UNIVERSITY OF HOHENHEIM

Center for Organic Farming

Master thesis

Small Ruminant Heat Stress in Temperate Regions: Agroforestry as a Mitigating Strategy

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Abstract

In heat stress agroforestry research, there is little data regarding the exact effects and benefits of particular agroforestry pairings, strategies, and methodologies to create suitable best practices for farmers to follow when investing in the adoption of agroforestry practices. Different agroforestry systems are expected to have different results within a system based on their morphology and interactions with animal behavior, so it cannot logically be assumed that linear hedgerows would have the same benefits as dispersed silvopastoral tree systems, particularly in the case of their use for the purposes of heat stress abatement for ruminants. A fieldwork experiment was conducted to test whether the windbreaking function of hedgerows would offset the benefits of shade provided in a linear hedgerow agroforestry system with grazing sheep in Baden-Württemberg, Germany, using a thermal imaging camera. Due to unstandardized weather conditions, the fieldwork had to be cancelled, so a literature review was conducted instead, analyzing the state of the literature on temperate agroforestry use for heat stress in ruminants. Some of the most notable gaps which were found were: a lack of diversity in research climate and geography, with a preference toward tropical and Mediterranean studies; a literature preference toward silvopastoral studies utilizing cattle and dispersed tree systems, rather than small ruminants and linear hedge systems; and a lack of sufficient animal behavioral data collection within thermal stress studies, such as through an over-reliance on the use of thermal indices. Recommendations were then made regarding the future of heat stress related agroforestry studies, including suggestions on standardizing methodologies and the use of various data collection tools to build on the quality of the literature base, as well as the establishment of Hedge Agroforestry Research Sites, which could serve as hubs for hedge agroforestry research.

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- Am – Equatorial monsoonal Köppen-Geiger climatic classification
- Aw – Equatorial dry winter Köppen-Geiger climatic classification
- B12 – Vitamin B12/Cobalamin
- BGHI/BGHTI – Black Globe Humidity Index
- BSh – Arid steppe hot arid Köppen-Geiger climatic classification
- BSk – Arid steppe cold arid Köppen-Geiger climatic classification
- C – Celsius
- CCI – Comprehensive Climatic Index
- Cfa – Temperate fully humid hot summer Köppen-Geiger climatic classification
- Cfb – Temperate fully humid warm summer Köppen-Geiger climatic classification
- Csa – Temperate dry summer hot summer Köppen-Geiger climatic classification
- Cw – Temperate desert
- e.g. – example given

- ERHL – Effective Radiant Heat Load
- F - Fahrenheit
- FAO – Food and Agriculture Organization
- Ha - hectare
- HLI – Heat Load Index
- i.e. – in essence
- ITSC – Index of Thermal Stress for Cows
- KG - Köppen-Geiger
- NPID – Not Positively Identifiable
- PAR – Photosynthetically active radiation
- THI – Temperature Humidity Index
- THI4 – Temperature Humidity Index 4
- THI_{adj-d} – Temperature Humidity Index Adjusted Daily
- TRH – Temperature Relative Humidity

1 Introduction

1.1 Thermal Concerns for Livestock as a Reality of Climate Change

Despite some popular beliefs, climate change is affecting our climates now, to drastic effects. Europe, the fastest-warming continent, had the hottest year on record in 2024 across much of the continent and was plagued by severe flooding and wildfires, and people experienced the second highest record of “strong, very strong, and extreme heat stress” days, despite increasing efforts from European cities to increase their climate adaptability ("European State of the Climate: extreme events in warmest year on record," 2025).

Climatic extremes such as these also affect our animals, particularly our livestock, in a variety of ways. Apart from the basics of increasing the energetic demand for maintaining homeostasis in a hotter environment, heat stress and climatic extremes also affect disease transmission, by weakening immune systems while providing range expansion for parasites and increased pathogen growth, increasing concerns for zoonotic diseases and epidemics (Anuta, Wang, & Kinay, 2025). Increasing wildfires and floods have direct impacts on livestock, burning, wounding, or sweeping away livestock which are unable to be evacuated in time, and destroying pasture and necessary infrastructure in their wake (Anuta et al., 2025). Meanwhile, droughts limit the growth of livestock, and some regions, such as the Mediterranean, must rely on supplementing feed with hay during the summer dry period (Cosentino, Gresta, & Testa, 2013; Sánchez, Lassaletta, McCollin, & Bunce, 2010; Sánchez & McCollin, 2015).

Defined as the combination of factors, both internal and external, which cause an animal’s body to increase in temperature and trigger a physiological response, heat stress limits appetitive behavior and reduces productive output, affecting the growth and reproductive rates of livestock (Anuta et al., 2025; Gupta et al., 2025), which subsequently shallows the profitability of already narrow-margin farm operations, and threatening food security, especially for communities with a high reliance on livestock for subsistence (Gupta et al., 2025).

Livestock heat stress is an industry-wide problem, but it does not necessarily affect all operations equally. Specifically, organic livestock are at a higher risk of heat stress, due to legal requirements regarding outdoor access and direct grazing during the growing season. Conventional livestock can be raised almost exclusively in a climate-controlled building, however, organic livestock in the European Union are required to have outdoor grazing access roughly from April to October, only being brought indoors during extreme weather events or for routine care ("Regulation (EU) 2018/848 of the European Parliament and of the Council of 20 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007," 2018). While indoor facilities can also exacerbate heat stress issues, such as with insufficient air movement, generally speaking this outdoor access during the growing season increases the risk of the animals experiencing heat stress due to less managerial control over the experienced climatic conditions. While there is an exception for extreme weather events wherein organic livestock can be housed indoors during the growing season, the law does not specify the length of time for which this is allowed. Thus, if a heat wave were to last weeks, it is a legal gray area for whether the livestock are permitted to be housed indoors during this period, or if the grazing rights must be restored. Further, many of the strategies available for mitigating the reproductive impact of heat stress are not available to organic farmers, primarily due to bans on in vitro reproduction and embryo transfer, as well as limits on the feeding of concentrate, which can be used to combat the appetite reduction effect of heat stress (Gupta et al., 2025; "Regulation (EU) 2018/848 of the European Parliament and of the Council of 20 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007," 2018).

Especially in tropical regions during the summer or dry periods of the year, it is expected that a certain degree of heat stress will occur, particularly for grassland/pasture-based livestock which are not housed indoors. However, temperate climates, such as the majority of the European continent, are not typically thought of as being at risk of heat stress (Ginane, Bernard, Deiss, Andueza, & Béral, in peer review), though recent studies show this to be an incorrect notion ("European State of the Climate: extreme events in warmest year on record," 2025; Wu et al., 2025). Regardless, temperate and tropical farmers and researchers are finding ways, rooted in historic practices, to reduce the risk of climatic extremes affecting the homeostasis and welfare of their livestock. In order to protect their livestock in the face of climate change, some are using agroforestry.

1.2 Agroforestry as a Mitigating Strategy

One of the ways farmers are increasing their farms' climate resilience is through the adoption of agroforestry practices. Agroforestry is the use of trees or shrubs within an existing agricultural production system, increasing the efficiency of the land use (Röhrig, Hassler, & Roesler, 2020). More specifically, agroforestry can be broken up into two main categories: silviculture, where trees or shrubs are integrated with crops; and silvopasture, where trees or shrubs are integrated with livestock production, typically grazing pasture (FAO, 2018). In agroforestry, the tree/shrub component can produce its own agricultural product, or as a permanent structure kept for the ecosystem services provided to the primary enterprise rather than being a financial boon in of itself (FAO, 2018). These ecosystem services often modify microclimatic conditions for the land area below or near the canopy, or serve as an alternative nutrient source (fodder use) (FAO, 2018). It is through the ecosystem services of providing shade, reducing ambient temperature, wind speed, and solar radiation exposure under the boughs that agroforestry practices can mitigate climate change, and the impact of extreme weather on crops and livestock. It is also through these ecosystem services that organic livestock farms can reduce the thermal stress placed upon their livestock, allowing for animals to remain on grazing land for a longer period during a hot period. Organic agriculture is particularly suited to the use of agroforestry practices, as it aligns very well with the Principles of Organic Agriculture, as set forth by IFOAM, benefitting the soil, livestock, natural environment, and wildlife (International).

However, agroforestry systems have a higher degree of managerial complexity than an intensive/monocrop system (FAO, 2018). The various components of the system must not significantly conflict or compete with each other. This is a particular concern when working with livestock, as they can unintentionally consume a crop, but they also have welfare concerns that are not present in crops, so any managerial decision must also take into consideration the provision of the highest degree of animal welfare possible, given the economic, managerial, and legal constraints. Thus, when designing a silvopastoral system, utilizing trees and shrubs alongside livestock, one must design a proper pairing.

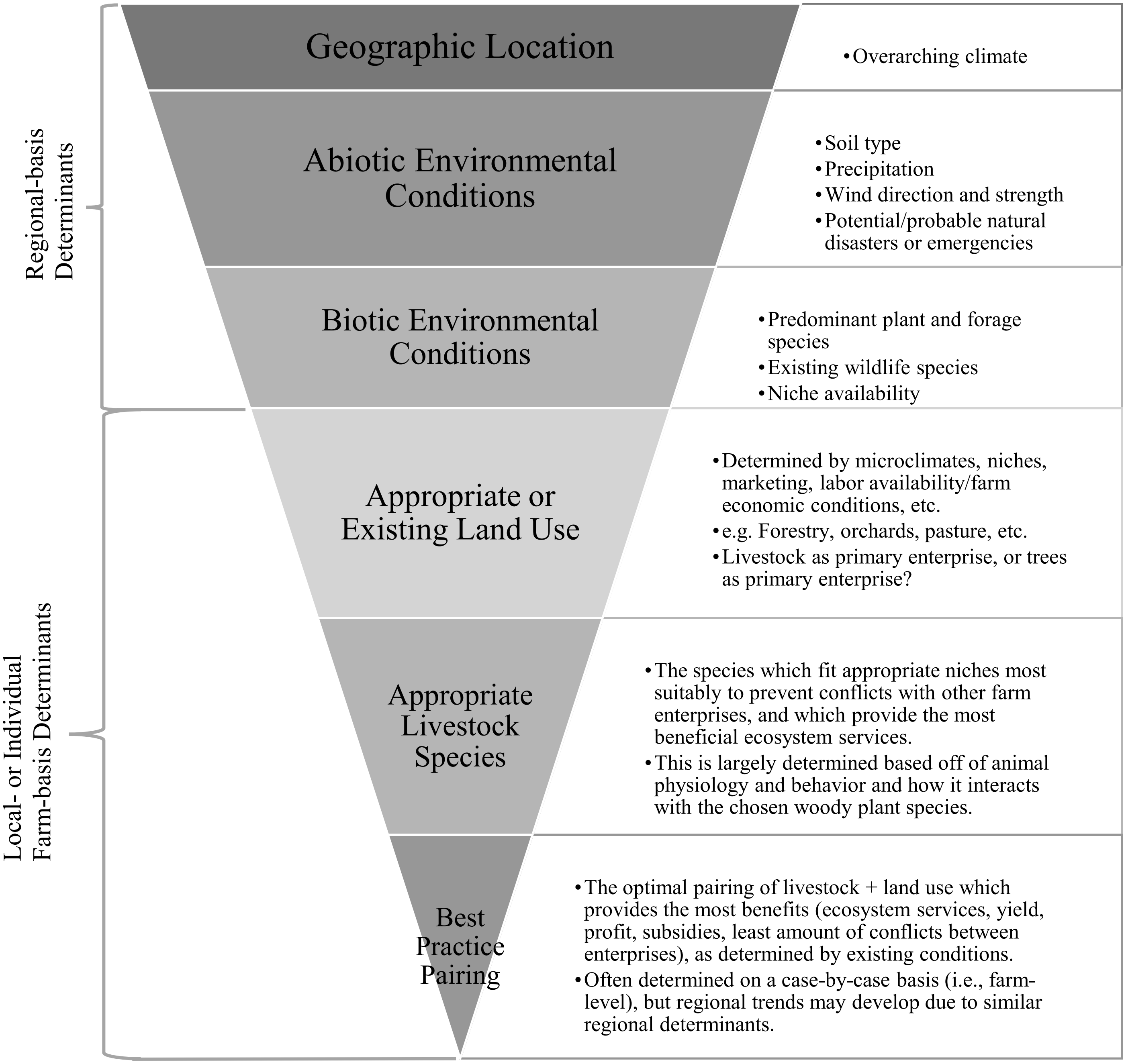
1.3 Importance of Agroforestry Pairings to Achieve Intended Effect: a Conceptual Framework

In agroforestry systems, two components are brought together into a managerial partnership, creating an agroforestry pairing. Due to the livestock focus of this review, only silvopastoral systems will be discussed after this point. When implementing agroforestry for a silvopastoral system, there is typically a pre-existing system, either grazing livestock or established tree or hedge plantings, and the complimentary component is integrated into the existing land use to create the agroforestry pairing in the agroforestry system.

