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Review

Silvopastures: Benefits, Past Efforts, Challenges, and Future Prospects in the United States

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Abstract: The global human population is projected to reach 9.7 billion by 2050, increasing the demand for food and fiber, but also raising concerns about the environmental impact of agricultural production scaled to meet their needs. Silvopastures—integrated tree–forage–livestock systems—have emerged as a viable practice to meet the required productivity and environmental stewardship outcomes. This review consolidates the extensive research on silvopasture practices in the United States and highlights the benefits of these systems. A comprehensive literature search across databases such as ScienceDirect and Google Scholar revealed 152 publications on silvopastures in the United States since 2000, indicating growing interest. These studies have primarily focused on the impacts of silvopastures on livestock welfare and productivity, forage production and composition, soil health and nutrient dynamics, and socio-economic factors. Geographical distribution analysis indicated that the research is more focused in the Southeastern United States, with Florida, Virginia, Alabama, Missouri, and Arkansas being the top five contributing states. The review also offers insights into the tree and forage species used across these states and discusses the challenges to silvopasture adoption among producers and land managers while exploring future prospects. This review may be used as a resource for understanding the multifaceted dimensions of silvopasture adoption, providing insights for researchers, policymakers, and practitioners alike.

Keywords: agroforestry; climate change; forages; pine; hardwood; heat stress; shade

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1. Introduction

The global human population is expected to increase to 9.7 billion by 2050 and 10.9 billion in 2100 [1]. With this, the demand for agricultural products is also expected to rise by about 70% [2], putting pressure on both the agricultural and non-agricultural lands around the world. As the global population increases, the impact of agricultural systems on the environment, including greenhouse gas (GHG) emissions, is also expected to increase [3,4]. In turn, climate change has a direct impact on agricultural production [5,6] through changes in weather patterns, increasing frequency of extreme weather events, and rising temperatures. Agriculture is also a significant contributor to climate change, through factors such as deforestation and other forms of land-use changes, the use of fossil fuels, and the use of synthetic fertilizers and pesticides [7]. Given these challenges, identifying and developing resilient production practices that can address the increasing demand for agricultural products while minimizing or mitigating the negative impacts of agriculture is urgent.

Silvopastures, a type of agroforestry practice, offer a promising approach to addressing the need for food, fuel, and fiber, while also mitigating the impacts of agriculture on climate change and the environment. Silvopasture systems integrate trees, forage crops, and livestock into a single production system on the same land [8]. Silvopasture systems can provide ecological benefits, such as improving the water quality, soil quality, and carbon sequestration, modifying the microclimatic conditions, and increasing biodiversity [9–17], along with enhancing animal welfare and productivity [18–25].

By sequestering carbon in trees and soils, silvopastures can also help mitigate the impacts of livestock systems on climate change. Although silvopastures are considered a common form of agroforestry in the United States, awareness and adoption of the practice are limited [26]. An increasing number of publications on the topic indicates a growing interest in silvopastures globally in recent years [27]. The majority of this research suggests that silvopasture systems can increase the overall system productivity compared with traditional forage–livestock systems [28]. However, only a limited number of comprehensive reviews and syntheses on the impacts of silvopastoral management (particularly in the United States) have been published over the past two decades. This review paper explores the current understanding of the potential of silvopastures in mitigating climate change and improving animal welfare and productivity. We begin by describing the challenges posed by population growth and climate change and how silvopasture can play some role in addressing these issues. We then discuss the benefits of silvopasture and synthesize silvopasture research efforts from the United States in the 21st century. The Section 6 summarizes the challenges and barriers to implementing silvopastures and discuss the future prospects for their implementation in the United States.

2. Silvopastures

2.1. Defining Silvopastures

Silvopasture is a land management practice wherein trees, forage crops, and livestock are integrated on the same land, providing both short-term as well as long-term economic returns from the area [8]. In silvopasture systems, trees are grown in combination with various forages and grazed by livestock. The trees provide shade for the animals and can serve as a source of browse, timber, and other non-timber forest products. Silvopastures can either be established by thinning an existing tree stand and planting forages underneath the trees or by planting trees within an existing pasture [29].

