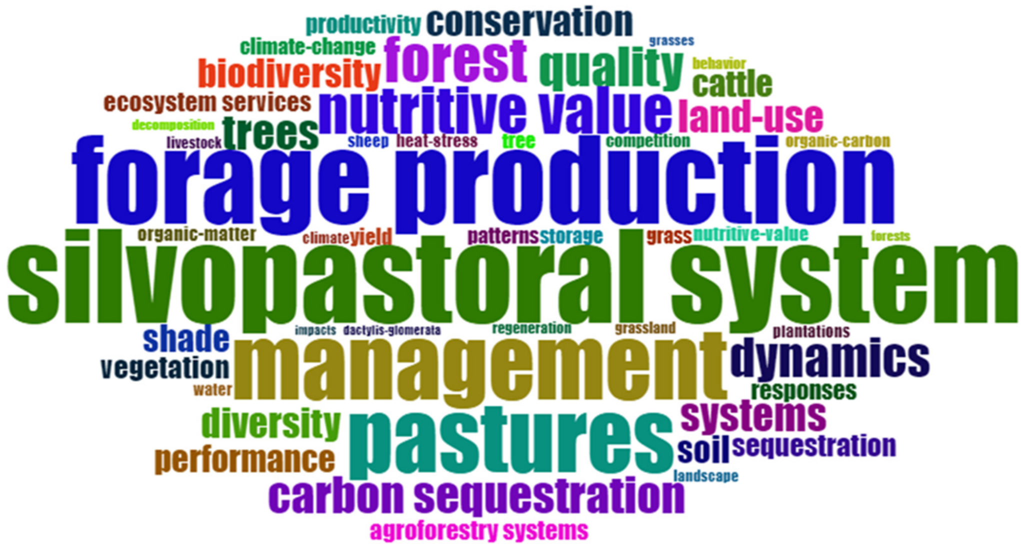

Figure 2. Word cloud of the first 40 author's keywords.

Figure 3 was also derived from the author's keywords, with clusters formed on the X and Y axes. The *X*-axis signifies centrality, providing information about the importance of a theme, while the *Y*-axis symbolizes density, serving as a measure of the theme's development [43]. Consequently, four quadrants are formed: the motor themes (well-developed and crucial for structuring the research field), the niche themes (of limited importance for the field), the emerging or declining themes (weakly developed and marginal), and the basic themes (concerning general topics transversal to different research areas within the field) [43]. We observe that the motor themes for silvopastoral systems studies have been associated with C sequestration, and keywords focused on nutritive value, such as crude protein and digestibility. Additionally, other terms related to forage, such as grazing and leaf area index, are prominent. Meanwhile, basic and well-developed themes like soil fertility, greenhouse gases, animal welfare and behavior, shade, and forage production are highlighted in the fourth quadrant.