The pre-existing environmental conditions are likely what determined the current land use. These environmental conditions then interact with the animal behavior to form the final result, whether it achieve the intended effects of not (as determined by the managerial intentions).

Livestock are complex components of an agroforestry system. Unlike crops or trees, they do not stay in one location, and often do not cooperate with what managers may intend or decide. For example, they may decide to eat the bark off of a silvopastoral tree, reducing the tree's value for lumber, or killing it outright. Livestock exhibit complex behaviors, morphologically, behaviorally, physiologically, and genetically, and any one of these which conflicts with the intended woody component could have unintended effects which may threaten the survival of the other. These various components of behavior must be considered in order to properly decide which tree or shrub system and species would be the most beneficial for one's livestock-based silvopastoral system. However, livestock don't behave completely randomly, and the typical behavior of livestock within certain agroforestry pairings can be studied to predict responses and expected downstream effects, creating a research base that practitioners can rely upon when establishing their own agroforestry systems on their farms, instead of relying on trial and error to establish the systems.

Agroforestry pairings must be decided on the basis of environmental context, species-by-species, and the specific agroforestry method (e.g. forest pigs, or orchard sheep). Figure 1 shows an original conceptual framework which shows the determining factors which influence the appropriate livestock-woody component agroforestry pairing for a given context. This conceptual framework was developed by this author for this review, and was not based on external sources. While many of the determinants are larger-scale and can be geographically generalized, others are much more context specific to the particular county, farm, or even the individual plot of land on a farm.



- Overarching climate

- Soil type
- Precipitation
- Wind direction and strength
- Potential/probable natural disasters or emergencies

- Predominant plant and forage species
- Existing wildlife species
- Niche availability

- Determined by microclimates, niches, marketing, labor availability/farm economic conditions, etc.
- e.g. Forestry, orchards, pasture, etc.
- Livestock as primary enterprise, or trees as primary enterprise?

- The species which fit appropriate niches most suitably to prevent conflicts with other farm enterprises, and which provide the most beneficial ecosystem services.
- This is largely determined based off of animal physiology and behavior and how it interacts with the chosen woody plant species.

- The optimal pairing of livestock + land use which provides the most benefits (ecosystem services, yield, profit, subsidies, least amount of conflicts between enterprises), as determined by existing conditions.
- Often determined on a case-by-case basis (i.e., farm-level), but regional trends may develop due to similar regional determinants.

Figure 1: Conceptual Framework of Determining Factors of Appropriate Livestock-Based Agroforestry Pairings

Once the existing environmental context is understood, as well as the strengths and weaknesses of the pre-existing system, the behavior of the animals must be understood as they would presumably operate within the agroforestry pairing. It must be considered whether the livestock will damage the woody component, such as through debarking or even direct consumption (Bhattrai, Karki, Poudel, McElhenney, & Paneru, 2020). If the goal of the system is to reduce heat stress, it is likely that direct consumption of the woody component would be undesirable. In this case, the palatability of the forage is incredibly important, as a palatable hedge is likely to be decimated by sheep and goats especially, but an unpalatable forage (such as alder, seen in Kendall et al. (2021)) will be more likely to survive the pairing, providing the desired ecosystem services. For trees, the palatability is of lesser importance, as the livestock will typically only be able to consume boughs which have fallen, but debarking becomes a potential concern, especially if the trees are intended to also be used as lumber, as debarking behavior reduces lumber value, and may hinder tree growth (Poudel, Karki, Karki, & Tillman, 2020).

If the woody component (trees/hedges/shrubs) is intended to be used as fodder, it becomes more important that the livestock be excluded from the area, or the planting to be protected in some way, until the planting is well established and can withstand browsing behavior (Poudel et al., 2020). Further, the nutritional content becomes important, as many plants have antinutritive compounds (e.g. tannins), are outright toxic, or have nutritional imbalances or mismatch to the needs of the livestock.

Further, it must be understood by the managers if the environmental benefits provided by the agroforestry pairing will be economically sufficient to compensate for additional managerial complexity and management costs imposed by the establishment and maintenance of the woody component of the system (FAO, 2018). The economic benefit can include additional income sources, such as subsidies, grants, and increased yield/livestock productivity, as well as decreased costs, such as labor, inputs, morbidity, mortality, or replacement. Finally, one must decide on the distribution of the planting, whether it should be dispersed or linear, as that alone can affect the success of the system as a whole, and will be discussed in detail later. All of these factors must be identified in order to choose the proper agroforestry pairing for one’s livestock.

1.4 Aim of Thesis

This review sought to characterize the literature regarding the effects of hedge agroforestry use for small ruminant heat stress in temperate climates; however, a notable lack of results was found. Thus, this review characterizes the peripheries of this literature gap, specifically regarding the geography/climate of existing studies, planting distribution and animal species used, and animal behavioral data collection within these studies. It then relates this knowledge base to small ruminant heat stress in temperate agroforestry systems, with a special interest in hedge-based agroforestry systems. A fieldwork study was also initially conducted, although weather, logistic, and methodology development problems forced a literature review instead; however, the lessons learned from that experience, combined with methodological limitations found within the literature, has informed suggestions for future methodologies within this area of study, as well as the area of agroforestry heat stress research as a whole.

2 Methodology

2.1 Brief Methodology of Attempted Fieldwork

A fieldwork study was attempted, and lessons were learned regarding how future studies could be more optimized. It was initially hypothesized that in a linear hedge agroforestry system, sheep would seek out shade during hot conditions, but that hedges would block the wind and reduce the effectiveness of shade, as represented by an insignificant difference in temperatures next to the hedgerow versus the center of the plot, as measured by a thermal camera.

The study location was in Baden-Württemberg, Germany, a temperate zone (Cfb Köppen-Geiger classification), on a 17ha sheep farm which had established linear poplar and willow hedges one year prior. This was not known before the initial visit to the farm, and the methodology had to be adjusted, as they hedges were immature, and not fully grown hedges as expected. Thus, the hypothesis was adjusted to be relevant only to immature hedges.

2.1.1 Herd Composition

The herd was composed of 27 sheep, 7 of which were marked with green chalk spray as focal individuals for behavioral observations. The marked sheep were all at least two years old, in good physical shape, and had not had lambs that year. The previous lambing season had been extremely small, with only 3 lambs born, due to Blue Tongue Disease. Only one sheep contracted the disease, and had been removed from the herd. This was not considered to be a continuing concern in the herd, but was noted.

2.1.2 Study Plots

Three study plots were created: Control, Feed Preference, and Heat Stress. Each plot was 36m long by 20m wide and fenced with temporary electric fencing. Each plot had 4 water sources, one in each corner, and two observation towers, placed in the corners opposite the hedgerows (in the most eastern corners of the plots) just outside the electric fences. These towers were constructed of wood, and 1m wide x 1m long x 2m tall. A thermal camera and video recorder were utilized centered on one of the areas of focus in each of the plots (alongside the hedgerow in plots containing hedges, and in the center of the plot in the control plot). The thermal camera was set to automatically take thermal photos every 10 minutes for 3 hours and 10 minutes to determine the temperature gradient of the plots, while the video recorder was set to record continuous video to track the movement of shade across the plot. Once the 3 hour observation period was over, the plots were enlarged to allow for a proper stocking density for grazing as part of the farm's rotational grazing plan. Thus, after a plot was observed, it was spent, and no further replicates were possible.

The Feed Preference was designed to determine whether a feed preference potentially affected the location of sheep, a concept derived from the Optimal Foraging Theory, as sheep might choose a location in or out of the shade depending on whether they preferred a certain forage over another. It was centered on a hedgerow with a mix of Poplar and Willow hedges, and was the southernmost plot. The Willow section was 15m long, and the Poplar was 17m long, with a total length of 32m of hedge within the plot. The poplar was comprised of two varieties, which were easily identifiable by varying heights. 4.5m of the Poplar was comprised of a shorter variety with a slower growth rate. Before and after photos were taken of the hedgerows to visually determine the severity of debarking. No hut shade was provided in this initial plot due to the study flock being accustomed to not having artificial shade structure under such temperatures (70-80 °F, 21-26 °C, though some panting was observed in some individuals, and despite these individuals not seeking out shade, subsequent observations were provided with a shade hut. This hut was 2m wide x 3m long x 2m high, and had a tarp as an opaque roof.

The Control plot was centered in an area where shade cast was minimal, west of the Feed Preference and Heat Stress plots, and no hedges were included in the fenced area. A hut was provided centrally along the back (easternmost) fenceline to allow for shade.

Finally, the Heat Stress plot was centered on an area of hedge which was entirely poplar, and which was the densest planting available on the farm, north of the Feed Preference plot. A hut was provided centrally along the back (easternmost) fenceline to allow for shade.

2.1.3 Ethogram

An ethogram was used to record the behavior of the sheep within the study plots. Scan sampling was performed by two observers, one in each observation tower, at three minute intervals for 3 hours for each plot, providing a total of 60 intervals for each plot. The ethogram included such behaviors as: location (in hedge shade, hut shade, or sun), proximity to hedge (in the 1/3 of the plot either closest to the hedge, furthest from the hedge, or in the middle 1/3), eating behaviors (willow, poplar, or grass), and other behaviors (drinking, locomotion, resting, ruminating, standing, or not positively identifiable). If sheep were not able to be positively identified as a focal study sheep within the flock, they were marked as Not Positively Identifiable (NPID).