Silvopasture is considered a traditional land-use practice and has taken various forms around the world for hundreds if not thousands of years. For example, in South and Central America, silvopasture practices have been used by indigenous communities for centuries as a means to jointly manage livestock and forest resources [30,31]. In Europe, silvopastoral practices have been implemented since the Middle Ages, particularly in the form of parkland grazing systems, where livestock grazed beneath trees in large open pastures [32]. Recent renewed interest in silvopastures as a land-use practice has occurred in part as a response to the challenges of climate change and the need for more resilient agricultural systems. However, motivations often vary among land managers and can range from shade/heat stress abatement to expanded grazeable acreage to conservation (for GHG emissions reduction) and biodiversity [33].

2.2. The Benefits of Silvopastures

2.2.1. Silvopastures as a Natural Climate Solution

Silvopastures as a land-use system can provide ecological, economic, and social benefits. A key benefit of silvopastures is the potential to enhance net primary productivity and sequester carbon, thereby reducing atmospheric GHGs. Silvopastures sequester atmospheric carbon (C) and nitrogen (N) due to gross primary productivity and heterogenous plant C storage patterns within the system [34], thereby aiding in mitigating climate change. Silvopastures have also been listed as a top solution to reverse climate change by Project Drawdown [35]. Haile et al. [36] reported that the roots of a slash pine (*Pinus elliotti*) extended to a greater depth compared to forage roots in a pine–bahiagrass (*Paspalum notatum*)-based silvopasture system thus resulting in a greater tree-derived carbon storage at deeper soil profiles. Another study by Howlett et al. [37] reported greater soil carbon storage in silvopastures with birch (*Betula* spp.) trees compared to silvopastures with pine (*Pinus* spp.) trees, which was thought to be due to the slow decomposition of pine needles that inhibited the understory forage growth. This indicates that both the forage and tree components within the silvopasture system can contribute to sequestering carbon in the system. Furthermore, effective grazing management in thinned woodlands, initiated shortly after forage establishment, elevated the total soil carbon levels within only a few years [38]. These studies highlight both the potential of silvopasture systems to sequester atmospheric carbon and their role as a resilient land management strategy in the face of change.

2.2.2. Silvopastures for Greater Soil Health and Water Quality

Another benefit of silvopasture systems lies in their capacity to enhance soil and water quality. Establishing trees within a pasture may thus contribute to improving overall soil health and enhancing system productivity [11,28,39]. Within silvopastures, trees capture excess nutrients that may be lost from the root zone of the understory forages and their roots may help to lower soil bulk density and thus improve soil physical properties [9,10,12]. Along with temperature moderation, these conditions facilitate increased microbial activity, diversity, and abundance [40]. Poudel et al. [16] reported greater soil organic matter content, microbial biomass C and N, and β-glucosidase and urease activities in black walnut-(*Juglans nigra*) and honeylocust-(*Gleditsia triacanthos*) based silvopastures compared to open pastures. Similarly, silvopastures integrating slash pine and bahiagrass contained 28–33% more total soil organic carbon than pastures with bahiagrass alone [12]. In a loblolly pine (*Pinus taeda*) silvopasture in Alabama, fertilizer application increased soil nitrogen and phosphorus levels, while areas without fertilizer maintained stable phosphorus and potassium levels with an increase in soil nitrogen due to goat manure and urine deposition [38]. In Florida, USA, sandy loam soils managed under silvopastures exhibited greater phosphorus storage capacity and lower phosphorus buildup than open pastures, suggesting that silvopastures reduce the risks of phosphorus loss to groundwater and surface water runoff [41]. Integrating agroforestry practices into the landscape can help mitigate nonpoint-source pollution from runoff originating from grazing land and other agricultural landscapes [42,43].