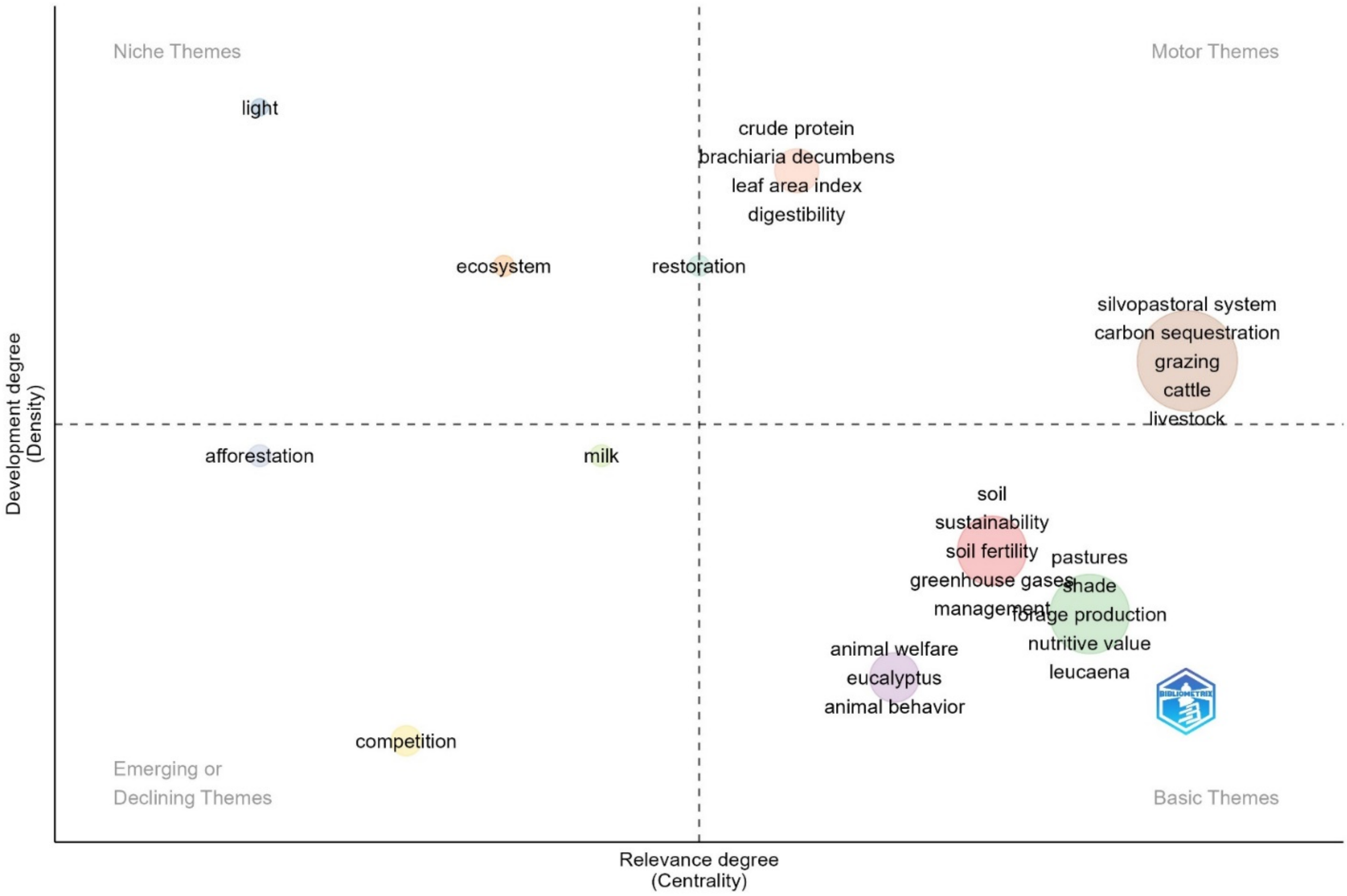

Figure 3. Thematic map showing clusters by the author's keywords.

The impact of silvopastoral systems management on forage production and nutritive value has been extensively studied [44–46], and the primary factor analyzed in these parameters has been shade and its effect on forage production and nutritive value [47–49]. Generally, the main impacts of excessive shade include increased in fiber content due to plant etiolation and enhanced lignification in the pursuit of vertical growth in competition for light [45,50]. However, benefits are observed in low to moderate shade, with forage production similar or superior to plants grown in full sun, presenting better nutritive value with enhanced crude protein content due to delayed maturity and reduced senescence rates [51,52].

Studies have reported that silvopastoral systems may enhance C sequestration in soil [53–55], which may be attributed to increased abundance of microbial species, improved soil nutrient cycling and stability, enhanced watershed function, more abundant biodiversity and wildlife habitat while simultaneously achieving higher levels of healthy food production [30]. Additionally, most tropical grass species use the C_4 photosynthetic pathway, resulting in higher rate of lignin deposition and reduced digestibility and voluntary feed intake, especially during periods of scarcity, such as dry seasons [34,56]. In silvopastoral systems, animals can use foliage, pods, and even fruits from trees or shrubs as feed complementation, helping overcome feed shortages in critical periods [10,57].