Table 1: Behavioral Ethogram

Location	Hedge Shade	Sheep is located in an area which is shaded by the hedgerow
	Hut Shade	Sheep is located in an area which is shaded by a hut structure
	Sun	Sheep is located in an area of no shade
Proximity to Hedge	Closest 1/3	Sheep is located in the area of the plot which is in the immediate proximity of the hedge, as divided into thirds
	Middle 1/3	Sheep is located in the area of the plot which is not in the immediate proximity of the hedge, nor the proximity of the observers, as divided into thirds
	Furthest 1/3	Sheep is located in the area of the plot which is in the immediate proximity of the observers, hut, or back fence line, opposite from the hedge
Eating Behavior	Poplar	Sheep is browsing on poplar hedge

	Willow	Sheep is browsing on willow hedge
	Grass	Sheep is grazing grass and is not browsing
Other Behaviors	Drinking	Sheep is interacting with the water trough (head in the trough)
	Locomotion	Sheep is moving from one location to another, at any pace, but is not grazing or browsing while moving.
	Resting	Sheep is lying down
	Ruminating	Sheep is ruminating or chewing without actively consuming organic material
	Standing	Sheep is standing motionless
	Not Positively Identifiable (NPID)	Sheep is not able to be positively identified as a focal sheep, marking is not visible

2.1.4 Field Conditions and Failures

Due to a variety of issues, including transportation, scheduling between observers, and the requirement for “hot days,” (i.e., around or above 20 degrees Celsius) with no precipitation, the plots could not be observed in a continuous streak. The Feed Preference plot was observed on June 10, 2025, with the Control on June 23, and the Heat Stress on July 1, with a different second observer on the Heat Stress plot, as the initial observer was no longer available.

Field conditions did not remain stable between observation days. Between the Control and Heat Stress, there were two weeks in which it did not rain, and the grass was brown and extremely dry. Then, on that day, a storm rolled in and destroyed the wooden structures. Thus, the Heat Stress plot could not be observed, and no relevant data was collected. The farm had to hay the fields, and further data analysis was no longer possible, as by the time the grass would grow back, the weather was not expected to pose a risk of heat stress.

After this series of events, particularly the unstandardized weather conditions, no conclusions regarding sheep behavioral responses to climatic conditions could be concluded. Despite being a study with climate relevance, similar forage conditions were needed between plots to determine whether a forage preference interacted with climate to determine an animal’s location, so once the grass died, the behavioral responses were no longer able to be reliably determined to be a response to a climatic variable, as the forage variable had changed as well. Further, no wind data was collected, despite hypothesizing about wind speed reduction as a result of windbreaking, and a suitable methodology to analyze the thermal camera data in a standardized way was unable to be determined. Thus, this literature review was born. However, the experience of this author in attempting to conduct a study has provided insight into how future studies can be designed to reduce variability and improve standardization.

2.2 Methodology of Literature Search

A literature search was conducted utilizing the database "Web of Science," utilizing keyword Boolean search. Search terms were:

- "Microclimate*" AND ("small ruminants*" OR "sheep*" OR "goats*")– 117 results
    - "Microclimate*" AND ("small ruminants*" OR "sheep*" OR "goats*") **AND "Agroforestry*"** – 5 results
- "Agroforestry*" AND "Microclimate*" – 364 results
    - "Agroforestry*" AND "Microclimate*" **AND "Hedge*"** – 20 results
    - "Agroforestry*" AND "Microclimate*" **AND ("Heat*" OR "Heat stress*")** – 31 results
- "Agroforestry*" AND ("small ruminants*" OR "sheep*" OR "goats*") AND "silvopasture*" – 30 results
- "Agroforestry*" AND "sheep*" AND "behavior*" – 17 results
- "Agroforestry*" AND "Sheep*" AND "Feed preference*" – 0 results
- "Agroforestry*" AND "Sheep*" AND "feeding behavior*" – 0 results

Studies were also limited to those published since 1990, and in English.

After initial literature identification, the titles and abstracts were read, and papers which did not focus on microclimates of agroforestry with a livestock reference, or climatic stress of ruminant livestock in agroforestry systems, were excluded. This excluded studies which focused on microbiology, non-ruminant focal species, transportation stress, barn construction or indoor housing, soil conditions, and economics, unless thermal stress was specifically mentioned in the abstract. Studies which had focuses on the nutritive value of silvopasture forages, light or shade, humidity or heat, thermal stresses, and/or the use of thermal cameras were kept for further review to determine eligibility.

One of the titles screened was a peer-review process feedback document for an unpublished study. Upon tracing the unpublished study, (Ginane et al., in peer review) was read in full and accepted.

After abstract read, 68 unique/nonduplicate studies were kept, and after full review, 21 studies in total were accepted. A visual representation of this process can be seen in Figure 2.

During this process, it was found that there were very few studies which analyzed hedge agroforestry x heat stress x small ruminants. Thus, the literature filter had to be broadened to include dispersed silvopasture and linear tree systems, ruminants as a whole (i.e. cattle), and broader climatic regions (tropical and Mediterranean climates). This is what led to the final count of accepted papers: 17 primary sources, 4 reviews, 21 total accepted papers.

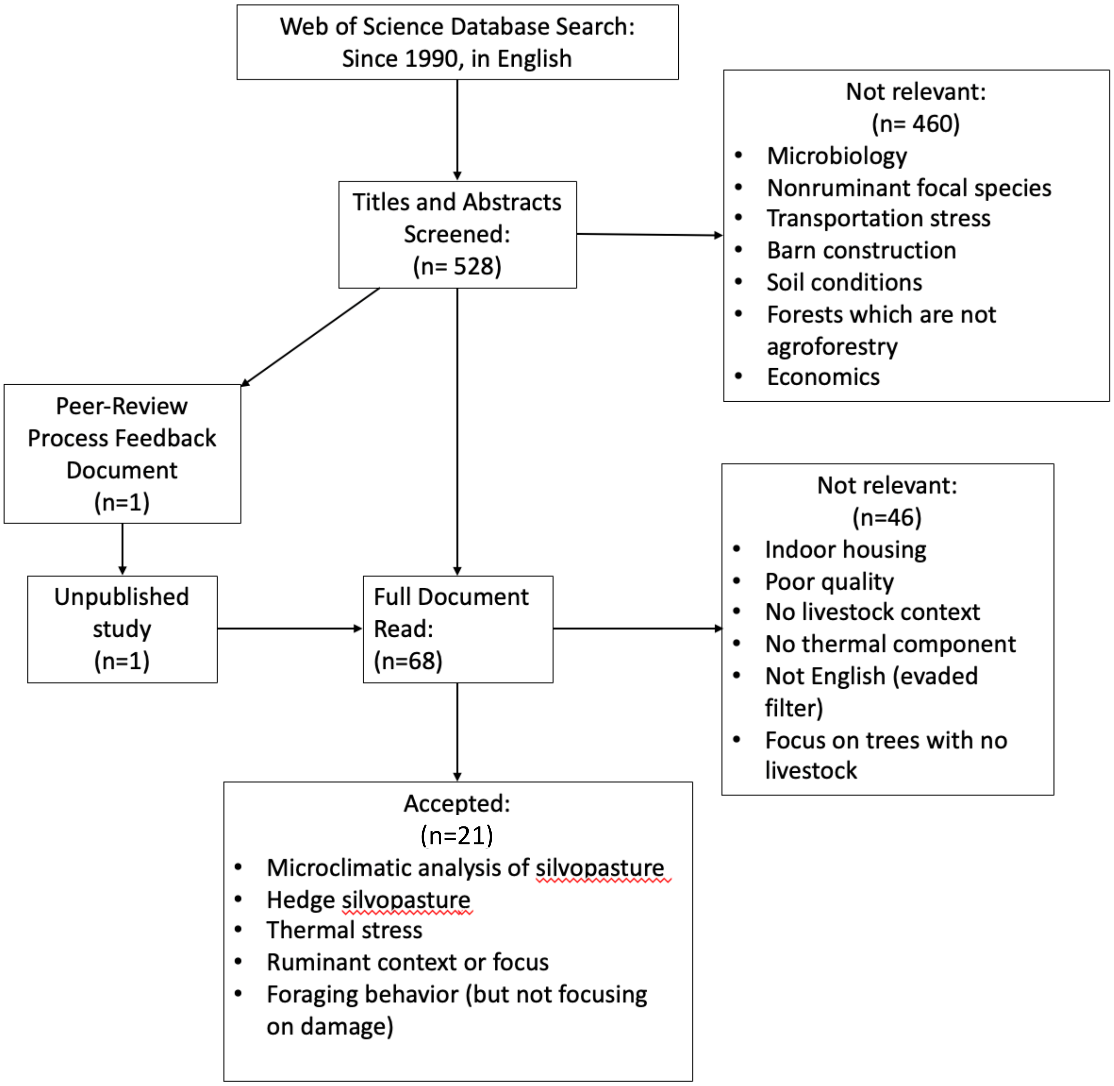


Figure 2: Literature Search Review Process

3 Results and Discussion

3.1 Location and Climate

In the reviewed studies, several trends were identified regarding the locations and climates studied (Figure 3). Namely, once reviews are excluded, the geography was skewed toward Brazilian (8/17, 47%) and Mediterranean (3/17, 17.6%) studies, with only two studies conducted in temperate Europe (2/17, 11.76%). This suggests that studies regarding thermal comfort of animals are more often studied in hotter climates, namely the tropical Brazil and more arid Mediterranean. This would logically track, as one would want to study heat stress in a location where it is of a higher probability, but those climates would likely pose different risks contributing to heat stress than in more humid temperate climates, such as the majority of Europe, leading to the information derived from such research not being one to one relevant for these temperate European climates (Ginane et al., in peer review)

However, broad-strokes geography alone does not accurately account for local conditions. For example, even on a continental basis such as with Europe, climates can vary to significant degrees, such as how the climatically distinct Mediterranean region is often separated in description from the rest of continental Europe, despite both considered to be temperate. The Mediterranean is more arid, and thus has different conditions for plants and animals to thrive there, so the Mediterranean and the rest of temperate Europe is not particularly comparable, despite both having 4 distinct seasons (based on Kottek, Grieser, Beck, Rudolf, and Rubel (2006)). However, the Köppen-Geiger classification system (KG system) can be used to make more accurate descriptors of climatic conditions which may be similar to other areas across the world, allowing for cross-comparison of otherwise different locales. This system classifies climates based on main climates, precipitation, and temperature, leading to a two or three letter climatic abbreviation descriptor (Kottek et al., 2006; Rubel & Kottek, 2010). According to the KG system, the Mediterranean can be compared to similar climates on the west coast of the United States, while temperate Europe can be compared to parts of eastern Australia and New Zealand (Rubel & Kottek, 2010). This allows for the ability to more relevantly directly compare, despite the geographic distance.