2.2.3. Silvopastures for Altering the Microclimatic Conditions

Trees within a silvopasture can alter the microclimatic conditions, offering a range of ecological benefits that contribute to the sustainability and productivity of the system. Past research has demonstrated that the silvopasture system can modify water and air temperature conditions, which positively influences soil, plant, and animal dynamics within the system. Karki and Goodman [44] reported that silvopasture with mature loblolly pine and bahiagrass had significantly lower air and soil temperatures, dew point, wind speed, and solar radiation compared to open pastures. Castillo et al. [45] reported that the temperature moderation provided by a silvopasture was consistent across different tree species, namely longleaf pine (*Pinus palustris*), loblolly pine, and cherry bark oak (*Quercus pagoda*) trees in North Carolina. They noted that microclimate effects depended more on seasonal changes and time of day rather than on tree species. This change in microclimatic conditions within the silvopasture system may also offer resilience against drought conditions [46]. The ability of silvopasture to modify microclimatic conditions not only enhances the viability of the systems but also plays a vital role in adapting to and mitigating the effects of climate change, thereby contributing to ecological resilience [47,48].

2.2.4. Silvopasture Potential for Heat Stress Abatement

Climate change and the attendant rise in the global average surface temperature negatively impact the livestock sector by altering the quantity and quality of feeds, exacerbating heat stress, and accelerating biodiversity loss [49,50]. Heat stress directly compromises livestock welfare and productivity in both extensive and intensive production systems [51]. In the United States, heat stress causes economic losses of $1.69 to $2.36 billion annually in the livestock industry [52], and this is predicted to become an increasing problem for the livestock industry [53].

Silvopastures may provide a means to improve animal welfare and productivity by buffering the environment and protecting livestock from weather extremes. The presence of trees in silvopasture systems offers shade, shelter, and diverse forage options for livestock, enhancing their well-being and reducing stress [22,54] and thus leading to healthier and more comfortable animals. In an open pasture system, radiant heat is more intense compared to a silvopasture system with shade [55]. During periods of hot weather, the cooler conditions within silvopastures create a more comfortable environment for grazing livestock [17,44,45,56]. This is particularly advantageous in humid subtropical and tropical climates where temperatures often exceed the thermoneutral or comfort zone of livestock. This will be of growing importance for livestock producers as conditions continue to warm up for much of North America in the future.

Recent studies have highlighted the benefits of silvopastures in moderating the effects of ambient conditions on livestock, thereby improving their welfare and productivity. Animals kept in silvopastoral environments experience lower stress levels, as indicated by cooler body temperatures, lower hair cortisol levels [19,22], and improved productivity and welfare [22,57] compared to those maintained on open pastures. Animals with access to shade exhibit energy-sparing behaviors, spending more time lying down and less time standing. In contrast, animals in open pastures spend more time standing, often with their heads under the bellies of another animal—an indication of stress—and often displaying agonistic behaviors [19,22,58,59]. These findings collectively suggest that the microclimatic modifications offered by silvopasture systems can significantly enhance livestock welfare and productivity by mitigating heat stress and improving overall living conditions. These studies underscore ways in which silvopastures provide a more comfortable environment for livestock, thereby enhancing their welfare and ultimately improving productivity [60,61].

2.2.5. Silvopastures for Greater Biodiversity

Silvopastures can also help enhance biodiversity by providing a habitat for a wide range of plant and animal species [62,63]. Trees in silvopasture systems provide microhabitats that support a variety of wildlife, including birds, insects, and small mammals. A silvopasture, if established properly, can support and attract wildlife such as wild turkeys (*Meleagris gallopavo*), deer (*Odocoileus virginianus*), and many songbirds to the area. Silvopasture systems can address the goals of wildlife conservation and are shown to reduce wildfire risk or severity [64]. This can contribute to the conservation of biodiversity, which is essential for the long-term health and sustainability of ecosystems. Overall, the multiple benefits of silvopasture make it a promising land-use practice that can contribute to the conservation of natural resources, the improvement in agricultural productivity, and the mitigation of climate change.

