



EFFECTS OF TREE ARRANGEMENTS OF SILVOPASTURE SYSTEM ON BEHAVIOUR AND PERFORMANCE OF CATTLE – A SYSTEMATIC REVIEW

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Abstract

This review aimed to provide a critical and systematic evaluation of the scientific literature about the effect of tree arrangements of the silvopasture system on the thermal environment, behaviour, and performance of cattle. We conducted a search using Web of Science and Google Scholar to identify the key literature of the theme. Peer-reviewed published articles written in English, comparing one or more tree arrangements of SPS to treeless pasture or comparing shaded and sunny areas within the SPS, were selected. The resulting manuscripts (n=191) underwent a four-step PRISMA appraisal process. This process resulted in a final sample of 37 articles, which were used for recording metadata, bibliometric analysis, and assessment of the results, using the software R. Of the 37 articles, 20 studies evaluated dairy cattle (behaviour: 14; performance: 7) and 17 evaluated beef cattle (behaviour: 6; performance: 12). The main behaviours evaluated were grazing (95%) and ruminating (90%), while weight gain (89%) was the main performance variable evaluated. The co-occurrence network analysis highlighted that the studies related the animals' response to improving the thermal environment promoted by silvopasture systems. The main difference among tree arrangements evaluated by the studies was tree density, which ranged from 5 to 800 trees/ha; most studies covered SPS with row of trees (single row, n=16 and multiple rows, n=19). Most studies (n=32) were carried out in Brazil. The evidence of this review showed that regardless of tree arrangement, the silvopasture system improves the thermal environment for cattle, although some effects on behaviour and performance are inconclusive.

Key words: agroforestry, bovines, tree spacing, livestock, shade, thermal comfort

The advance of monocultures emerged with the premise of reducing hunger in the world (Tilman, 1998). However, this so-called “conventional agriculture” model is considered unsustainable, as it depends on inputs from outside the farm and is inadequate to respond to significant societal challenges, which include the adverse impact of climate change on agriculture, pollution, dependence on fossil energy, and loss of biodiversity (Rosati et al., 2021). On the other hand, the same authors stated that the agroforestry systems are based on agroecosystem diversification of the productive components (soil, pasture, cattle, and trees) and the intensification of agroecological relationships. The type of agroforestry can be defined by its main agricultural components, such as tree-based systems combining trees and arable crops and silvopasture systems, which combine trees, livestock, and pasture in the same area (Burgess and Rosati, 2018). There is evidence of the success of agroforestry practices worldwide (Desmiwati et al., 2021; Musa et al., 2019; Varella et al., 2016). Overall, the silvopasture systems are considered beneficial for animal welfare (Broom, 2017; Morales et al., 2017) and the environment (Lima et al., 2017), de-

spite the significant variability of arrangements (e.g., design and spacing), species of trees and pasture used in these systems (Jose et al., 2019).

The lack of information about the optimal spacing and tree arrangement for livestock in silvopasture systems is one of the challenges holding back the adoption of this system (Vieira Junior et al., 2022). The choice of tree arrangement involves decisions that must follow the objectives, expectations, and skills of farmers (Jose et al., 2019). When planning the silvopasture system, it is necessary to determine the design of the trees (Jose et al., 2019), such as single or multiple rows of trees, a row of trees on the border fence or following the slope of the terrain, or scattered trees. Another important factor is determining the distance between trees and rows; this will depend on the features of tree species, like the canopy (Jose et al., 2019). The density of trees can affect the local microclimate (De-Sousa et al., 2021 a; Pezzopane et al., 2019) and pasture production (Pezzopane et al., 2020; Vieira et al., 2021 a); the greater tree density, the greater shaded area and less incidence of radiation on the pasture (Vieira Junior et al., 2022). In contrast, a low tree

density means more light to pasture growth (Paciullo et al., 2017) and improves the growth of trees (Paula et al., 2013). The improvement in pasture and tree growth will result in greater financial returns to the farmer, as the performance of animals will not be impaired, and the better development of trees will ensure reasonable sale prices.

Extreme heat stress is expected to increase in many parts of the tropics and temperate zones and negatively impact livestock farming (Thornton et al., 2022). Thus, production costs will likely increase in all cattle systems because of the need to cool cattle (Thornton et al., 2022). Agroforestry has an overall positive effect compared with conventional cattle production, i.e., monoculture and without trees. Like any production system, the results can vary according to types of tree arrangement and management practices. To boost the dissemination of silvopasture systems and help identify research gaps on the silvopasture system, this study aimed to provide a systematic review of the scientific literature about the effect of tree arrangements of silvopasture systems on the thermal environment, behaviour, and performance of cattle.