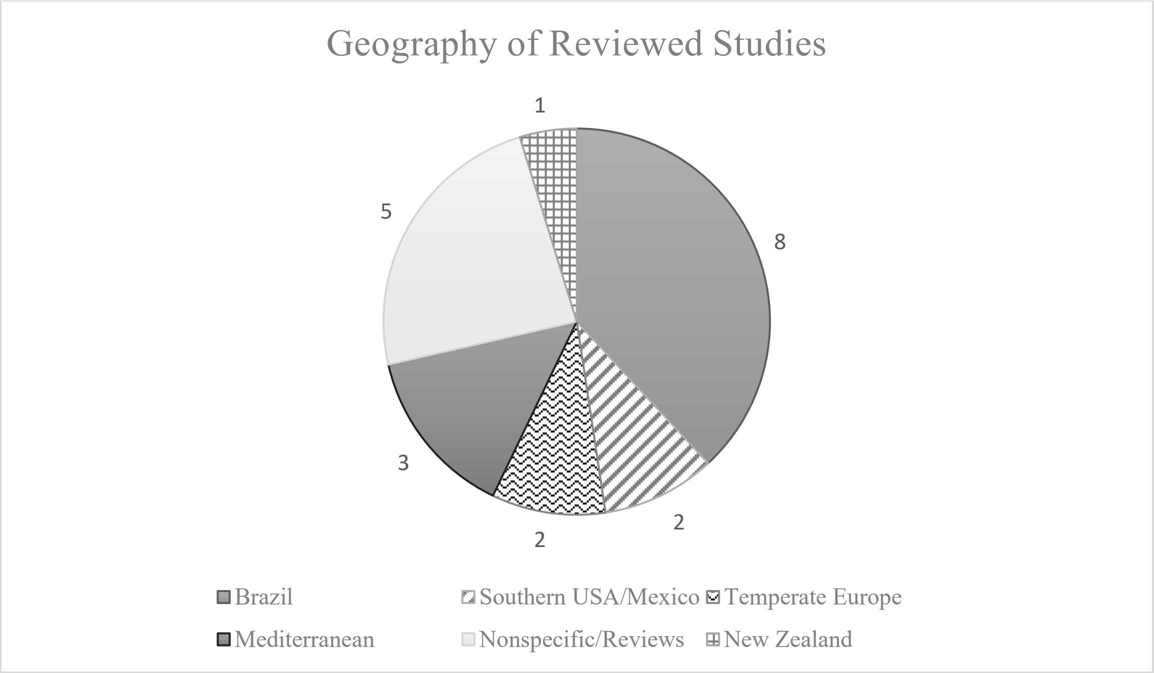


Figure 3: Geography of Reviewed Studies

This long-established system, however, is not always used when it would be relevant to do so (Figure 4). Of primary studies in this review (17 of 21 total), 35.3% did not provide specific Köppen-Geiger classifications of their research sites, and instead decided to provide temperature and precipitation descriptions, geographic landmark descriptions, or no description of typical climate. This makes it more likely that a post-publishing analysis such as this would err in assigning an appropriate KG classification, as it can be assumed that the researchers themselves would be most qualified to determine the relevant KG classification for their research site. However, for functionality's sake in this analysis, the post-publishing classification assignment was attempted.

[1]

	Köppen-Geiger Provided						Köppen-Geiger Absent				
Description	Cw	Cfa	Cfb	Am	Aw	Cfa-Aw Transition Zone	Non-climatic Specific	Reviews with no specified climatic focus	Subtropical	Tropical	No description provided
No. of Studies	1	2	1	1	2	1	1	3	1	2	6

Figure 4: Köppen-Geiger and Other Climatic Descriptions Provided in Studies

The following was estimated based on visual estimations of site locations as provided in study methodologies on maps created by Rubel and Kottek (2010) which projected the change in Köppen-Geiger classifications over time on a pixelated, color-coded global map. Of these unclassified studies, 2/6 were Brazilian, and were identified as likely warm temperate fully humid hot summer (Cfa) (Dada et al., 2021) and likely either equatorial desert (Aw), warm temperate fully humid hot summer (Cfa), or arid steppe hot arid (BSh) (Sousa et al., 2015). Mediterranean climates made up 3/6 of the unclassified studies, and were identified as being likely warm temperate steppe hot summer (Csa) or warm temperate steppe warm summer (Csb) (Ripamonti et al., 2025; Sánchez et al., 2010), and likely Csa, Csb, or arid steppe cold arid (BSk) (Sánchez & McCollin, 2015). The last unclassified study was Welsh, and thus is likely to be warm temperate fully humid warm summer (Cfb) (Atkin-Willoughby et al., 2022). As stated previously, there is much potential for error in this after-the-fact classification, as reliable maps available do not zoom in far enough to discern landmarks even as general as major cities, nor are they searchable by

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[1] Figure 4 Abbreviations: Cw – Warm temperate, desert; Cfa – Warm temperate, fully humid, hot summer; Cfb – Warm temperate, fully humid, warm summer; Am – Equatorial monsoonal; Aw – Equatorial desert

coordinates, both of which are often provided in these studies as location reference. The estimations of location therefore had to be conducted based on loose estimation of uniquely shaped international and coastal borders, hence the uncertainty. There is another, more detailed, map which exists (Jerue), though it was created by an individual whose qualifications could not be properly vetted, and it was not directly linked to any officially published peer-reviewed source material, hence the use of the pixelated maps created by Kottek et al. (2006) and Rubel and Kottek (2010).

Thus, best practice would be to provide the Köppen-Geiger classification for a study within the methodology, for ease of comparison, and for accuracy in review. A summary of the full Köppen-Geiger classifications of the reviewed papers can be found in Table 1.

At this point, please refer to the supplementary document to view

Table 2: Climatic Descriptions, Agroforestry Type, and Livestock Species per Paper

It would typically be inserted into this document here, however formatting issues necessitated a separate document.

When establishing and managing agroforestry systems, one must be acutely aware of the climatic conditions at hand, as those determine, at a broad scale, whether a system or pairing will function or fail to achieve the desired result. It thus is sensible to not unquestioningly accept conclusions derived from climates which are not relevant, or similar, to one’s own. With so much of the agroforestry x climatic stress research focused in equatorial and arid locales, it provides little to no information which is relevant for agroforestry researchers and practitioners in wetter temperate climates, such as those which characterize much of Europe, the eastern half of the United States, and significant parts of Argentina, Uruguay, China, Australia, and New Zealand, to name a few. Instead, research needs to be branched out to cover this rather large gap of temperate agroforestry heat stress, especially as climate change threatens the welfare of our livestock in different ways compared to these equatorial and arid locales. We need to know how to design and manage agroforestry systems for buffering the effects of climate change in temperate climates.

3.2 Type of Agroforestry: Dispersed Trees vs Linear/Hedge

One of the major descriptors of an agroforestry system, apart from whether it will be crops or livestock produced, is how the woody component is distributed: clustered, dispersed, or linear. In agroforestry, clustered plantings are typically pre-existing trees, such as a patch of forest left over from clear-cutting, or attempts to re-establish forest on previously clear-cut land, and it is typically not considered to be agroforestry due to the lack of intentional planting or management for the benefit of crops or livestock (Jordon, Willis, Harvey, Petrokofsky, & Petrokofsky, 2020).

3.2.1 Dispersed Trees

One of the most common forms of silvopasture is the use of dispersed trees in a paddock or grazing livestock under lumber trees. This theoretically creates a well distributed network of shade patches which are more or less evenly distributed within the grazing area, allowing for a comparatively more or less spatially homogenous microclimate. While linear silvopasture has been shown to have non-homogenous temperature fluctuations within a plot (Karvatte Junior et al., 2021), it is unknown to this author whether a thermal camera has been used to test whether hotspots are commonly present in dispersed silvopastoral plantings. In hot climates, dispersed tree silvopasture is extremely common and popular as a natural shade structure for animals to rest and graze under, and this is also represented in the literature. Of the primary studies included in this review, 50% concerned dispersed tree silvopastoral planting, with 31% concerning linearly planted tree rows, and only 13% concerning linear hedges. Only one study (6%) directly compared dispersed tree silvopasture with linear hedges.

3.2.2 Morphology of Trees vs Hedges

There are significant morphological and managerial differences between trees and hedges. While the effects of dispersed tree silvopasture are relatively well-established regarding microclimates in the literature, the effects of hedges are grossly understudied. Yet, when agroforestry benefits are presented, it is often reporting dispersed silvopasture benefits and extrapolating them as being benefits of agroforestry as a whole, and this may not be the case. One does not expect a field full of umbrellas to work in the same way as a field full of walls. A tree, like an umbrella, provides protection from above, but little from the side. Meanwhile a wall provides minimal protection from above, but more from the side. Thus, if one were to shelter from rain or intense sunlight, one would prefer an umbrella or a tree, but if one were to shelter from strong wind, one would cast the umbrella aside for sheltering behind a wall. Trees and hedges have different strengths and weaknesses, just as umbrellas and walls. Trees, due to their protection from above, are more effective at blocking solar radiation, but this can create a wide area for competition for light, hindering forage growth potential. Meanwhile, hedges have to provide shade from the side, and thus would cast less overall, potentially reducing their effectiveness as a shade structure for animals to shelter under. However, they would compete less with forage for solar radiation, potentially maintaining higher forage biomasses in linear hedge systems compared to dispersed trees (Baker, England, Brooks, Stewart, & Mendham, 2025). Thus, hedges may not be the most suited for climates or conditions where shade is of great importance, and this may be a reason why so few hedge studies exist, as heat stress agroforestry is geographically and climatically focused in the equatorial tropics, such as Brazil, and shade would be of great, or even primary, importance there. This, of course, can be altered to a certain degree based on morphological changes (e.g. increasing the hedge height to cast more shade), and planting orientation relative to the equator, but the exact effects of these variables are also understudied within hedge agroforestry for the purposes of heat abatement, so it can only be theoretically generalized. On the other hand, hedges have been historically used as windbreaks to protect livestock from winter extremes, reducing the effect of wind chill (Atkin-Willoughby et al., 2022; Sánchez & McCollin, 2015). While hedgerows are found globally, in temperate climates they were of great historical importance for the fencing containment and winter survival of livestock (Smith, 2010). While trees can also have a wind reduction effect, they likely require relatively high densities compared to hedge plantings in order to achieve a similar effect. However, due to the lack of direct one-to-one comparison in the literature, these claims can only be hypothesized. Baker et al. (2025) found in their review evidence to suggest that dispersed tree systems are more likely to protect livestock from extreme weather events, primarily due to their direct overhead shade and larger area of microclimatic alteration than linear systems, even at lower densities of 50 trees/ha, however this is not officially tested. While wind speed reduction is analyzed in studies for both dispersed trees and linear hedges, they cannot be one-to-one compared in terms of effect size without a direct comparison study or a meta-analysis, the latter of which was not found in the search during this review.

3.2.3 Direct Effect Comparison of Dispersed Trees vs Linear Hedges

Only one study in this review was found to directly compare linear hedges versus dispersed silvopasture, in the Mediterranean dehesa/montado in Spain (Sánchez & McCollin, 2015). Sánchez and McCollin (2015) found that dispersed tree silvopasture (dehesas) had similar temperatures to linear hedges, but hedges had an average of 25.1% higher soil water levels and 16.6% higher soil organic carbon under hedgerows compared to the dehesas. They also observed greater wind reductions in dehesa, but lower total wind speed values in the hedged landscape (Sánchez & McCollin, 2015). This was theorized to be due to the quiet zone effect put forth in Cleugh (1998), where a windbreak reduces the wind speed heavily over a distance of 5-10 times the height of the windbreaking vegetation, creating a "quiet zone" in a right angle triangular area behind the windbreak. The taller the vegetation, the longer the quiet zone distance behind the windbreak. However, one must also consider the permeability of the windbreak. As permeability increases, the less windbreaking will occur. Thus, if a tree has most of its volume high above the ground, it is likely to be more permeable at livestock height than a hedge, which has its volume focused closer to the ground than a tree. However, once again this can only be hypothesized, as no studies were found which directly quantified the differences in permeability between trees and hedges. This difference is likely to be affected by many factors, including species and season (e.g. deciduous vs evergreen in winter) and life stage. The latter was observed particularly during the attempted fieldwork presented previously, as the hedges were immature at the intended research site, and had not yet knit together into a more-or-less impermeable wall that hedges are known for. Instead, the immature hedges visually resembled feathers and would wave wildly in the wind, and while wind speed data collection was overlooked, it did not appear as though any amount of wind speed reduction was taking place.