While there are several benefits of silvopastures, it is very important to acknowledge the challenges associated with its establishment and management. Silvopasture establishment, either by thinning out existing woodland or by planting trees in an existing pasture, requires significant initial investment and time until it can be utilized to the fullest. Also, forage productivity within the silvopasture may be reduced as a result of competition with trees for light, water, and nutrients, and this can ultimately reduce the carrying capacity of the system. However, the integration of trees, livestock, and forage in a well-managed silvopasture system can lead to overyielding, where the combined productivity of all components exceeds that of a monoculture pasture [28]. This synergistic effect underscores the long-term sustainability and economic viability of silvopasture, despite some of the challenges associated with its establishment and management.

3. Silvopastures in the United States: Research Efforts in the 21st Century

Silvopasture has been viewed as a management practice to diversify income and provide shade to livestock by producers and land managers [65,66]. The practice holds substantial promise in the United States, with projections suggesting a potential expansion of acreage from around 5.6 to 25.3 million hectares, particularly in the eastern region [66]. Such an increase would result in a 6% change in global silvopasture coverage, potentially sequestering 4.9 to 25.6 Tg CO_2e yr.$^{-1}$ [67]. However, adoption of this practice remains low in the United States, as less than 1.5% of the farms employ some form of agroforestry practice, such as silvopastures [68]. This low adoption rate prompts a reevaluation of the assumption that merely increasing research and outreach efforts will suffice to expand silvopasture practices.

To assess the research landscape on silvopastures in the United States since the turn of the 21st century, we conducted a comprehensive literature search utilizing ScienceDirect, Google Scholar, and other search engines, targeting published peer-reviewed journal articles, conference proceedings, theses, and dissertations. The search employed specific terms, including "silvopasture", "silvopasture in the USA", "agroforestry", "woodland grazing", and "silvopastoral", selecting content published between 2000 and 2023 in the United States. Field-based or socio-economic research experiments, modeling, and case studies specific to particular locations within the United States were included, while review papers were deliberately excluded from the count. Additionally, to streamline the findings, thesis or dissertation works that had been published in part or in full as peer-reviewed journal articles were excluded to avoid redundancy. Research studies conducted across multiple states were treated as a single study when calculating the total count while being considered independent studies for individual state counts.

The review identified 152 relevant peer-reviewed articles, theses, dissertations, and conference proceedings related to silvopasture published between 2000 and 2023 in the United States. On its face, this volume of output may suggest that barriers to adoption in the United States extend beyond a simple lack of information or research efforts. However, for comparison, it is worth noting that Google Scholar searches on commodity crops corn '"*Zea mays*" USA' and soybean '"*Glycine max*" USA' from 2000 to present yielded about 214,000 and 163,000 hits, respectively. Forages, perhaps, would provide a better metric, and searches for common temperate species such as red clover '"*Trifolium pratense*" USA', white clover '"*Trifolium repens*" USA', '"*Festuca arundinacea*" USA', and '"*Dactylis glomerata*" USA' each yielded more than 16,000 results. Even a search for the lowly turnip ('"*Brasica rapa* spp. *rapa*") USA' yielded 765 hits.

While the Google Scholar search hit numbers are telling, general audiences are probably using more typical search tools not geared toward academics. Searching up "silvopasture" on Google yielded 416,000 hits (compared with over 2 billion hits for "corn" and almost 330 million hits for "soybean"). Such results suggest both that information is available to producers, but also that while the body of information on these systems is growing, silvopasture research and outreach efforts have some way to go to reach the levels of awareness and interest given to other commodities.