Methodology

This review was conducted following the guidelines of Preferred Reporting Items for Systematic Review and Meta-analysis protocols (Moher et al., 2015).

Search strategy

Peer-reviewed articles written in English and published before January 2022 were systematically re-

viewed. The systematic searches were conducted using the Web of Science and Google Scholar databases with the integration of Boolean operators (i.e., AND, OR, NOT) to string together words or phrases, as well as wildcard truncations (denoted as “”) to designate a range of possible word forms. The “*” symbol was employed to account for alternate spellings (e.g., American versus British English). All the search terms are shown in Table 1.

Table 1. Population and outcome search term strings used for the final search in the systematic review

Acronym	Search string
Interventions	(silvopastoral OR silvopasture OR agroforestry OR “crop-livestock-system”)
Population	(cattle OR bovine OR beef OR dairy)
Outcome	(“thermal comfort” OR microclimate OR “thermal environment” OR thermal stress) AND (behavio* OR performance)

Study inclusion criteria and screening

We selected experimental studies that described the effects of different tree arrangements of silvopasture system (SPS) on the thermal environment, behaviour, and performance of cattle. To confirm the effects of tree arrangements of silvopasture systems, we considered studies that compared one or more tree arrangements of SPS with treeless pasture or that compared shaded and sunny areas within the SPS. Exclusion and inclusion criteria for the systematic review were developed a priori and agreed upon by all authors.

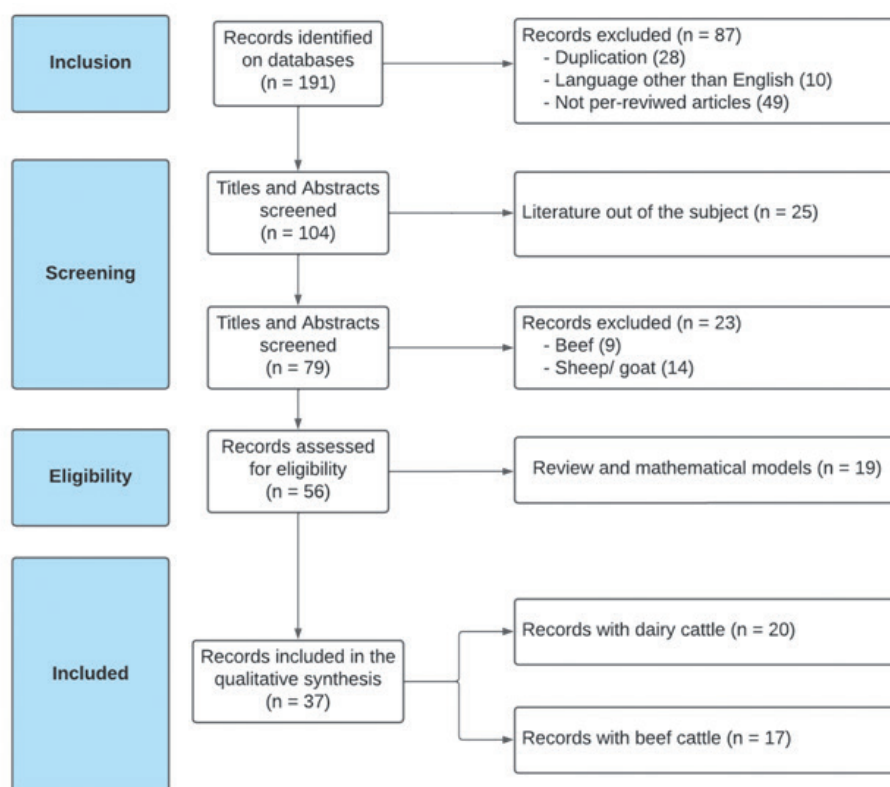


Figure 1. Flowchart following PRISMA guidelines (Moher et al., 2015) showing the total number of publications identified and the number of publications filtered at each stage of the selection process of the systematic review