3.2.4 Pasture Productivity by Planting Distribution

When benefits of agroforestry were reviewed in Baker et al. (2025), it was found that competition and yield effects differed based on whether dispersed or linear agroforestry were used, and based on whether crops or livestock were produced in the system with a high degree of variability. Windbreak paddocks for livestock had an 8.3% reduced forage yield compared to open field controls, but there was a wide standard deviation between the studies, and there were relatively few studies analyzing yields for livestock pasture (Baker et al., 2025). Further, alleys reduced yield by 17.63% on average, but the effect was also highly variable, with the width of the alleys significantly affecting total paddock yield, with spacings under 10 tree heights predicted to have reduced yields compared to controls, and as much as a 25% yield reduction when the width is less than 2.5 tree heights (Baker et al., 2025). Meanwhile, dispersed agroforestry had an average yield reduction of 20.8%, with tree density significantly affecting the size effect, as much as 30% when densities exceeded 800 trees/ha.

However, other studies which analyzed pasture/forage production according to tree density found different scales of effect. Ginane et al. (in peer review) found a 50% reduction in sward biomass between dispersed tree densities of 60 and 150 trees/ha, with a difference in forage nutrition, as other studies have observed. Studies have found an increase in crude protein content in forages under tree shade, and have suggested that the higher protein content can compensate for reduced forage biomass and maintain competitive livestock weight gains compared to open pasture (Fedrigo et al., 2019; Ginane et al., in peer review; G.J. Pent, Greiner, Munsell, Tracy, & Fike, 2020). However, this effect varies greatly from study to study. In the case of Ginane et al. (in peer review), this compensatory effect was not enough to prevent weight loss in otherwise unsupplemented ewes, losing 10% of body weight in year 1 and 25% in year 2, though the growth of their twin lambs was not impaired and increased linearly. Further, increased density is often paired with shorter grazing periods or reducing stocking densities (Ginane et al., in peer review; G.J. Pent et al., 2020). Ginane et al. (in peer review) suggests an optimal dispersed silvopastoral tree cover of approximately 30 trees/ha, between their lowest (1 tree/ha) density and their medium (60 trees/ha) density, specifically to balance the effects of trampling and feces spread under the trees reducing the grazeability of the shaded areas (since sheep prefer to rest under the shade when it is a limited resource, but will graze under it when it is more plentiful), and maintaining the productivity of the pasture and subsequent biomass availability.

A review conducted by Jordon et al. (2020) found that 53% of studies which analyzed pasture production found either “an outright negative effect on production or that it showed an incremental decrease with increased tree density… cover.. or proximity to pasture measured… However only 20% of livestock growth studies found an outright negative effect,” once again suggesting that crude protein content can have a compensatory effect on livestock growth rates. Further, Jordon et al. (2020) found a positive effect of linear systems (shelterbelts, windbreaks, and hedges) on livestock growth, heat stress, cold stress, milk yield, and weather-related mortality, but found little evidence about the effect of these systems on pasture productivity specifically.

Despite this statement, or perhaps because of it, dos Santos et al. (2025) found that in the Brazilian rainy season, linear silvopasture had the highest forage availability in the center of the rows (i.e. the sunniest area between tree rows), and in the dry season the monocultural pasture forage only reached the production values similar to the shaded areas in the silvopasture. Thus, the silvopasture had an overall greater forage production, though there were managerial differences in the cattle rotation schedule between treatments, which may negate the value of this data altogether. Instead of maintaining the same entry/rotation criterion for both treatments, dos Santos et al. (2025) used the pasture height criterion for rotation in the silvopasture treatment, and the fixed days criterion under the open pasture/monoculture treatment. The stocking densities were significantly different between treatments in the first year (16 animals in SP and 75 in pasture monoculture in year 1) to reflect their claim about intensification potential in silvopasture, but this may prove to be the result of the different entry criterion used, not just that of the silvopasture variable (dos Santos et al., 2025). If the entry management is truly not the culprit, it is possible that the silvopastoral forage increase may be due to the overabundance of solar radiation that characterizes the Aw climate. If solar radiation is not the limiting factor, as it likely is not in this case, then the higher relative humidity found in the silvopastoral treatment may be a determining reason why the SP had a higher forage production (dos Santos et al., 2025). A higher relative humidity in that treatment could have stimulated an increased forage growth compared to the drier monoculture pasture treatment.

Ultimately, dos Santos et al. (2025) recommended an optimal density of 200 trees/ha when using linear eucalyptus silvopasture in an Aw climate.

3.2.5 Microclimatic Factors and Thermal Comfort by Planting Distribution

Many of the microclimatic studies in this review agree on the alterations provided by agroforestry systems – the air and soil temperature are lower in the shaded areas, and the relative humidity is higher. Due to the fact that most of these studies were tropical, Brazilian, and analyzed dispersed silvopasture, it makes sense that they would have similar results. However, some of their conclusions about the benefits of these microclimatic alterations are not necessarily able to be extrapolated out to temperate climates. Namely, as pointed out by Ginane et al. (in peer review), the risk factors of heat stress differ between tropical and temperate climates. In tropical climates, relative humidity poses a much higher risk of heat stress than in temperate climates. In Ginane et al. (in peer review), a temperature-relative humidity (TRH) synthetic climatic parameter was created, and was found to explain 77% of the variance in thermal comfort, with increasing TRH values equating to increasing temperatures and radiation, but lower humidity, a notable difference from most of the thermal comfort indices used in heat stress studies, as those were largely developed in tropical climates where humidity poses a larger risk (Ginane et al., in peer review). The reasons behind the creation of the TRH parameter will be discussed in the “Thermal Comfort Indices” section of this review.

Further, while livestock can become acclimatized to higher humidity (Sousa et al., 2015), this is only to a certain point, after which animals can become overwhelmed. Due to the windbreaking nature of agroforestry plantings, mainly linear silvopasture and hedgerows, the windspeed is slower within these plantings, potentially staling the air and reducing the ability of the animals to alleviate heat stress. One of the primary ways in which small ruminants will reduce heat is by standing in a windy area, but if the wind speed is reduced through the use of a windbreak, this may worsen heat stress conditions for the animals, particularly if the humidity is higher than can be tolerated (Gupta et al., 2025). Thus, the question becomes whether the windbreaking function of linear silvopasture and hedgerows would create more severe heat stress conditions in livestock, despite any shade provided. This is the question the attempted fieldwork meant to answer, whether the windbreaking by hedgerows would worsen heat stress conditions by reducing the effectiveness of one of the main behavioral strategies used by sheep to reduce heat stress, or if the meager shade provided by such structures was enough to compensate for this effect. If this were to be the case, then hedges may prove to be harmful structures in the face of climate change, despite their significant historical use to improve lamb winter survival. In fact, this may be one of the factors influencing the understudy of hedges in heat stress contexts – they were historically used for winter survival, and thus are associated with winter conditions, not summer heat. If we are to fully understand the effects of agroforestry systems on livestock welfare in the face of climate change, then we must also study hedges within this context.

3.3 Thermal Stress: Heat Stress and Animal Behavior

When analyzing the risk of heat stress occurring, microclimatic factors only make up half the equation. The other half, which is often overlooked in such studies, is the animal behavior. Animals are complex beings with complex behaviors that are not always logical or cooperative, nor do they always make the best decision. Animals are not omniscient, and make mistakes. While we may be capable of taking in all the information available to make the best decision given current conditions, the animals may not have all said information, and their individual motivations may alter which decision they make. Thus, we must always consider the animal behavioral component and its role in heat stress. When livestock begin to experience undesirable climatic conditions, they have several mechanisms which can alleviate the problems and maintain homeostasis, primarily morphological changes, physiological changes, and behavioral changes (Seijan, Bhatta, Gaughan, Dunshea, & Lacetera, 2018).

3.3.1 Morphological Prevention of Climatic Stress Conditions

One of the easiest examples of morphological changes driven by climate are hair growth in the autumn, and hair shedding in the spring, as animals create and eliminate insulation on a seasonal basis. Further, many heat-tolerant livestock breeds have extensive horns, long ears, or fat tails used to transmit heat back into the environment (Seijan et al., 2018). These are important factors for heat dissipation largely within a genetic context, as livestock can be selectively bred to have these features. Morphological features are typically an adaptation for a particular climate built over selective breeding or natural selection over generations, and not a response to acute heat stress. Due to winter survival of livestock being more significant of a concern for temperate climates such as the majority of the European continent, many livestock breeds are more adapted to face cold stress than heat stress, with such features as thick wool and hair, large bodies, and strong heat-producing metabolisms. These features have been cemented over generations of selective breeding, and now serve as a potential genetic and morphological disadvantage in the face of a warming climate.

3.3.2 Adaptive Responses to Onset of Heat Stress

Physiological and behavioral changes tend to be responses to heat stress when it occurs.

Physiological changes as a response to heat stress are often difficult to identify without handling the livestock, as they start as subtle changes, but indicate when the body is initially responding to an acute, or even chronic, heat stress condition. Some of the most common physiological changes seen in heat stress studies include an increased heart rate, increased respiratory rate, an increased panting score, changes to blood glucose levels, alterations in milk production, increased skin surface temperatures, increased rectal temperatures, reduced rumination rate, reduced dry matter intake, and increased blood or hair cortisol, among others (Seijan et al., 2018). Oftentimes the studies will measure a handful of related relevant physiological parameters, such as respiratory rate and panting (Ginane et al., in peer review), skin surface temperatures and rectal temperatures (Vieira et al., 2021), and altered blood glucose levels and hair cortisol (Ripamonti et al., 2025), but will not study a broad range of them. Some physiological parameters are more indicative of acute heat stress (e.g. respiratory rate, panting score, rectal temperatures), while some are more indicative of chronic conditions (e.g. hair cortisol, milk production). However, the final determination of heat stress severity can differ greatly depending on which data are collected and which parameters are used, even on an individual level. Some individuals (or genetic lines) may be more tolerant of certain conditions than others, and may have different physiological responses as a result, for example, if they have differing morphological adaptations (Seijan et al., 2018). In other cases, individuals may be equally tolerant of certain conditions, but have differing levels of stress depending on other factors, namely behavior.

Livestock behave as both individuals and as groups, as ruminants such as cows and sheep are highly social, and group dynamics are known to influence individual behavior. Hierarchies can influence resource access, and socially dominant individuals can hoard resources and prevent those lower in the hierarchy from accessing those resources (e.g. access to water sources, shade, and desirable forages) (Barroso, Alados, & Boza, 2000; Woodcock et al., 2019). In the case of heat stress, when these resources are scarce or limited, it can be the socially subservient individuals which may suffer. This is one of the reasons why welfare is considered on the individual level, as these group species are not egalitarian, and while the highest-ranking individuals may be thriving, the lowest-ranking may be suffering.

Further, livestock have to be somewhat aware of the variation in conditions in order to choose conditions which are suited to their needs. If they are unaware of a better suited location, or are otherwise unable to access it, perhaps due to social displacement by dominant conspecifics, they may not make the "objectively correct" decision as determined by a human manager. Thus, managers must allow for "livestock-error" when designing the environment they are housed in, and provide enough of necessary resources to allow for equal access and reduce resource guarding as much as possible.