The increasing number of U.S. research publications on silvopasture by year from 2000 to 2023 highlights the growing interest in these systems and recognition of their potential benefits (Figure 1). These 152 published research works were also categorized based on the methodological approach used for the study and were parsed into four different categories (Figure 2) including the following:

1. Field-Based Experimental Studies: Research conducted within silvopasture systems, aiming to understand the intricate interactions between soil, plant, and animal interactions.
2. Modeling Studies: Studies using statistical or computational models to predict outcomes, assess scenarios, or understand complex interactions within silvopastoral systems.
3. Socioeconomic Studies: Research focusing on the economic viability, social impacts, or policy aspects of silvopasture.

4. Case Studies: In-depth analyses of specific instances of silvopasture implementation to highlight successes, challenges, and lessons learned.

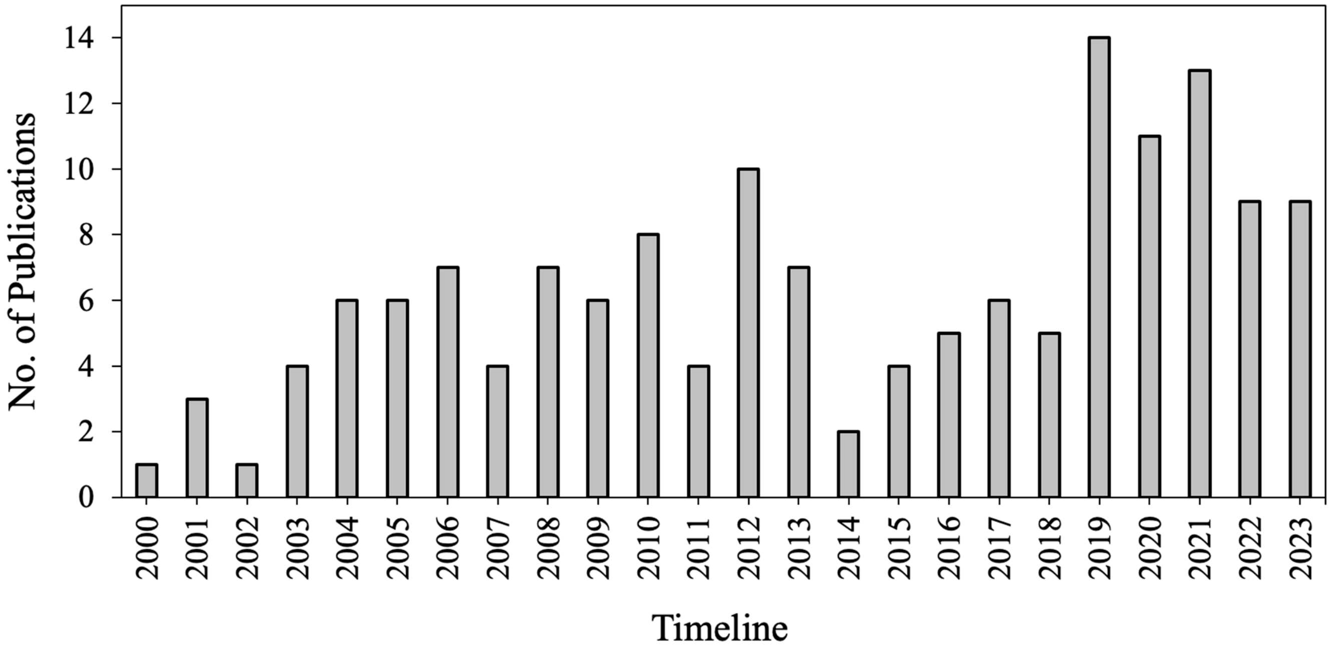

Figure 1. Publication trends in silvopasture research within the United States from 2000 to 2023, encompassing peer-reviewed journal articles, dissertations, theses, and conference proceedings.