The search on Web of Science returned 24 results, and the search on Google Scholar returned 167 results. All Web of Science results were also returned from Google Scholar. All results ($n = 191$) were included directly in a Mendeley® account through a Google Chrome plugin. The results received treatment at Mendeley®, where duplicates were initially excluded. The articles were selected based upon a 4-step screening and appraisal process (Figure 1): Step 1 – Publications written in a language other than English were excluded as we could not critically assess the methods and evaluate the results. Also, the thesis, books, book chapters, conference proceedings, and reports were removed, as we could not be certain that these sources had been peer-reviewed. Step 2 – Titles and abstracts were evaluated to identify and remove articles not relevant to the topic and out of interest (e.g., housed animals, dairy-herd economics, artificial shade, ecosystem services of the silvopasture system, and pasture production). Step 3 – In this step, all titles and abstracts were screened again to identify and remove additional articles not relevant to the topic of dairy and beef cattle. In this step, articles that evaluated other animal species, e.g., sheep, goat, and buffalo, were excluded. Step 4 – Finally, review articles were removed, and full texts of the remaining articles were read in detail. Studies containing experimental research were excluded if the experiment itself did not address the relationship between the behaviour or performance of dairy and beef cattle raised on a silvopasture system. In addition, studies about mathematical models were excluded if the parameters analyzed were sourced from other literature or if insufficient information about real-world data collection was provided to permit the recalculation of model parameters. The articles remaining at this stage were included in the systematic review and in multiple sections (thermal environment, cattle behaviour and/or performance) if they described more than one relevant effect. A deep examination of the characteristics of the articles demonstrated that the studies selected did not use the same methodology, so we discarded the meta-analysis approach. To provide a comprehensive overview of the literature on the topic of this review, no additional restrictions were placed upon publication year, study type, sample size, journal, or overall quality.

Data extraction

Two investigators independently screened full texts for all articles. Intra-observer reliability for data extraction (for all categories except for authorship and publication year) was tested by a contingency matrix, and we obtained 100% agreement. The bibliometric analysis was performed by the Bibliometrix R package (Aria and Cuccurullo, 2017; R Core Team, 2021). The Bibliometrix determines the intellectual structure of scientific domains using network analysis with multiple correspondence analyses on keywords, titles, and abstracts of the articles. To determine whether the choice of search terms in the databases was appropriate, a word cloud contain-

ing the 25 most cited words in the abstract was built. In addition, the co-occurrence network and link (relationship between knowledge areas) between the words used in the abstracts of the articles were built (Cobo et al., 2011). For interpretation purposes, the size of the label and circle of a term is determined by its weight, i.e., the number of times the term was used in the articles (Van Eck and Waltman, 2014). The links show the relationship between the knowledge areas, i.e., the closer terms have a stronger relationship.

The information extracted from the articles were the systems evaluated (treatments), characteristics of the silvopasture system (tree arrangement, density, and species), the season when data collection was performed, animals breed, number of animals that were evaluated and the variables evaluated (thermal environment, behaviour, or performance). Due to the diversity of naming for the silvopasture system (e.g., integration-livestock-forestry or integration-crop-livestock-forestry), in this review, we use the silvopasture system to refer to all systems where tree-pasture-animal are managed simultaneously. Also, we use the term treeless pasture to refer to all pasture systems described without trees.

Results and discussion

Overview

Of the 37 articles selected (Table 2), 32 studies were carried out in Brazil, two in Uruguay, one in the USA, one in Mexico and one in Colombia. The main characteristics of the studies are presented in Supplementary Material 1. In summary, of the 37 articles that met our selection criteria, 20 studies evaluated dairy cattle and 17 evaluated beef cattle. The number of animals evaluated ranged from 8 to 130, but 5 articles did not present this information. In total, 20 evaluated cattle behaviour (dairy: 14; beef: 6) and 19 evaluated animal performance (dairy: 7; beef: 12). Of the 37 studies, 21 (57%) compared the silvopasture system with treeless pasture, 13 (35%) compared different tree arrangements, and 5 (13%) compared shade and sun within a silvopasture system. Regarding the tree arrangement, 4 (11%) articles did not report the tree arrangement (i.e., tree design), 7 (19%) did not report the tree density, and 5 (13%) did not report complete information about the arrangement, (e.g., spacing between trees). Of the 32 articles that described the tree arrangement, only 3 studies evaluated scattered trees, 16 evaluated the single row arrangement, and 19 studies evaluated the multiple row arrangement. Tree density, which ranged from 5 to 800 trees/ha, was the main difference between the tree arrangements evaluated in the studies.