Moreover, pastures in such systems exhibit increased productivity. They can influence grazing area microclimate parameters, providing reduced temperature, and increased humidity, benefiting animal behavior, and allowing for extended grazing periods due to more favorable environmental conditions [58,59]. In a silvopastoral system with *Andropogon gayanus* grass pasture cultivated alongside native trees in the northeast region of Brazil, Zambrano et al. [60] observed that Anglo-Nubian goats dedicated more time to grazing than animals in an *A. gayanus* monocultural system. These authors also noted increased forage biomass production and reduced environmental temperature in the silvopastoral system compared to the monoculture. Another benefit of silvopastoral system for animal production is the increased shade area in pastures due to the presence of trees, mitigating heat stress in grazing animals, especially in regions with hot climates, as frequently observed in tropical and subtropical countries of Latin America [48].

Using an in vitro fermentation system, Ovani et al. [61] assessed the inclusion of *Chloroleucon acacioides* tree fruits in tropical grass-based diet substrates. These authors observed greater estimated microbial biomass production and short-chain fatty acids synthesis, associated with increased organic matter degradability in treatments containing *C. acacioides* fruits compared to the control treatment consisting of 100% tropical grass hay. Furthermore, the authors highlighted the potential for incorporating this tree species, native to the Brazilian Amazon, into tropical grass pastures, as its fruits can serve as a nutrient source for animals during periods when forage quality and biomass production are reduced, such as in dry seasons.

A widespread beef cattle management in many parts of the world is to raise animals on a continuously grazing system, and then, for finishing stages, the animals are taken to feedlot systems and fed on grain-based diets so they can increase their weight faster and be ready for the market. Usually, this practice is associated with lower GHG emissions per unit of generated product since lower overall time is required from rearing to slaughter. However, this kind of statement does not consider all the emissions generated by feedlot operations, including those of grain crop production or machinery utilized in such management, a factor that usually underestimates GHG emissions from feedlot systems [30]. Undoubtedly, standard grain production practices can be changed and more regenerative, reducing its overall emissions and impacts. However, in addition to the C sequestration potential that well-managed grazing systems present, grazing is a natural behavior for cattle. Consequently, pastoral systems provide an opportunity for increased welfare conditions for these animals [29,62]. In addition to the ecosystem services that conventional grazing systems can provide [36], in silvopastoral, trees and shrubs by-products can be a source of phenolic compounds that interfere both positively or negatively with feed intake and digestibility [10], and several of these plants, especially those containing tannins, offer a range of benefits, including the increased flow of dietary amino acids to the small intestine, control of gastrointestinal nematodes infections, reduction of bacterial loads in feces, decreased occurrence of frothy bloat in animals consuming legume forages, and mitigation of enteric CH_4 production during ruminal fermentation, characterizing one of the most prominent benefits of silvopastoralism considering all the concerns about ruminant production in a climate change scenario [34,63–66]. Albores-Moreno et al. [67] used an in vitro system to evaluate the impacts of tree foliage consumed by cattle in Mexico on ruminal fermentation parameters. These authors reported reductions in CH_4 production of up to 31% when diets were supplemented with 300 g/kg DM of foliage in substrates in relation to the control treatment, containing only tropical grass forages; in this study, the authors highlighted that the presence of condensed tannins could be one of the possible explanations for such reductions.

Soltan et al. [68] fed Santa Inês sheep with a tropical-grass-based diet supplemented with *Leucaena leucocephala*, a tannin-containing legume tree/shrub used in silvopastoral systems in Latin America [69]; these authors observed reduced CH_4 emissions when compared to the control diet, with no supplementation. In addition to a direct reduction of CH_4 production in the rumen, dietary tannins may also lead to reduced emissions of another important GHG: some tannins may form complexes with dietary protein, increasing their flux and absorption in the small intestine and also shifting the excretion of nitrogen (arising out of these proteins) from urine to feces, which can be an advantage in terms of nitrous oxide (N_2O) emissions, since fecal nitrogen is in its organic form and less prone to volatilization, while urinary nitrogen is mostly urea, which can be easily converted into N_2O [70,71].