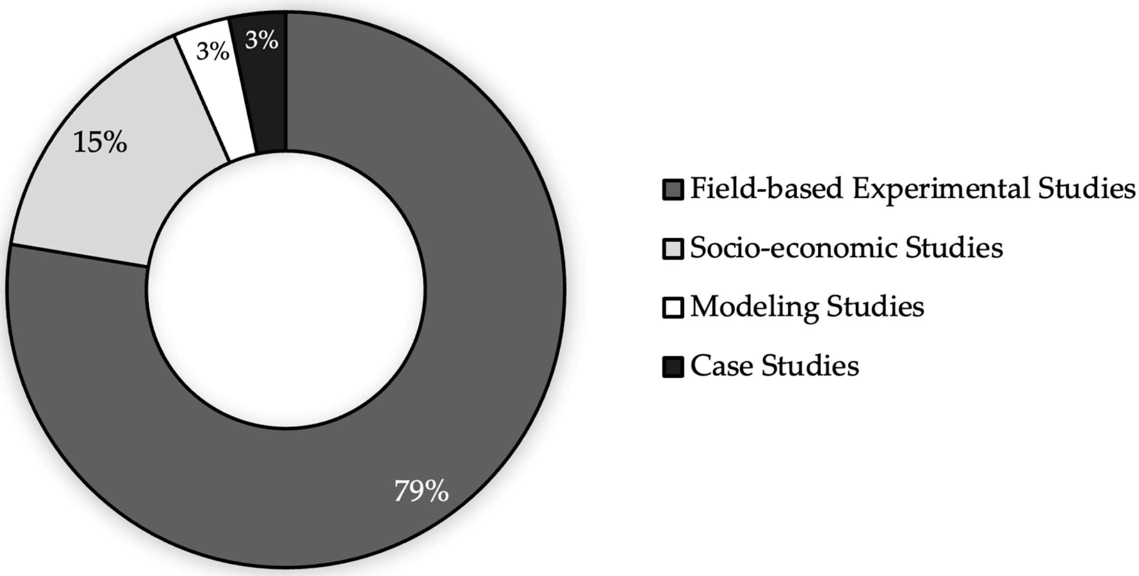

Figure 2. Distribution of silvopasture research publications in the United States by methodological approach, including peer-reviewed journal articles, dissertations, theses, and conference proceedings, from 2000 to 2023.

The majority (79%) of published works were field-based experimental studies primarily addressing forage production and composition, animal health and productivity, soil health and nutrient dynamics, and tree health and productivity (Figure 2). A color-coded intensity map showing the geographical distribution of these research efforts (since 2000) is presented in Figure 3 (www.mapchart.net). This snapshot of a roughly 20-year research period showcases both the areas where concentrated study is occurring and where knowledge gaps are significant.