Our review highlighted the importance of Brazil in research with cattle raised on pasture with trees. A scientometric study performed by Silva et al. (2021) also identified Brazil as the country with the highest production of scientific knowledge on crop-livestock-forestry integration systems. Despite this, these integrated systems are not widely adopted by Brazilian farmers (Márquez et al.,

2021). Although the number of research about silvopasture system has increased in the last 10 years (the publication years identified in this review ranged from 2010 to 2021), most of the results obtained from this system are still at the research level. The majority (53%) of the Brazilian studies were conducted in the Midwest region, where one unit of the main public research company in the country is located (acronym in Portuguese: EMBRAPA). The fact that studies from other continents were not included in our review does not mean that the silvopasture system is not studied in other regions. Many studies from other continents have focused on variables not related to cattle response (farmer income: Desmiwati et al., 2021; socioeconomic issues: Musa et al., 2019; perspectives of stakeholders: Camilli et al., 2018). Brazil is located in the intertropical zone, which favors pasture-based livestock (Latawiec et al., 2014) and justifies the number of Brazilian studies evaluating silvopasture system. Our results identified a predominance of studies carried out in Brazil evaluating the effect of the silvopasture system on the cattle response (e.g., behavior and performance of cattle). The lack of adherence to the SPS and the scarcity of research in other regions may be related to the lack of easily accessible tools to farmers, in addition to the lack of technical assistance and public policies. Therefore, it is important to highlight that research at the farm level is extremely necessary, as well as the study of implementation and management strategies that are accessible and easy for farmers to adopt.

Table 2. Articles (author and year) included in the systematic review

Records with dairy cattle		Records with beef cattle	
author and year	author and year	author and year	author and year
Améndola et al., 2018	Souza et al., 2017	Baliscei et al., 2012	Huertas, 2018
Carnevali et al., 2020	De Souza et al., 2019	Giro et al., 2019	Huertas et al., 2021
De-Sousa et al., 2021 a	Vieira et al., 2020	Karki and Goodman, 2010	Lemes et al., 2021
De-Sousa et al., 2021 b	Vizzotto et al., 2015	Oliveira et al., 2021	Neves et al., 2021
Deniz et al., 2020	Álvarez et al., 2021	De Souza et al., 2010	Santos et al., 2018
Deniz et al., 2021	Lima et al., 2019 a	Bertogna et al., 2022	Silva et al., 2020
Lopes et al., 2016	Lima et al., 2019 b	Carvalho et al., 2019	Pontes et al., 2020
Mello et al., 2017	Martins et al., 2021	Domiciano et al., 2020	
Reis et al., 2021	Paciullo et al., 2011	Domiciano et al., 2016	
Skonieski et al., 2021	Paciullo et al., 2021	Fedriga et al., 2019	

The main tree arrangement evaluated in the studies included in this review was the multiple rows. Usually,

this tree arrangement presents a high density of trees, which is indicated for wood production, whereas the tree arrangement of a single row on the border fence is associated with low tree density and high sun incidence on pasture (Resende et al., 2020; Vieira Junior et al., 2022). When a single row of trees is planted on the border fence, it is possible to use the paddocks' fences to isolate the trees. Additionally, the greater spacing between the tree lines in this tree arrangement guarantees the transit of agricultural machinery. Regarding environmental benefits, the multiple row arrangement has high soil organic carbon, which is a global desire; in contrast, the single row arrangement would allow more benefits for livestock, pasture production and the environment (Resende et al., 2020).

Silvopasture systems can be implemented using several combinations of tree species, arrangements, and planting densities, resulting in a variation in the level of solar radiation intercepted by trees (Bosi et al., 2020). Also, the orientation of the tree is an important factor in determining the amount of light for the pasture. The best designs highlighted for improving the crop irradiance were north-south tree lines and east-west tree lines, which are recommended at high and low latitudes, respectively (Dupraz et al., 2018). Intercepting solar radiation and wind by trees directly implies microclimatic characteristics (Deniz et al., 2020; Pezzopane et al., 2015; Herbut et al., 2018), animals' thermal comfort (Angrecka and Herbut, 2015; Pezzopane et al., 2019; Magalhães et al., 2020), production and composition of pasture (Pezzopane et al., 2020; Vieira et al., 2021). In a study evaluating the microclimate in two tree arrangements of SPS (single row on the border fence and scattered trees), De-Sousa et al. (2021 a) found differences in soil surface temperature and black globe humidity index between tree arrangements. This difference may be related to the thermal load that each area received due to the interception of solar radiation by the tree canopies (border fence: 84%; scattered trees: 78%). This highlights the importance of the adequate choice of tree species, plant density, tree arrangement, and management. Management practices like pruning and thinning can be used to allow more light input to improve the growth of trees and pastures (Brunetti et al., 2022; Pezzopane et al., 2020). Furthermore, it allows wind movement (Oliveira et al., 2021), which helps the thermal exchange of animals (Fournel et al., 2017).

The word cloud (Figure 2) highlighted the words most used in the abstract of studies. It is important to note that the search terms that we used were similar to the 30 most frequently used words in the abstract of the 37 articles included in this review. The co-occurrence network analysis and links among the most relevant words used in the abstracts are shown in Figure 3. The smallest circles represent themes that have been explored in fewer studies.