Silvopastoral systems using legume trees or shrubs can benefit from the ability of these plants to do biological atmospheric nitrogen fixation. This process leads to increased inputs of this element into the soil, reducing the need for nitrogen fertilization [72]. Nitrogen fertilization is a chief source of N_2O emissions from agriculture since microbial processes that nitrogen goes through in the soil, especially nitrification and denitrification, lead to the production of this gas. In addition to direct emissions from the application of fertilizers, it is also necessary to consider emissions deriving out of nitrogen that lixiviates from agricultural fields that may also lead to N_2O emissions [73]. Therefore, the presence of legumes in silvopastoral systems may provide this additional benefit concerning GHG emissions and production sustainability.

4. *Tithonia diversifolia* and Sustainable Ruminant Production

As previously observed in this review and highlighted by other authors [74–76], many tree and shrub species can be used in silvopastoral systems, including both cultivated and native plants. One such shrub species is *T. diversifolia*, known as titonia, botón del oro, Mexican or wild sunflower. Belonging to the Asteraceae family, *T. diversifolia* originates from Mexico but has now spread widely across the humid and sub-humid tropics in Central and South America, Asia, and Africa [77,78]. It typically grows between 1.5 to 4.0 m tall, presenting leaves with serrated edges and peduncles ranging from 5 to 20 cm long, with yellow inflorescence [79]. Among the forage options for tropical silvopastoral systems, *T. diversifolia* presented characteristics such as high CP compared to tropical grasses, good adaptability to harsh environmental conditions, high biomass production, and have led to increased volatile fatty acids production and microbial protein synthesis on in vitro trials, characteristics that made this plant stand out as a promising option for such systems [14,77,80,81].

In the African continent, a study was conducted to verify the biomass production of *T. diversifolia* under different pruning practices, with the idea of using residues from pruning as natural fertilizer for the soil [82]. The authors observed that adopting a cutting height of 50 cm above soil on a bi-monthly frequency could lead to an annual DM production as high as 7.2 t ha^{-1}, which makes evident how productive and effective this forage can be in providing available biomass for grazing ruminants. This author highlighted that productivity numbers may vary according to region.

Also, given the fast decomposition of *T. diversifolia* plant material and its ability to mobilize soil phosphorus, it is a good option for green fertilizer. The high productivity of this plant, combined with its adaptability to various environmental conditions, makes it easy to grow and spread. Consequently, it is often considered an invasive species in both agricultural and non-agricultural lands, being commonly observed in marginal areas along roads or crop fields, not requiring great soil fertility and demonstrating good tolerance to acidic soils and short periods of drought, the later due to its longer roots compared to grass forages, allowing it to explore deeper soil profiles in search for water and nutrients [38,83–85].

A significant number of studies in the literature using different *T. diversifolia* sources reported CP levels varying around 200 g/kg DM, illustrating the agronomic potential of *T. diversifolia* (Table 1).

Table 1. Nutritional composition of *Tithonia diversifolia* in different studies. Except for dry matter (DM), all values are presented as g/kg on DM basis.

References	DM	CP [1]	NDF	ADF	Obs.
Argüello-Rangel et al. [86]	190	252	337	145	
Calsavara et al. [14]	200	165	476	333	Whole plant
Calsavara et al. [14]	195	225	410	261	Leaves
Chin and Hue [87]	146	239	384	n/a	
Durango et al. [88]	212	185	462	343	
Guatusmal-Gelpud et al. [89]	n/a	267	331	150	

Table 1. *Cont.*

References	DM	CP [1]	NDF	ADF	Obs.
Lezcano et al. [90]	101	219	n/a	n/a	Rainy season
Lezcano et al. [90]	127	190	n/a	n/a	Dry season
Londoño et al. [91]	185	273	268	169	No fertilization
Mahecha and Rosales [79]	172	242	253	304	
Mahecha et al. [92]	n/a	223	359	181	
Naranjo and Cuartas [93]	191	241	386	345	
Van Sao et al. [77]	146	239	384	n/a	
Verdecia et al. [94]	198	289	436	276	Rainy season
Verdecia et al. [94]	182	275	404	241	Dry season

[1] CP—crude protein; NDF—neutral detergent fiber; ADF—acid detergent fiber; n/a—information not available on papers; Obs.—Observation, reflecting extra information on forage samples when made available by referred authors.