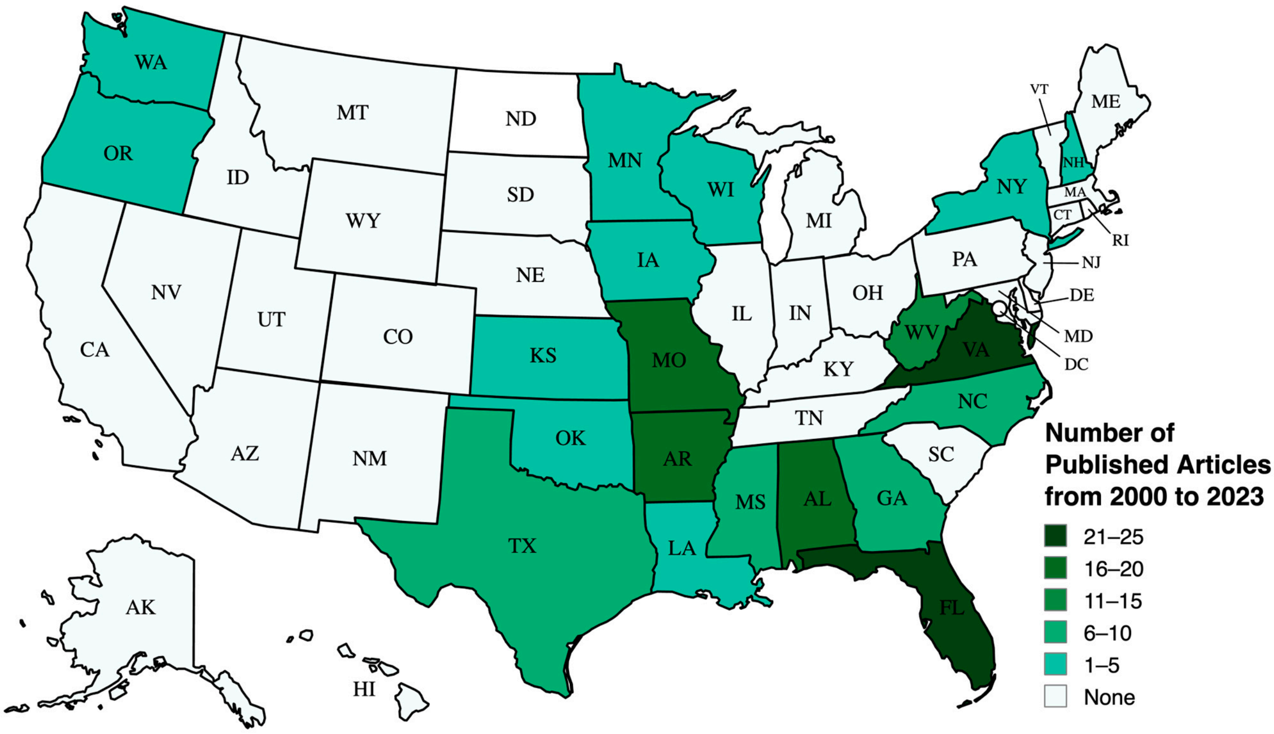

Figure 3. Geographical distribution of silvopasture research in the United States, illustrating the number of studies (including peer-reviewed journal articles, dissertations, theses, and conference proceedings) conducted in each state from 2000 to 2023.

Most silvopasture research—both historically and since 2000—has been concentrated in the Southeastern United States. Except for very few studies from Kansas and Oklahoma, no studies on silvopastures have been reported from states beyond the 100th meridian (which roughly delineates the start of the drier Great Plains) and west to the Rocky Mountains and arid Southwest. This is not surprising given the limited rainfall of these regions. Similarly, only a few studies have been reported from the Pacific Coast (from Oregon and Washington) in this time, although Oregon historically (pre-2000) has had a significant silvopasture research footprint. Unlike these western regions, the Midwest and transition zone states (Kentucky and Tennessee) are generally more well-suited for tree production and silvopastures. It is notable that little to no effort on silvopastures has been published from these regions in the last 20 years. This likely reflects that agriculture (and thus effort) in many of these states is dominated by commodity cropping systems.

Research output by state appears to occur in distinct timeframes (Figure 4). The trajectory of research programming likely reflects both changes in personnel and the availability of funding over time. Sustaining research programs across changes in faculty (through retirements or departures) is a particular challenge given the long-term and complex nature of these systems.