The diagram is a complex network of nodes and edges, representing the relationships between various factors in a silvopastoral system. The nodes are colored blue, red, and green, and the edges are colored blue, red, and green. The central node is 'silvopastoral system'. The blue cluster at the top includes nodes like 'black globe', 'humidity index', 'thermal comfort', 'weight gain', 'stocking rate', 'eucalyptus trees', 'average daily', 'animal production', 'animal performance', 'herbage accumulation', 'grass monoculture', 'beef cattle', 'livestock systems', 'daily gain', 'weight gain', 'body weight', 'dairy heifers', 'crude protein', 'livestock production', 'integrated crop', 'grazing time', 'livestock forestry', 'animal welfare', 'time spent', 'dairy cows', 'milk production', 'heat stress', 'penning score', 'temperature humidity', 'surface temperature', 'air temperature', 'globe humidity', and 'soil surface'. The red cluster on the left includes 'crop livestock' and 'grazing time'. The green cluster at the bottom includes 'weight gain', 'stocking rate', 'eucalyptus trees', 'average daily', 'animal production', 'animal performance', 'herbage accumulation', 'grass monoculture', 'beef cattle', 'livestock systems', 'daily gain', 'weight gain', 'body weight', 'dairy heifers', 'crude protein', 'livestock production', 'integrated crop', 'grazing time', 'livestock forestry', 'animal welfare', 'time spent', 'dairy cows', 'milk production', 'heat stress', 'penning score', 'temperature humidity', 'surface temperature', 'air temperature', 'globe humidity', and 'soil surface'.

The co-occurrence network analysis highlighted three main clusters, showing that studies focusing on the animals' response (behaviour and performance) related these variables to the improvement of thermal environment promoted by silvopasture systems. In total, 24 studies evaluated microclimatic variables, and the main variables registered were air temperature ($n = 24$), relative humidity ($n = 23$), and black globe temperature ($n = 12$). Of the 24 articles, only 11 presented statistical analysis between the evaluated systems. Overall, there was no difference for microclimate variables and thermal comfort indicators between the evaluated tree arrangements. However, when the studies compared a silvopasture system to a treeless pasture, regardless of tree arrange-

humidity ($n = 23$), and black globe temperature ($n = 12$). Of the 24 articles, only 11 presented statistical analysis between the evaluated systems. Overall, there was no difference for microclimate variables and thermal comfort indicators between the evaluated tree arrangements. However, when the studies compared a silvopasture system to a treeless pasture, regardless of tree arrange-

ment evaluated (e.g., Martins et al., 2021: single row, 267 trees/ha; Neves et al., 2021: single row, 187 trees/ha and multiple rows, 446 trees/ha), the lowest values of microclimate variables and thermal comfort indicators were registered on the silvopasture system.

In total, 22 studies evaluated thermal comfort indicators, among which the most used were the temperature humidity index (THI; $n = 15$) and the black globe humidity index (BGHI; $n = 12$). Regarding the different tree arrangements, De-Sousa et al. (2021 a) evaluated two tree arrangements of the same density, finding a lower value of BGHI in scattered trees compared to a single row of trees on the border fence. In contrast, Neves et al. (2021; single row: 187 trees/ha and triple-row: 446 trees/ha), Souza et al. (2017; two-rows: 385 trees/ha and triple-row: 720 trees/ha) and Lopes et al. (2016; trees along the border fences: 49 m between rows and 15 m between rows) found no difference in thermal comfort index between the tree arrangements evaluated. As expected, the SPS presents lower average values of thermal comfort indicators than treeless pasture. Still, when it comes to evaluating different tree arrangements, the results are inconclusive since they depend on several factors, such as tree species and pasture, tree density, management, etc. In addition, few studies explored soil surface temperature ($n = 4$) and solar radiation ($n = 3$). The incidence of solar radiation and, consequently, radiant thermal load varies as a function of tree arrangement and position, which can impact on soil surface temperature and consequently influence the lying behaviour of cattle (De-Sousa et al., 2021 b). To reach a consensus on the positive and critical points of each tree arrangement, more research is needed; importantly, studies must give complete details of the characteristic of SPS.