Krüger et al. [12] also observed CP levels around 200 g/kg DM during the dry season in southeastern Brazil. Moreover, Pérez-Márquez et al. [81], working with an in vitro fermentation system with inclusion levels of *T. diversifolia* on a 60:40 forage:concentrate ratio substrates, observed higher iso-valerate, iso-butyrate, as well as microbial biomass production in the first 24 h of incubation. Both iso-valerate and iso-butyrate are branched-chain fatty acids that originate from the degradation of branched-chain amino acids and rumen microbes utilize them for microbial protein synthesis [95]. Cellulolytic bacteria might benefit from using these fatty acids for their growth, potentially leading to increased fiber degradability [96]. In addition, increased branched-chain fatty acid production can be indicative of good protein degradability [34], which, if combined with the potential positive impact on microbial protein synthesis, makes it evident that *T. diversifolia* can be an excellent feeding resource to increase protein supply for animal in grazing tropical production systems, especially in the dry season. In this period, tropical grasses may show CP levels lower than 70 g/kg DM, which can be critical for the ruminal ecosystem [97,98]. Panadero and Montaña [38] also emphasized the potential of this plant for recovering degraded soil areas, a scenario often observed in the tropics.

In terms of CH_4 production, a review of the literature reveals how the inclusion of *T. diversifolia* affects this variable (Table 2). Despite the lack of a consistent pattern across studies, there are several examples where the inclusion of *T. diversifolia* has led to reduced CH_4 production. In most of these cases, authors attributed the reduction to a direct action on methanogenic microorganisms due to the presence of polyphenols in *T. diversifolia* (such as tannins) or to a reduction in the acetate:propionate (A:P) ratio [16,76,99,100]. The lack of consistency among studies demonstrates that the effect of *T. diversifolia* on CH_4 production is closely associated with the quality and type of substrate in which *T. diversifolia* is included. As observed by Akanmu et al. [100], the inclusion of *T. diversifolia* was more pronounced in fibrous substrates.

Despite Terry et al. [80] observing that the *T. diversifolia* inclusion led to increased CH_4 production, this increased methanogenesis was accompanied by higher acetate production, which can lead to improved animal performance in production systems. Elevated acetate production can be essential, especially to dairy production systems, as this fatty acid is an important precursor of milk fat, which in turn is an indicator of milk quality [101,102], allowing farmers to potentially have additional incomes from their product. On the other hand, Rivera et al. [103] observed that when including around 150 g/kg (fresh material) of *T. diversifolia* in a grass-based diet of cows, the presence of this shrub reduced their CH_4 emissions when expressed on a daily basis, per unit of DM intake, and per unit of degraded DM intake as well. The authors attributed this reduction to several factors, such as the decreased fiber content of *T. diversifolia*, accompanied by its increased CP, digestibility, and the presence of plant secondary compounds, reinforcing the multiple positive aspects of this plant as a feeding resource for ruminants.

Table 2. In vitro methane (CH_4) production, fiber content, and results found in the literature of *Tithonia diversifolia* (TD) in association with different substrates.