Managers also must be aware of the behavioral adaptations to heat stress. Physiologically, livestock tend to reduce their consumption of feed during hot periods, and have been known to behaviorally adapt by grazing at night, an adaptation which has been observed to maintain body weights even despite a reduced feed intake during daytime observation periods (Marchand et al., 2015; Seijan et al., 2018). Sheep will also stand at rest instead of lying on the ground, particularly in conditions where the soil/substrate temperature is too high to wick away body heat from lying on it (Seijan et al., 2018). Instead, they utilize wind to wick away this heat. However, hedges in particular have historically been used as a windbreak due to concerns over winter wind chill threatening livestock survival. In the context of heat stress, this could be an issue, as reducing the wind speed through this windbreaking function could reduce it to the point where the livestock are unable to perform this standing-in-the-wind behavior, removing one of the main behavioral outlets for reducing heat stress. This was the basis of the aforementioned attempted fieldwork, that the use of agroforestry hedges may reduce the ability of sheep to thermoregulate in hot conditions due to their windbreaking function, and that the shade provided by the hedges may not be enough to compensate for this wind reduction effect. This has yet to be tested in the literature.

3.3.3 Thermal Comfort Indices

One of the most concerning issues within thermal stress studies and their relation of animal behavior is the use of thermal comfort indices. While they are incredibly helpful for cross-study comparison, as they create a standardized value range specifying the thermal comfort or thermal stress risk severity for a species, they are often used inappropriately for the specific situation being analyzed, and are woefully inadequate in properly describing the risk factors involved in thermal stresses. Some of the most popular indices will be briefly described here, though a more comprehensive review can be found in (Wang, Bjerg, Cho, Zhong, & Zhang, 2018), which this section is based upon, due to the value and clarity of their review.

THI, or the temperature humidity index, is the most simple of the thermal indices, having been developed to describe human comfort in summer by using temperature and relative humidity variables, and was later extended to cover indoor housed dairy cattle, where conditions would have low air circulation and little to no solar radiation due to roof structures (Wang et al., 2018). Despite its severe limitations through not incorporating solar radiation or wind speed factors, THI is commonly used in the reviewed studies, regardless of the fact that outdoor conditions in agroforestry or pasture systems would be greatly influenced by these excluded factors. THI was modified in subsequent versions to improve its accuracy (Wang et al., 2018).

The Black Globe Humidity Index (BGHI, or BGHTI) is also commonly used, and describes outdoor conditions better than the THI due to its consideration of wind speed and solar radiation, and is commonly used in the reviewed studies (Wang et al., 2018). However, it was developed for use in cattle, as most thermal indices were, not for other ruminant species. The black globe temperature is obtained by measuring the surface temperature of a black copper sphere 1m or 2.1m above the ground, and despite the fact that BGHI was found to correlate more with milk yield than THI4 (a subsequent variation of THI), no difference was found between THI4 and BGHI for shaded cattle, indicating that BGHI may be equally as inaccurate or inappropriate to use in agroforestry conditions as THI (Buffington et al., 1982; Wang et al., 2018).

The heat load index (HLI) incorporates the black-globe temperature, relative humidity, and wind speed for predicting heat stress in an indoor housing context (Wang et al., 2018). It was developed using panting scores from Angus beef steers and treats any increase in relative humidity as a heating effect, which may not be the case in temperate environments, as suggested by the inverse relationship between heat stress and relative humidity found in Ginane et al. (in peer review), and supported by claims by Marcone, Kaart, Piirsalu, and Arney (2021).

The comprehensive climate index (CCI) is the only index which can cover both heat stress and cold stress (Wang et al., 2018). To describe hot conditions (air temperature above 5°C), CCI uses relative humidity, wind speed, and solar radiation as climatic factors, with panting scores as the physiological response factor, and is considered to be more accurate than THI in estimating the cooling effect of increasing wind speed when wind speed is low, as it uses a logarithmic adjustment, while THI uses linear (Wang et al., 2018).

Finally, the index of thermal stress for cows (ITSC) was developed in 2015 to describe the effect of solar radiation on cattle in tropical environments (Wang et al., 2018). It was not used in the reviewed studies, despite its focus on tropical cattle. This may be due to the fact that it was developed using Holstein cattle (Wang et al., 2018), a dairy breed which is known for being rather heat intolerant. Thus, ITSC may overestimate the amount of heat stress being experienced by cattle which are more suited to tropical climates. ITSC also includes the effective radiation heat load (ERHL) as a part of its calculation, which estimates the amount of thermal energy emanating from the ground and surrounding objects, a factor which is usually not considered in other indices, despite being of importance in heat transfer theory and potentially being one of the factors influencing standing at rest behavior in heat stressed livestock (Wang et al., 2018). However, Wang et al. (2018) also finds that despite the theory that the ITSC should increase as the ERHL increases, as there would be more heat in the surrounding environment, the opposite occurs, as the ERHL has a negative coefficient, providing another point of contention with its application in subsequent studies, despite the well-intentioned inclusion of such a factor.

Each index has its own numerical thresholds at which it is said that the probably risk of heat stress begins and intensifies, but these thresholds can differ based on a variety of compounding factors, including cattle breed, coat color, health status, acclimatization to the environment, access to shade, etc. which only HLI attempts to consider (Wang et al., 2018). It must also be considered that many of the studies were conducted using Holstein dairy cattle, a high-yielding Dutch breed, and thus may underreport the heat stress potential due to Holsteins being particularly heat intolerant, as a result of their high milk yield necessitating a larger heat transfer into the environment, which is not as feasible in tropical environments (Santana Jr., Bignardi, Pereira, Stefani, & El Faro, 2017). Hammami, Bormann, M'hamdi, Montaldo, and Gengler (2013), as described in Wang et al. (2018), found that livestock raised under temperate conditions had lower heat stress thresholds than tropical, subtropical, and Mediterranean conditions because of reduced adaptability to hot conditions, a speculation supported by Marcone et al. (2021) who found that Estonian sheep experienced heat stress even in relatively mild overcast summer days, as shown through increased panting scores.

Generally speaking, Wang et al. (2018) found that, of the indices described here, BGHI, THI_{adj-d}, and CCI performed better in most of their reviewed datasets, and highlighted that factors such as breed of livestock, physiological response included when creating and analyzing the index, experiment location, and management can alter results even under similar environmental conditions. Table 3, taken from Wang et al. (2018), summarizes the thermal indices, the breed of cattle used to create them, the climatic factors included in their calculations, where they were developed, and whether solar radiation was considered. As Ginane et al. (in peer review) points out rather clearly, none of these indices were developed in an agroforestry context, and all are exclusive to cattle. There are no small ruminant- or agroforestry-specific thermal indices, and the co-opting of cattle indices and thresholds reduces the accuracy of thermal stress conclusions in small ruminant studies.

Table 3: Overview of thermal indices and factors included in their development, cited from (Wang et al., 2018).

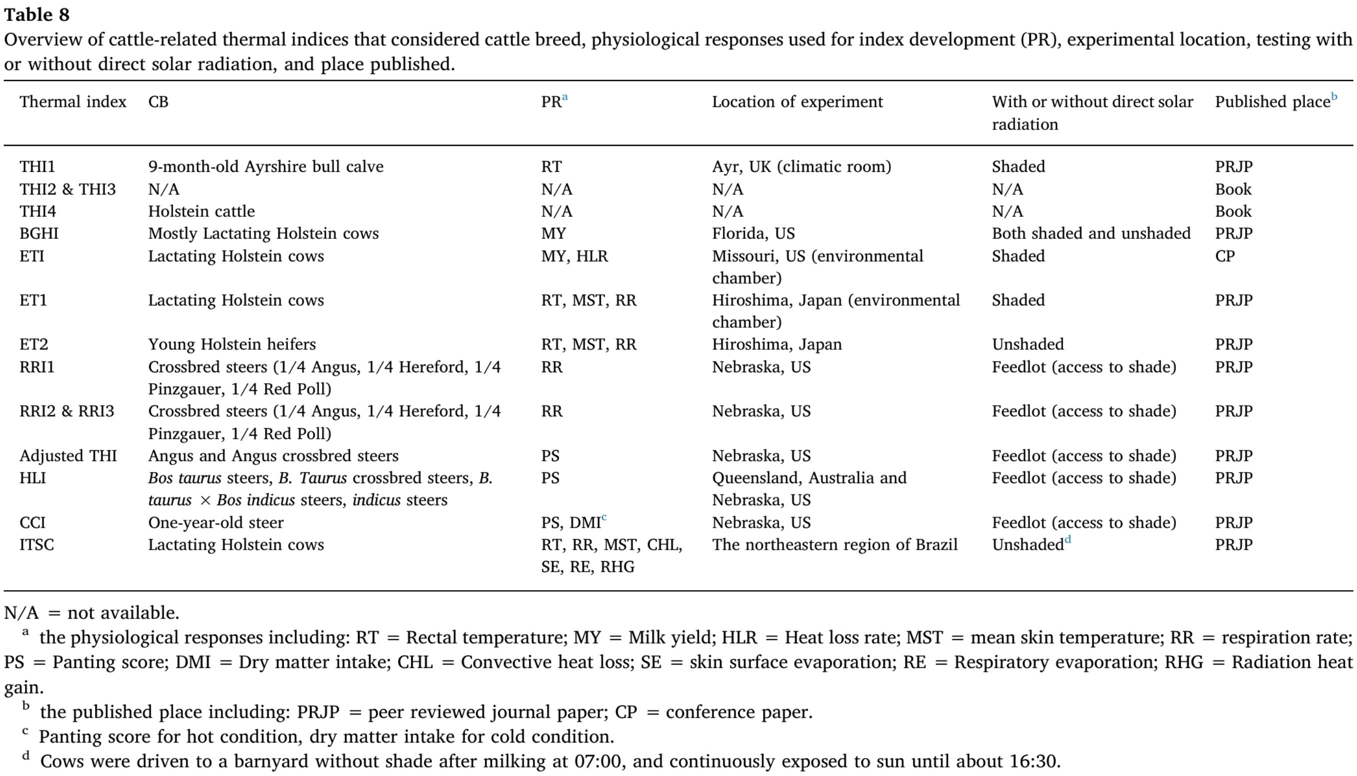

Table 8

Overview of cattle-related thermal indices that considered cattle breed, physiological responses used for index development (PR), experimental location, testing with or without direct solar radiation, and place published.

Thermal index	CB	PR[a]	Location of experiment	With or without direct solar radiation	Published place[b]
THI1	9-month-old Ayrshire bull calve	RT	Ayr, UK (climatic room)	Shaded	PRJP
THI2 & THI3	N/A	N/A	N/A	N/A	Book
THI4	Holstein cattle	N/A	N/A	N/A	Book
BGHI	Mostly Lactating Holstein cows	MY	Florida, US	Both shaded and unshaded	PRJP
ETI	Lactating Holstein cows	MY, HLR	Missouri, US (environmental chamber)	Shaded	CP
ET1	Lactating Holstein cows	RT, MST, RR	Hiroshima, Japan (environmental chamber)	Shaded	PRJP
ET2	Young Holstein heifers	RT, MST, RR	Hiroshima, Japan	Unshaded	PRJP
RRI1	Crossbred steers (1/4 Angus, 1/4 Hereford, 1/4 Pinzgauer, 1/4 Red Poll)	RR	Nebraska, US	Feedlot (access to shade)	PRJP
RRI2 & RRI3	Crossbred steers (1/4 Angus, 1/4 Hereford, 1/4 Pinzgauer, 1/4 Red Poll)	RR	Nebraska, US	Feedlot (access to shade)	PRJP
Adjusted THI	Angus and Angus crossbred steers	PS	Nebraska, US	Feedlot (access to shade)	PRJP
HLI	*Bos taurus* steers, *B. Taurus* crossbred steers, *B. taurus* × *Bos indicus* steers, *indicus* steers	PS	Queensland, Australia and Nebraska, US	Feedlot (access to shade)	PRJP
CCI	One-year-old steer	PS, DMI[c]	Nebraska, US	Feedlot (access to shade)	PRJP
ITSC	Lactating Holstein cows	RT, RR, MST, CHL, SE, RE, RHG	The northeastern region of Brazil	Unshaded[d]	PRJP

N/A = not available.