Cattle behaviour

Of the 20 studies that evaluated animal behaviour, 15 presented statistical analysis comparing cattle grazing behaviour between the different pasture systems evaluated. Of the five studies that evaluated grazing behaviour in different tree arrangements, three did not find a statistical difference, and the other two found a higher ($P \leq 0.05$) grazing frequency in the SPS with low tree density compared to the arrangement with high tree density. From a behavioural point of view, tree density can influence animal activities; for example, longer grazing time was observed in a system with low tree density (Oliveira et al., 2021: 5 trees/ha) than in a system with higher tree density (Oliveira et al., 2021: 227 and 357 trees/ha); also, animals graze longer in treeless pastures than in silvopasture systems (De Souza et al., 2010; Lopes et al., 2016). Despite the low tree density (Oliveira et al., 2021: 5 trees/ha), the animals had access to the areas around the trees, which may have affected their behaviour. Deniz et al. (2020), evaluating the thermal environment in a silvopasture system, highlighted that the thermal environment in the sunny areas around the trees is better for cows than areas far from trees. The longer time spent grazing in the

treeless pasture and low tree density SPS can be explained by the quality of the pasture, as these systems generally have lower forage quality (e.g., lower crude protein; Pezopane et al., 2020), which can lead to greater selectivity by animals, resulting in animals spending more time in grazing behaviour. In addition, the longer grazing time is also related to cows' walking activity. Of the six studies that evaluated walking behaviour, three found a higher frequency of walking in the treeless pasture than in SPS (Vizzotto et al., 2015; Lopes et al., 2016; Améndola et al., 2018).

Two of the five studies that evaluated rumination between different tree arrangements found a statistical difference. Evaluating different tree densities, Carnevali et al. (2020) and Oliveira et al. (2021) observed a higher frequency of rumination in the higher tree density arrangement compared to a lower tree density during the cold seasons (Oliveira et al., 2021: 357 trees/ha; Carnevali et al., 2020: 714 trees/ha). However, during the summer, Carnevali et al. (2020) found the highest frequency of rumination in the moderate tree density. Ruminating generates heat, and usually, the peak of this behaviour occurs in the hottest hours of the day, indicating that it is more comfortable to perform it in the shade (Deniz et al., 2021 b). De-Sousa et al. (2021 a) found that cows spent less time ruminating in the scattered tree arrangement than in the single row of trees on the border fence; in the arrangement of scattered trees, the cows spent more time performing other behaviours, which, according to the authors, may be related to grooming behaviour. However, when shaded areas are a limited resource, it increases the number of competitions among animals. For example, when the available shaded area for animals increases, the number of disputes decreases (Schütz et al., 2010), and the time spent in shade areas increases (Stivanin et al., 2019), therefore, comfort behaviours (rumination and idleness activities) are preferably carried out in the shaded areas.

Cattle are gregarious animals, and their social hierarchy regulates the use of available resources in the production system. Deniz et al. (2021 a) evaluated the behaviour of dairy cows raised on an SPS with a single row of trees on the border fence and found that, even with enough shaded area for all animals to access at the same time, the cows always remained close together, resulting in some cows staying in the shade and others in the sun. The authors also found that subordinate cows were more likely to perform their behaviours in sunny areas but visited the water trough more frequently. Under heat challenge, cows have a higher motivation to seek water (McDonald et al., 2020), shaded areas (Cardoso et al., 2021), ventilated areas (Vieira et al., 2021 b) or sprinklers areas (Chen et al., 2013). Animals raised in areas without shade visit the water trough more frequently than animals raised on SPS (Vizzotto et al., 2015; De Souza et al., 2019; Giro et al., 2019; Vieira et al., 2020; De-Sousa et al., 2021 a). Giro et al. (2019) found that beef cows raised on silvopasture system have a 23% lower

frequency of visits to a water trough than cows in treeless pasture. Although the frequency of visits to the water trough is recognized as an important behaviour for animals raised in areas without shade to maintain their body homeostasis, this behaviour was not evaluated in six of the 37 articles included in this review.

Of the five studies that evaluated idle behaviour in different tree arrangements, four found a statistical difference. In general, these four studies found that the larger the shaded areas, the longer the animals spent idling. When comparing the silvopasture system to treeless pasture, there is no agreement among the studies. Of the 11 studies that statistically compared the silvopasture system to the treeless pasture, five found longer idle time on the silvopasture system, four found longer idle time on treeless pasture and three found no difference between the systems evaluated. What we can see in this review is that studies in pasture areas have paid little attention to the lying posture, given that only five articles reported idle while lying down. Idle is a comfort behaviour, and the posture (i.e., standing or lying down) in which the animals perform this behaviour can indicate heat stress. Tree arrangements with high tree density can harm the thermal exchange of animals during hot days and lying in the shade under these conditions can be uncomfortable, as the high relative humidity and low airflow reduce the animals' ability to lose heat to the environment (see review Tullo et al., 2019). The idle behaviour while standing may be associated with the animal's attempt to maintain its body homeostasis, because remaining inactive can reduce endogenous heat production and the standing posture increases the surface area for heat exchange (Nordlund et al., 2019). On cold days, the lying posture can be beneficial to avoid heat loss, but this can be influenced by the heat exchange capacity of the surface (Gebremedhin et al., 2016). Therefore, to understand the influence of posture on the thermal comfort of animals raised on pasture, new studies should consider the posture of animals and relate it to the behaviours (e.g., rumination and idling) and thermal environment.