Treatments	CH_4 Production		Unit	NDF (%)	ADF (%)	A:P Ratio		Authors' Discussion	Reference
	TRT [1]	CON				TRT	CON		
10% TD with *Lolium perenne*	29.3	30.5	mL/gDM	53.8	27.1	2.00	2.06	No differences in CH_4 and A:P ratio. Decreased CH_4 due to the presence of tannins.	[103]
20% TD with *Lolium perenne*	25.9			52.1	28.9	1.95			
33% TD with *Pennisetum purpureum*	1.5	2.4	mmol/g	69.1	52.1	2.16	2.06	No differences in CH_4 and A:P ratio.	[104]
75% TD with *Pennisetum purpureum*	8.6	18.9	mL/gDOM	59.1	49.6	3.27	2.63	Decreased CH_4. Similar acetate and decreased propionate.	[105]
75% TD with *Cynodon dactylon*	4	7.3	mL/gDOM	61.3	48.3	3.41	3.04	No differences in CH_4. Similar propionate and increased acetate.	
TD extract with Commercial Concentrate (TMR)	25.3	42.9	mL/kgDOM	30.1	21.4	1.39	1.99	Decreased CH_4 due to the presence of tannins. Similar propionate and decreased acetate.	[100]
TD extract with lucerne hay	18.2	36.8		40.6	32.1	1.71	2.16	Decreased CH_4 due to the presence of tannins. Similar propionate and decreased acetate.	
TD extract with *Eragostis curvula*	5.8	47.7		78.4	49.2	1.63	2.48	Decreased CH_4 due to the presence of tannins. Increased propionate and decreased acetate.	
6.9% TD with sugarcane and concentrate	0.7	0.5	mL/gIDM	29.4	-	0.90	0.71	TD inclusion produced more CH_4 due to increased A:P ratio. Increased acetate and decreased propionate.	[80]
15.2% TD with sugarcane and concentrate	1.2			30.7	-	1.09			
29.2% TD with sugarcane and concentrate	3.3			34.5	-	1.55			
25% TD with *Urochloa brizantha*	~22.9	26.2	mg/gIDM	~55.5	~38.3	2.37	3.56	Decreased CH_4 due to decreased A:P ratio. Decreased acetate and increased propionate.	[76]
30% TD with *Cynodon nlemfuensis*	0.9	6.5	mL/100 mL	-	-	-	-	Decreased CH_4 due to the presence of tannins.	[16]
30% TD with *Cynodon nlemfuensis*	9.2	65.2	uL/gDM	33.4	29.5	-	-	Decreased CH_4 due to the presence of tannins.	[106]
30% de TD with *Cynodon nlemfuensis*	47.2			35.3	30.4	-	-	Decreased CH_4.	
100% TD	15.7	43.4	mL/gDDM	39	27.2	-	-	Decreased CH_4 due to the presence of tannins.	[99]
5% TD with *Cechrus clandestinum*	34.8	43.4		-	-	4.01	4.52	Decreased CH_4 due to the presence of tannins. Decreased acetate and increased propionate.	
3% TD with *Cechrus clandestinum*, concentrate and fat	41	60.3		-	-	3.97	4.80	Decreased CH_4 due to the presence of tannins. Similar acetate and increased propionate.	

[1] TRT—Treatment group; CON—Controls; NDF—neutral detergent fiber; ADF—acid detergent fiber; A:P—acetate:propionate ratio; DM—dry matter; IDM—incubated dry matter; DDM—degraded dry matter; DOM—degraded organic matter.

Additionally, *T. diversifolia* is a source of a wide range of secondary compounds [15]. In a study to characterize the phytochemical composition of this forage, Olayinka et al. [107] prepared aqueous and ethanol extracts with stems, leaves, and root of this plant. In both cases, extracts tested positive for alkaloids, flavonoids, saponins, terpenoids, tannins, and other phenolic compounds. Tagne et al. [15] analyzed more than 160 scientific articles, and identified more than 100 secondary metabolites isolated from different *T. diversifolia* extracts. Thanks to that extensive diversity of compounds, several properties, activities, and effects of interest for human medicine, such as anti-inflammatory activity, anti-protozoal effect, repellent against insects, antidiabetic effect, antibacterial and antifungal activities, antiviral, antioxidant, antiproliferative (i.e., against cancer cells), and even effects against gastrointestinal disorders, have been listed by the authors and attributed to the use of this plant.