[a] the physiological responses including: RT = Rectal temperature; MY = Milk yield; HLR = Heat loss rate; MST = mean skin temperature; RR = respiration rate; PS = Panting score; DMI = Dry matter intake; CHL = Convective heat loss; SE = skin surface evaporation; RE = Respiratory evaporation; RHG = Radiation heat gain.

[b] the published place including: PRJP = peer reviewed journal paper; CP = conference paper.

[c] Panting score for hot condition, dry matter intake for cold condition.

[d] Cows were driven to a barnyard without shade after milking at 07:00, and continuously exposed to sun until about 16:30.

Despite these severe limitations, and the fact that indices are meant to identify *risk* of heat stress, some studies rely entirely on the assumption that thermal indices equate directly to the thermal comfort of animals without confirming this with animal-based data. In this review, this was seen specifically in Magalhaes et al. (2020) and da Silva et al. (2024). These studies sought to analyze the thermal comfort of cattle in Brazilian silvopasture, but did not collect any physiological, or even behavioral, data regarding the cattle. They simply assumed that the index value derived from climatic data directly equated to the thermal comfort of the cattle, so much so that they might as well not have had cattle in the field at all. By utilizing these indices without any behavioral or physiological data to confirm their conclusions, all these studies are really doing is confirming that shade is cooler than direct sunlight without much further benefit to the literature base, and assuming that the relative risk identified by the index values equates to the factual presence of heat stress. However, it must be noted that of the two papers, Magalhaes et al. (2020) is of higher quality, as it describes the seasonal variation of photosynthetically active radiation within a silvopastoral planting of single tree rows and triple-planted tree rows, providing insight into the effects of planting strategies of silvopastoral trees, as well as silvopasture versus open pasture. Despite this, it still relies too heavily on thermal comfort indices without behavioral or physiological data confirmation. Meanwhile da Silva et al. (2024) largely focuses on the use of thermal cameras as a tool for determining that shade is cooler than direct sunlight, to the detriment of any indication as to the actual welfare of the cattle (as opposed to the assumed degree of welfare as determined by the contextually irrelevant index). Vieira Junior et al. (2019) also assumes that thermal comfort indices directly indicate animal comfort, though they record animal behavioral responses over 3 days out of the year. While this is better than nothing, the strength of the behavioral data could be greatly improved with more representative days for each season. Because there are no replicate observation days within a season, one day is essentially representative of the whole season, shallowing the value of the behavioral observations, and thus, the strength of the paper as a whole.

With the additional information of behavioral, or even better, physiological, data, more can be contributed to the literature base regarding the behavior/physiology/index divide, where different results might be derived from utilizing different metrics, and these studies can be applied more broadly in other reviews and meta-analyses for a variety of other subjects.

Ginane et al. (in peer review) makes this point with the aid of Wang et al. (2018)and Herbut, Angrecka, and Walczak (2018), mentioning specifically that none of these indices were created with agroforestry in mind as a relevant context, and that they were mostly developed in a tropical context, where the weather components that increase the risk of heat stress are different from temperate climates. Specifically, many of the thermal climatic indices utilize relative humidity as a component, as high relative humidity is a large risk factor for heat stress in tropical regions. However, this was found to not be the case in temperate regions by Ginane et al. (in peer review) and Marcone et al. (2021), where relative humidity was found to not be a significant contributing factor to heat stress. This leads to thermal comfort indices to be entirely nonrelevant to these kinds of studies (temperate, small ruminant, agroforestry heat stress studies). Thus, Ginane et al. (in peer review) rejects the use of these indices as the primary method of comfort analysis altogether, and utilizes a systematic climatic parameter based on the site-specific climatic factors that most explain the variance in responses they found.

Ginane et al. (in peer review) notably did not create their own index. It is debatable whether creating new indices to cover a wider range of scenarios is advisable, considering how many there would need to be. The existing indices are extremely narrow in their range of conditions in which they could be considered to be accurate, due to their development methodologies. This has to do with them largely ignoring the thermal tolerance variation amongst species, breeds, and individuals, as discussed in the "Heat Stress and Animal Behavior" section; ignoring the behavioral response of the livestock within a study plot, as seen when studies do not collect ethogram behavioral data, nor treating heat stress as an individual condition; and they are grossly misapplied to irrelevant climatic conditions. Thus, in order to preserve the useful metric of an index for cross comparison between studies, they would need to cover a range of climatic conditions (such as following the Köppen-Geiger classification), livestock species and subcategories (such as beef vs dairy cattle, or hair vs wool sheep, though these can become infinitesimally more specific following certain genetic lines or adaptations), housing/management type (indoor, indoor ventilated, open pasture, and varying densities of agroforestry plantings, both linear and dispersed), and other relevant geographic or climatic variances that add further complexity to the site (such as mountainous regions, unique topography, el Niño, etc.) Thus, it was incredibly wise for Ginane et al. (in peer review) to utilize their own parameter created from site-specific conditions which are the most relevant to the local climate as possible, and at least for now, until the question of further index development is properly addressed, creating these systemic climatic parameters may be the best option moving forward, rather than de-facto relying on THI and BGHI as most of the studies analyzed in this review did.

This creates the problem, though, of the systematic climatic parameters not being directly comparable across studies for use in meta-analyses and reviews. This is the gap that thermal comfort indices were originally created to bridge, however, there are other ways in which this can potentially be addressed. As mentioned before, new indices could be created, despite the infinitesimal complexity required to adequately describe a particular climatic and managerial niche, which would be a massive undertaking likely requiring decades of research alone. Secondly, we can do as Ginane et al. (in peer review) did, and still reference existing indices, despite their severe limitations and potential irrelevance/inaccuracy, for the purposes of comparison with other literature, though this must always be discussed in detail in each papers' discussion. Or thirdly, we can find a way to standardize the climatic conditions through the repeated use of certain sites for a vast number of studies. That is to say, we can create research sites or institutions, which can host a great number of studies, effectively making the systematic climatic parameters into research-site-specific indices. This would essentially allow for in-house comparison of studies based on shared geography and climates, further increasing standardization. By using institutional research sites, we can reduce the stochastic weather variability between studies and attribute response differences more so to experimental variables, contributing to more certainty in the literature base. This can build a more well-established literature based within a particular geographic context, benefitting local farm operations through the establishment of localized best-practices based on the recommendations put forth by the relevant institution.

4 How to Bridge the Gap

4.1 Investing in Research: a Hedge Research Site, and Lessons from the Fieldwork

One of the areas most in need of continued research, as seen in this review, is in the use of hedge agroforestry for use by temperate climate livestock farmers. There is little to no peer-reviewed information about the specifics of heat stress dynamics in a hedge agroforestry system, especially in temperate regions, and particularly for small ruminants.

One of the difficulties which was encountered in the attempted fieldwork for this study was the lack of standardization in the planting of the research site. Not only were the hedges too immature to properly test the original hypothesis, but there were also no duplicate treatment plots available. This lack of available replication of plots forced an end to the data collection without the ability to retry the observations in a particular treatment, a notable problem in the Heat Stress Plot, as the weather became incompatible to continue observations, and the animals were unable to re-enter the plot at a later date to reattempt the data collection as it would breach the single-entry methodology for the two previous treatment plots.

Farms are frequently not standardized, scientifically organized, or homogenous from one field to another. This creates complication for researchers performing studies on these sites, as they must work within the boundaries of the farm's design, conditions, and management. However, should a dedicated research institution be set up, it can design its research plots to be as uniform as possible within a particular research area, reducing this heterogeneity between research plots. Further, researchers are reliant on the presence of appropriately established and maintained systems in order to research them, a problem experienced in the fieldwork when the hedgerows were grossly under-established compared to expectations and needs. If an institution were to exist, it can have a plan to plant these structures in an organized way, on a regular basis (such as yearly), and in hypothesis-relevant orientations (such as grid patterns, different orientations relative to the angle of the sun, etc.). This can allow for a wider range of available establishment stages of the plant infrastructure, and a wider range of data to be collected across these axes (age of structures, planting orientation angles, suitability of plant species in a particular system, etc.), contributing further to the value of such studies to the research base.

The livestock can also be managed by the institution, allowing for research animals to be more acclimated to and tolerant of certain data collection methods, such as blood draws, as these are typically stressful for unacclimatized livestock, and can affect short term stress data points (e.g. blood cortisol). Further, a wider range of breeds can be managed, to allow for experiments with breed or genetic variables, more than an operational farm would traditionally be capable of managing.

By repeatedly using plots and institutional research sites for a larger body of research, the climatic variability from year to year can be better understood, and a larger body of same-site data over a longer period of time can provide more insight into the true effects of treatments rather than as a result of yearly weather stochasticity (i.e. we can identify whether an effect is potentially the result of studying during a one-off abnormal year, because we have the data characterizing normal conditions at that particular site, whereas with other single-year studies there is not the data base to establish whether a season was an outlier). It can also reduce the complicating effects of varying topography of sites from otherwise similar studies, as the topography would be similar if conducted within a tighter geographic range. The data derived from the site would be as geographically and climatically relevant for local farmers as physically possible, and recommendations and best-practices can be created by the institution using this local data, for local farmers, reducing the risk of trial and error by farmers when making the transition to using agroforestry practices. The institution can also house outreach and agroforestry adoption practices to expand the use of agroforestry within its geographic range of relevance, serving as both an educational authority figure, as well as a source of valuable aid in making the managerial transitions.

Further, if multiple of these institutional sites were to be created in a variety of climates, countries, and regions, data can be compared between institutions, allowing for a cross-disciplinary study of these regional and climatic differences, particularly if they maintain a more or less standardized methodology across institutions.

4.2 Standardization of Methodology

One of the issues noted during this review was the general lack of standardization amongst studies with similar research questions. One of the most obvious is the lack of adoption of a particular, unified thermal stress indicator which is relevant to a particular area, as a standard of practice/index adoption does not exist and authors instead choose based on popularity and perceived relevance. However, aside from some studies not collecting animal data and instead assuming that index risk equals heat stress, studies also vary greatly in their physiological or behavioral parameters which are used to determine whether heat stress is occurring. Particular methods of note which were encountered during this review included the use of thermal cameras, skin surface temperatures, using panting scores, testing hair cortisol levels, and analyzing the frequency and locations of standing and resting behavior. Oftentimes studies had a narrow range of data which was collected. For example, Ginane et al. (in peer review) focused on the use of panting scores as a method of analyzing heat stress onset in sheep, which could be useful for farmers and managers to utilize for immediate analysis. However, they did not collect other physiological (i.e. non-respiratory) data points to confirm the accuracy of this parameter relative to other well-established physiological heat stress indicators. While this can be classified as keeping a study focused within its niche, it also makes it harder to use in subsequent meta-analyses which may seek to draw associations between responses of various physiological factors in heat stress conditions (e.g. correlation between heart rate and respiratory rate as a factor of heat stress severity determination).