Performance variables

Of the 19 studies that evaluated animals' performance, 16 evaluated weight gain (dairy: 5; beef: 11), two milk production, and three studied characteristics of reproduction (dairy: 1; beef: 2). Of the four studies that evaluated different tree arrangements, two found a statistical difference between the tree arrangements. Domiciano et al. (2020) found higher average weight gain per hectare of Nellore steers in the single row (90 trees/ha) compared to the triple-row (270 trees/ha). Santos et al. (2018) evaluated two double-row SPS with different tree densities (417 trees/ha vs 715 trees/ha), finding greater weight gain per area of Nellore heifers in the lower density system. The higher weight gain per area can be explained by the fact that the pasture area was smaller in the SPS but of better quality (Paciullo et al., 2021). Of the 16 studies that compared a silvopasture system to a treeless pasture, nine did

not find a statistical difference between the systems regardless of tree arrangement evaluated (e.g., Domiciano et al., 2020: single row, 90 trees/ha and triple-rows, 270 trees/ha; Huertas et al., 2021: double-rows, 830 trees/ha).

The fact that the studies did not find statistically better performance in the SPS is not a bad result or one that justifies the low adoption of this system. Among farmers, there is a culture that trees reduce forage production (Frey et al., 2012). This fact has been proven by several studies, which reported that the higher the shading level, the lower the forage production (Pezzopane et al., 2020). However, the low forage production is compensated by the better nutritional quality of the pasture, so the performance of the animals is not affected (Devkota et al., 2009; Paciullo et al., 2021, 2017). The shading effect is more prominent when the pasture species is not adapted to shading (Devkota et al., 1997; Vieira et al., 2021 a); that is, in the planning of the SPS, the pasture species that already exist on the farm must be considered to define which tree arrangement will be used. The tree arrangement has a significant effect on the incidence of radiation in the pasture, resulting in different levels of pasture production (Vieira Junior et al., 2022). The effect of solar radiation on pasture production can be adjusted in four ways: (i) row spacing, through tree density and planting arrangement; (ii) selection of tree species with an open canopy (e.g., Eucalyptus trees); (iii) management practices such as thinning and pruning of trees; (iv) planting shade-tolerant pasture species.

Some studies evaluated the effect of SPS on pasture production (see details in Table S2). Although it was not the purpose of this review, we show these results because pasture production is directly related to animal performance. Of the 37 articles, 15 studies evaluated some characteristics of forage production, such as forage mass or crude protein. Of the 10 studies that statistically compared the forage mass between the SPS and the TLP, nine found lower forage mass values in the SPS. However, this difference varied with the time of implementation of the SPS and the season evaluated. Both Domiciano et al. (2020) and Lima et al. (2019 a) evaluated multiple row tree arrangements with different tree densities (270 vs 50 trees/ha); they found no difference in forage mass between SPS and TLP in cold seasons but found higher production in TLP during warm seasons. On the other hand, Silva et al. (2020), evaluating a multiple row tree arrangement (270 trees/ha), found no difference in forage production between SPS and TLP in the rainy season (summer) but found higher forage production in the dry season (winter) in the TLP than in the SPS. Lima et al. (2019 b) evaluating multiple rows (342 trees/ha) found no difference between the SPS and TLP after 6–7 years of tree implantation, while in the subsequent years there was a progressive increase in shade levels in the SPS, which resulted in a reduced total and green forage mass compared to treeless pasture.

The results of milk production were not conclusive since only two studies evaluated this variable, and the