For ruminant nutrition, a group of secondary compounds that for decades has been eliciting interest from the scientific community are the tannins, due to the beneficial effects of these extensively studied molecules [34,71,108] for the metabolism of ruminants as described in the previous section of this paper. Concerning the tannins found in *T. diversifolia*, Delgado et al. [16] reported moderate concentrations of these compounds. They observed reduced CH_4 concentrations in total in vitro gas production, along with a decreased protozoa population compared to other plants tested in their experiment. Such effects were attributed to the presence of tannins in *T. diversifolia*. Additionally, other authors in different studies who observed the reduction of CH_4 production due to the inclusion of *T. diversifolia* also pointed out that these results were due to the presence of tannins (Table 2). However, it is consolidated that the gold standard method to evaluate the biological effects of a certain tannin source on the metabolism of ruminants is doing in vitro or even in vivo trials using a tannin-neutralizing agent such as polyethylene glycol [109,110]. Therefore, studies using *T. diversifolia* with this experimental design are still warranted in order to provide a more accurate understanding about the tannins of this plant.

Nitrous oxide (N_2O) emissions data from operations using *T. diversifolia* in the diet of ruminants are still scarce in the literature. However, several researchers have assessed the impact of *T. diversifolia* inclusion on the animal's nitrogen balance (Table 3), which directly impacts the amount of N excreted and the subsequent conversion of N into N_2O since N balance and N excretion means (i.e., urine or feces) have significant influence on the potential of N_2O emissions from soils [70,71].

As observed for CH_4 production, it seems evident that the plant's influence on N balance is also dependent on associated diets' characteristics (Table 3). Associations with fibrous diets show more pronounced results than those with concentrated ones, as noted by Yousuf et al. [111], Ribeiro et al. [11], and Chacón Góngora [112], who used *T. diversifolia* in concentrated diets and found no significant differences in N retention compared to diets without *T. diversifolia*, while Ramírez-Rivera et al. [113], Castañeda Serrano et al. [114], Fajemisin et al. [115], and Durango et al. [88], associating *T. diversifolia* with exclusively forage diets, reported an increase in N retention compared to diets without *T. diversifolia*. Recently, Rivera et al. [116] evaluated soil N_2O emissions from grazing sites using cross-bred dairy cows in the Colombian Amazon by employing static closed chambers and reported that the silvopastoral system using *T. diversifolia* have led to lower N_2O emissions than the conventional grazing systems, which was composed by partially degraded *Brachiaria humidicola* areas. Therefore, silvopastoral systems with *T. diversifolia* arise as a sustainable production alternative for pasture-based systems, playing a crucial role in minimizing environmental footprint and promoting ecosystem services, which are becoming progressively vital and sought after in the current landscape of climate change.

Table 3. Nitrogen (N) balance of diets including *Tithonia diversifolia* (TD) in the literature.

Treatments	DMI [1] g/Day	NI g/Day	NF % NI	NU % NI	NR % NI	Authors' Discussion	Reference
0% TD extract + Cassava + concentrate	378	6.98	39	39.8	21.2	80% TD resulted in decreased fecal N excretion and higher urinary N excretion. N retention was similar in all treatments except at 80%.	[111]
20% TD extract + Cassava + concentrate	374	6.92	31.4	46.7	22		
40% TD extract + Cassava + concentrate	371	6.87	29.7	46.4	23.9		
80% TD extract + Cassava + concentrate	318	5.88	25.9	56.3	17.9		
0% TD + *Dichanthium aristatum*	410	9.78	24.9	12.9	62.1	TD inclusion resulted in decreased N excretion in feces and urine. N retention was higher with TD inclusion.	[114]
25% TD + *Dichanthium aristatum*	704	68.93	6.8	7.3	85.9		