Further, a wider range of climatic data should be collected as well. As discovered in Karvatte Junior et al. (2021) with the use of a thermal camera, the heat flows within a linearly planted tree silvopastoral system are not homogenous within the field, despite a regular, standardized planting. Further, these linear plots did not have regular striations or stripes of hotspots parallel to the tree lines, as would be expected in a linear system – instead, they were more globulous, and not always centered in the middle of a pasture strip (i.e. the hotspots were not always centered on the pasture point equidistant from two tree rows). This indicates that heat flows, even within a relatively homogenous planting distribution, are not necessarily as homogenous as theorized. Thus, it would be of great managerial and scientific interest to also map these hotspots within a dispersed tree silvopastoral planting, with a methodology allowing for direct comparison. More often than not, studies use only a handful of single-point data collection hubs within a field, and typically use averages to characterize an area. This does not capture the nuance necessary to understand the heat flows within an agroforestry plot, but the use of a thermal camera does, as seen in da Silva et al. (2024) and Karvatte Junior et al. (2021). The use of thermal cameras can allow for a more nuanced understanding of heat flows and microclimatic conditions, particularly if other related data points are able to be captured by the cameras, such as relative humidity. Further, thermal cameras or physiological data tracking collars (livestock “fit bits”) can be used to measure the physiological data of research animals from a distance, reducing the labor involved in physiological data collection.

Shade must also be quantified in a more concrete way. Many of the studies in this review did not quantify shade strength whatsoever, and only reported whether an animal was in the shade, of any strength (essentially a “Yes/No” data point). This strength of shade is an important factor determining the heat stress status of a particular animal, especially once social hierarchies are taken into consideration, as high-ranking individuals may block lower ranking individuals from accessing shade of a suitable strength to alleviate heat stress, and 10% shade would be theoretically less cooling than 50% shade. One of the ways in which this can be conducted is through the measurement of photosynthetically active radiation (PAR), as it is a measurement of the amount of light that permeates through the tree canopy, and thus would be expected to be inverse to the strength of shade, though this needs testing and confirmation as a methodology. This is another way in which studies based on tree density can classify their plantings, as plantings with the same tree/hectare density can have different PARs due to different characteristics of tree branches amongst species, and thus different forage potential and shade strength.

Until indices are able to be created for small ruminants as a whole, as well as based on silvopastoral management, BGHI seems to be the most reliable and popular thermal index, combining the recommendations made in Wang et al. (2018), and the popularity of its use within the reviewed studies. However, extreme caution must be exercised when using these cattle-based indices as reference for heat stress in small ruminants, and should only be used until small ruminant indices are created, which should be of the highest research priority.

4.3 Future Research Subjects of Interest

4.3.1 Agroforestry Foraging Behavior and Forage Preference

Notably, documents representing the intersection between in-situ agroforestry, sheep, and feeding behavior or feed preference were absent from the database, indicating an area where further research is needed. It is well established within scientific circles that animal behavior is often affected by the nutritional status of the animal. A hungry chicken will work more for food than one that has eaten recently (Bokkers, Koene, Rodenburg, ZImmerman, & Sprujit, 2004). A cow requiring salt will seek it out (Kume, Sato, Fukasawa, & Ogura, 2025). We even have evidence to show that livestock will self-medicate by grazing certain forages (Grade, Tabuti, & Van Damme, 2009). Optimal Foraging Theory also discusses the decision-making that occurs regarding resources such as food. Thus, we must accept that an animal is likely to feel conflict between choosing a climatically comfortable location versus a highly preferred feed, or vice versa.

As previously stated, animals don’t always behave in the ways we’d like as managers, and thus we should know, when designing agroforestry systems, how animals change their foraging behavior based on what is planted and where, and what the relative value of that forage is, and across seasons. Only one study was found during this review process which discussed the palatability of agroforestry forages versus their objective nutritional value (Kendall et al., 2021),and while it had no relevance for a thermal stress review, it does have relevance for determining best-practices for farmers. Despite being incredibly nutritious, alder is known to be one of the least palatable forages for livestock, so it is best to not plant an entire silvopastoral system with alder with the intention of it being a fodder plant, and willow may be more suitable for that application (Kendall et al., 2021). Still, we need repetition of that study, and we need more studies investigating the nutritional content of agroforestry fodder, the preferences of the relevant livestock involved, and the performance of such livestock. One such European study is Walker, Stoate, and Kendall (2022), which investigated the use of willow as a cobalt supplement in weaning lambs and the subsequent effect on B12 levels.

4.3.2 Other Temperate Agroforestry Small Ruminant Studies

A handful of similar studies have also been conducted in the southern United States, such as the forage value of honeylocust (*Gleditsia triacanthos*) pods as winter feed. Honeylocust pods were found to be a competitive alternative to corn for winter small ruminant feed, after livestock were acclimated to it (G. J. Pent & Fike, 2019), however it is not a typical European planting, despite some use as a decorative tree since its introduction in the 19th century (Dana, Garcia-de-Lomas, Jiménez-Cantizano, & Verloove, 2022). While it is not considered to be invasive in most of Europe, and is naturalized in Italy, Honeylocust is invasive in many parts of South America and Australia, primarily in Cfa and Cfb climates (Dana et al., 2022). It was reported in Dana et al. (2022)to have also become invasive in a riparian region in Spain, a Csa climate, which is on the drier side of its precipitation tolerance range (Dana et al., 2022). What makes it invasive is also what makes it highly interesting for silvopastoral use – it produces intense shade which outcompetes native species, which can thus theoretically greatly benefit livestock in periods of high risk for heat stress, alongside the leguminous forage provided through their seed pods (Dana et al., 2022). However, the widespread use of the plant as silvopastoral livestock forage is not geographically relevant outside of its native range unless a widespread eradication effort is warranted, as it is not quite prevalent enough in Europe to be commercially viable as an alternative, and caution would be warranted in creating a market demand for the tree, due to its invasive potential. In fact, it is banned in Portugal due to the principle of precaution (Dana et al., 2022), and creating a market demand for the forage may cement its place in European ecosystems, to the detriment of native plants.

With so much of the agroforestry x climatic stress research focused on equatorial and arid locales, it provides very little information which is relevant for agroforestry researchers and practitioners in temperate climates, as previously discussed. However that is not to say that temperate silvopastoral agroforestry research does not exist. Instead, their focus is different. When conducting this review, it was noted that there was a cluster of agroforestry x small ruminant behavior papers in the southern United States, largely focused on the suitability of forage for goats and sheep in browsing in pine timber forests, and the managerial complications which arise from such an arrangement, primarily the incidence of debarking and the appropriate managerial strategies that can be utilized to reduce the economically significant damage to the trees while eliminating the need for manual ground clearing before logging takes place (Bhattrai et al., 2020; Bhattrai, Karki, Poudel, Paneru, & Ellis, 2022; Karki et al., 2019; Karki et al., 2022; Poudel, Fike, & Pent, 2022; Poudel, Karki, Karki, & Tillman, 2019; Poudel et al., 2020; Poudel, Karki, McElhenney, Karki, & Tillman, 2019). Importantly, this is a different agroforestry type than is the focus of this review; instead of a true silvopasture, it is a temporary woodland clearing operation, in a timber forest. However, it would still be incredibly pertinent to understand how this arrangement affects the welfare of the livestock involved, as debarking could be interpreted as a foraging "by-catch" of sorts, or as a selection due to a nutritional deficiency or other such temporary nutritional mismatch. While these studies do measure the nutritional content of the forage, they typically characterize the welfare of the animals only in terms of FAMACHA parasite scores, and productive weight gain during the study periods. It would be interesting to perform a more in-depth welfare analysis during these periods of forest browsing, as well as measuring the heat stress related parameters, such as the physiological and behavioral responses. Such cross-sectional studies are rare in the literature, as studies tend to focus purely on their research question likely for simplicity's sake and operational and funding reasons, but this notably leaves out the potential for other interesting findings which could contribute to a meta-analysis study across a wider variety of contexts. While this review found a lack of direct comparison studies between dispersed silvopasture and linear hedge agroforestry systems in terms of microclimatic factors and overall heat stress parameters, it would also be of great scientific value to cross-compare with woodland agroforestry once that literature gap is addressed.

4.3.3 Reproductive Effects of Heat Stress and Considerations for Organic Producers

Other studies have investigated the effect of heat stress on the reproductive success of dairy cattle in tropical regions, such as Brazil (Barajas-Pardo, Avila-Valbuena, Perez, Perez, & Lopera-Vasquez, 2025). It begs the question: how does chronic heat stress impact the reproductive capability of other livestock species? Are goats, perhaps, more likely to maintain fertility under heat stress than sheep or cattle? Are there certain breeds of cattle, or small ruminants, which maintain a significantly higher fertility in hot conditions? And what are the potential downstream effects of these changes brought about by reproduction under chronic heat stress? This information may be incredibly valuable for geneticists and livestock breeders in future decades, particularly if the ecological adaptability diverges from the interests or preferences of the market (e.g. smaller body size as resilience vs demand for larger carcass sizes for processing efficiency). Further, many of the known treatments that can improve fertility in chronically heat stressed livestock are not organic. Heat stress is already a challenge to manage in conventional agriculture, but it is even more so in organic, as organic producers are banned from such interventions as hormonal treatments and embryo transfer (Gupta, Vaidya, Kumar, Singh, & Osei-Amponsah; "Regulation (EU) 2018/848 of the European Parliament and of the Council of 20 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007," 2018). Thus, it would also be necessary to investigate more organic alternative treatments for preserving fertility in heat stressed livestock, or for policy to adapt to the challenges and loosen organic requirements.

4.3.4 Genetic Climatic Adaptability Classification

It would also be pertinent to understand in more detail the climates to which our livestock breeds are adapted. For example, we know that hair sheep are more heat tolerant than wool sheep, and that certain breeds such as Katahdins are generally parasite tolerant, but we don’t have in-detail classification of breeds based on the particular aspects of a climate they are adapted to. Petit and

Boujenane (2018) discusses this, and then classify Morocco’s 5 distinct sheep breeds along humidity and heat lines, providing crucial information for those interested in crossbreeding temperate European breeds with these more heat-tolerant Moroccan sheep. This basic climatic tolerance classification provides necessary information for the determination of crossbreeding potential with European sheep breeds, and subsequently allowing for a genetic shift in the European sheep breeds to be more tolerant of expected climatic shifts. However, this kind of crossbreeding for climatic tolerance can take a very long time, so further investigation into the genetic climatic tolerances of potential crossbreeding sources is urgently required in order to reduce the impact on livestock, populations, food systems, and ecosystems over the long term.

5 Conclusion

Agroforestry research regarding small ruminant heat stress in temperate climates is still in its infancy, particularly within a western European context. Given the projections of climate change, it is necessary to create best practices designed for agroforestry systems in temperate climates. The current state of the literature and the importance of standardization and the inclusion of animal behavioral observations in such studies is discussed. A proposal is set forth for repeatable, standardized Hedge Agroforestry Research Stations to allow for a more expansive, cross-comparable research base to be established. This may allow for the development of localized agroforestry best practices for farmers to invest in the best agroforestry systems for them, reducing the risk of on-farm trial and error and more effectively combatting climate change and its impact on our Agri-food systems. This is especially important for organic producers, as they provide not only food stability, but also beneficial ecosystem services which improve the condition of the surrounding environment, and can even combat climate change in and of themselves. Ultimately, agroforestry systems are a promising tool for maintaining animal welfare in outdoor, grazing livestock systems.

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