conditions were different. Álvarez et al. (2021) evaluated three levels of canopy cover (high: 20.4%, medium: 14.8%, and low: 4.2%) of trees dispersed in the pasture area. They found a small difference in milk production, with the highest ($P \leq 0.05$) milk production with the medium (4.4 ± 0.21 kg/cow/day) and high (4.4 ± 0.21 kg/cow/day) level of tree cover, followed by the low level of tree cover (4.1 ± 0.21 kg/cow/day). On the other hand, Martins et al. (2021) found no difference in milk production between SPS (11.2 kg of milk, single row – 267 trees/ha) and treeless pasture (11.4 kg of milk). For reproductive performance, the studies found better animal performance in the silvopasture system. Lemes et al. (2021) evaluated the recovery rate of oocytes of beef heifers and found a higher number in SPS (74.3%) compared to treeless pasture (65.3%), but there was no significant difference in embryo production between the systems. Martins et al. (2021) found an effect of season and treatment on the reproductive variables evaluated (total follicles, total oocytes, viable oocytes and blastocysts) in lactating Gyr cows; they found a higher ($P \leq 0.05$) number of ovarian follicles (OF) and viable oocytes (VO) during the winter in cows raised on SPS (OF: 37, VO: 6.3) compared to cows raised on treeless pasture (OF: 31.7, VO: 3.4). Bertogna et al. (2022) found higher ($P \leq 0.05$) mean values of IGF-I (547 ng/ml) and weight gain (290 kg) on Nellore heifers raised on SPS of triple-rows (135 tree/ha) compared to SPS of single row (509 ng/ml and 288 kg; 90 trees/ha;) and treeless pasture (476 ng/ml and 279 kg). Considering that weight gain and serum levels of IGF-I are physiological predictors of bovine sexual precocity, Bertogna et al. (2022) suggested the adoption of integrated production systems for anticipating puberty in Nellore heifers. Performance variables are difficult to study, due to the need to follow the animals over time. However, studies that evaluated performance variables are important to understand the economic potential of silvopasture system.

Potential limitations

We performed the search in two databases, Google Scholar and Web of Science. Google Scholar is more comprehensive than Web of Science, as it searches within the main body of the paper, except those journals that charge access to the article and thus limit Google's search to the title and abstract. In addition, we only considered articles published in English, because this is considered the international language of science (<https://www.nature.com/articles/d41586-021-00899-y>). We only excluded 6 articles that were written in a language other than English. Also, we did not place any restriction on publication year, yet the distribution of publications included in our final review was right-side, meaning that the bulk of publications occurred within the last decade. In the second step of the PRISMA approach (screening and appraisal), we evaluated the title and abstracts of the articles. Therefore, articles that did not mention in the abstract experimental procedures that related thermal

environment and behaviour and/or performance of cattle were excluded. Furthermore, we only included articles with a clear comparison between one or more tree arrangements of silvopasture system to treeless pasture or studies that compared shaded and sunny areas within the silvopasture system. For example, if a study evaluated the microclimate of different tree arrangement on SPS, but did not evaluate the cattle response, it was excluded.

To provide a comprehensive view of the effects of different tree arrangements of silvopasture systems on the thermal environment, behaviour and performance of cattle, no exclusion criteria were applied regarding the journal's quality and the study. The main limitation that can affect a systematic review is publication bias (methodological limitations), in addition to difficulties in combining studies that compare different tree arrangements. Furthermore, the lack of a detailed description of the statistical analysis, and the lack of information such as the number of days of data collection, and time of evaluation, made it impossible to have a more in-depth assessment of the statistical power of the studies and to carry out a meta-analysis. A fundamental limitation of comparing tree arrangement is the considerable variation among farms. Besides the local characteristic of each farm, farmers also vary in their quality of management and how much they follow recommended practices. Thus, we caution readers that the results of the studies we have reviewed are likely due in part to factors associated with farms' location (such as relief, soil quality and climate) and design of tree arrangement (position and density).

General discussion

The main characteristic that varied among arrangements was the tree density; although this characteristic is directly related to the quality of the thermal environment and pasture production, studies that compared different tree densities did not find differences in these variables. Therefore, we can conclude that the introduction of trees on pasture, regardless of the arrangement, is beneficial for the animals when compared to areas without trees. Overall, we could not find a pattern in the results of thermal comfort, animal behaviour, and performance among the tree arrangements, which may be related to the variability of the conditions evaluated, such as the amount and quality of shade, and the season evaluated. Due to the small number of studies that describe in detail the characteristics of the evaluated silvopasture system, we cannot indicate which tree arrangement would be better for livestock farming.

The challenge for future research is to evaluate, within each climate and region, the main farmers' objectives in adopting a silvopasture system and to identify the main difficulties farmers face during this process. As we mentioned in this review, the silvopasture system is complex, making the determination of the best tree arrangement almost impossible. The climate of the region will influence the availability and choice of tree species and the determination of the position of the trees in the

pasture. Furthermore, future research should evaluate the behaviour and performance of cattle raised on a silvopasture system throughout the year. Due to climate change, the silvopasture system can be beneficial to livestock not only in hot seasons but also in cold seasons. The silvopasture system can mitigate the negative effects of climate extremes (e.g., heat or cold waves) by reducing the thermal amplitude and offering shelter to animals.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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