Table 3. *Cont.*

Treatments	DMI [1] g/Day	NI g/Day	NF % NI	NU % NI	NR % NI	Authors' Discussion	Reference
0% TD + *Brachiaria decumbens*	652	63.23	48	35	16	TD inclusion resulted in higher N excretion in feces and urine. N retention was higher with TD inclusion.	[88]
35% TD + *Brachiaria decumbens*	840	113.48	34	26	39		
0% TD + *Panicum maximum*	312	7.59	31.5	14.5	54	No difference in fecal N excretion. Inclusions of 20% and 30% resulted in decreased urine N excretion. N retention was reduced by 20% and 30% TD diets.	[117]
10% TD + *Panicum maximum*	311	6.84	31.9	14.8	53.4		
20% TD + *Panicum maximum*	306	5.83	37	11.3	51.6		
30% TD + *Panicum maximum*	305	5.76	42	6.3	51.7		
TD 0% + sugarcane + concentrate	1860	563	34.5	11	54.6	No significant effects of TD inclusion on N excretion and nitrogen balance.	[11]
TD 6.5% + sugarcane + concentrate	1890	564.1	35.6	10	54.4		
TD 15.4% + sugarcane + concentrate	1870	557.2	35.5	11.4	53.1		
0% TD + *Pennisetum purpureum* + sugarcane	1050	13.05	50.73	39.2	9	TD inclusion increased N excretion in feces and urine. Only at 20% inclusion was there positive N retention. Other inclusions were not significant.	[113]
20% TD + *Pennisetum purpureum* + sugarcane	1510	19.93	47.22	30	23.3		
35% TD + *Pennisetum purpureum* + sugarcane	1550	25.51	47.75	34.1	18.7		
50% TD + *Pennisetum purpureum* + sugarcane	1520	30.11	47.23	37.6	15.6		
0% TD + *Brachiaria* + concentrate	1471	66.4	25.1	55.4	19.5	No effect of TD inclusion on fecal N excretion. Urinary N excretion was Decreased with 12% TD inclusion.	[112]
6% TD + *Brachiaria* + concentrate	1432	66.4	24.9	54.4	20.7		
12% TD + *Brachiaria* + concentrate	1452	66	27.1	43.7	29.2		
0% TD + *Panicum maximum*	1580	30.5	-	-	76	TD inclusions led to increased N retention.	[115]
25% TD + *Panicum maximum*	1970	56.6	-	-	71.9		
50% TD + *Panicum maximum*	2070	64.4	-	-	75		
75% TD + *Panicum maximum*	2130	72.8	-	-	76.7		

[1] DMI—dry matter intake; NI—N intake; NF—N in feces; NU—N in urine; NR—N retention; For easier comparison across studies, N values in feces, urine, and retained were expressed as a percentage of N intake.

5. Conclusions

With the mounting pressure from a scenario marked by a growing human population, higher demand for animal-derived food production, and increasing concerns about climate change, sustainable food production seems an inevitable requirement for humanity in the next few years. Tropical grasslands, abundant in Latin America, could be crucial in addressing these challenges. They offer rich biodiversity and have management practices that can improve food production, particularly protein, while reducing adverse impacts and promoting sustainability of the production system. Silvopastoral systems, while not yet widely adopted, seem to be one of the most promising practices, as evidenced by the literature gathered in this review, showing that these systems can preserve and recover natural resources such as soil and groundwater, while providing benefits to animals such as abundant nutrient sources, improved welfare, and offering cultural and ecosystem services for communities and populations reliant on these systems. Our research also showed that *T. diversifolia* is a shrub excellently suited for tropical silvopastoral systems, boasting significant potential for exploration. Its high-quality nutritional composition, agronomic adaptability to various tropical conditions, and potential to enhance animal performance while reducing GHG emissions intensity all underscore its importance. The information compiled in our review makes it clear that silvopastoral systems, as well as *T. diversifolia* should be mandatory topics in future discussions on sustainable ruminant production grazing systems in tropical environments. However, more thorough studies are still warranted to accurately characterize its impacts on animal performance and metabolism, while the scientific community should dedicate especial attention to its secondary bioactive metabolites and their direct impacts on GHG production, information not well enough detailed and clarified in the literature, making it an area of expertise to be further explored.

Author Contributions: A.M.K.—conceptualization, literature research, and writing of the original draft; P.d.M.T.L., V.O., S.P.-M. and H.L.—literature research, manuscript review, and editing; A.L.A., conceptualization, supervision, manuscript review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES—Finance code 001), and Fundação de Amparo à Pesquisa do Estado de São Paulo (grant no. 2016/26035-3).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

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