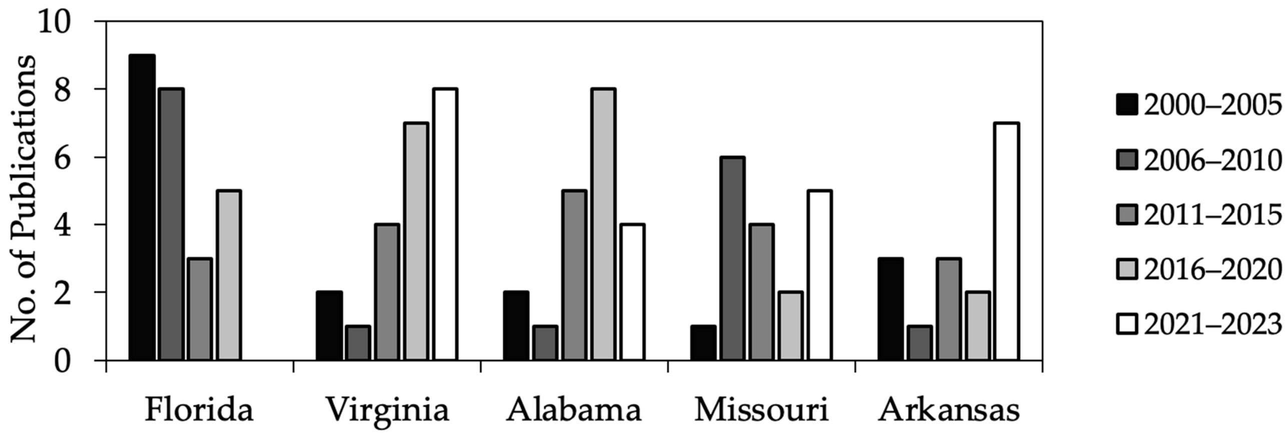

Figure 4. Trends in silvopasture publications by the top five states, segmented into five-year intervals from 2000 to 2023.

The survey of research efforts from among the five states with the highest number of published research works also provides insights into commonly used trees and forage species for silvopastures (Table 1). Pines (*Pinus* spp.) emerged as the predominant tree type used in silvopasture research. This likely reflects the genus' broad adaptation across regions, the rapid growth of several pine species, and the broad availability of timber markets for these trees. Hardwood trees were also frequently cited as being utilized in silvopasture systems, but silvopastures were not dominated by any single genus.

Table 1. Commonly used tree species and forages in silvopasture across the top five states with the highest number of publications on silvopasture since 2000.

SN	State (No. of Publications)	Tree Species	Forage Species	Citations
1	Florida (N = 25)	Loblolly pine (*Pinus taeda*); Slash pine (*Pinus elliottii*)	Bahiagrass (*Paspalum notatum*); Florida carpon desmodium (*Desmodium heterocarpum*); Shaw vigna (*Vigna pakeri*); Saw palmetto (*Serenoa repens*); Wiregrass (*Aristida stricta*); Creeping bluestem (*Schizachyrium stoloniferum*)	Karki and Goodman [44]; Xu et al. [69]; Nair et al. [70]
2	Virginia (N = 22)	Honeylocust (*Gleditsia triacanthos*); Black walnut (*Juglans nigra*); Loblolly pine (*Pinus taeda*); White oak (*Quercus alba*); Locust (*Robinia pseudoacacia*); Hickory (*Carya* spp.); American hazelnut (*Corylus americana*); Persimmon (*Diospyros virginiana*), Southern red oak (*Quercus falcata*); Virginia pine (*Pinus virginiana*); Shortleaf pine (*Pinus echinate*); Yellow poplar (*Liriodendron tulipifera*)	Tall fescue (*Schedonorus arundinaceous*); Meadow fescue (*Schedonorus pratensis*); Orchardgrass (*Dactylis glomerata*); Perennial ryegrass (*Lolium perenne*); Red clover (*Trifolium pratense*), White clover (*Trifolium repens*); Alfalfa (Medicago sativa).	Thomsen et al. [55]; Paneru et al. [57]; Poudel et al. [22]; Pent et al. [20]; Frey and Fike [71]

Table 1. *Cont.*

SN	State (No. of Publications)	Tree Species	Forage Species	Citations
3.	Alabama (N = 20)	Longleaf pine (*Pinus palustris*); Loblolly pine (*Pinus taeda*);	Bahiagrass (*Paspalum notatum*); Crabgrass (*Digitaria sanguinalis*); Sericea lespedeza (*Lespedeza cuneata*); Rye (*Secale cereale*); Crimson clover (*Trifolium incarnatum*); Marshall ryegrass (*Lolium multiflorum*); Arrowleaf clover (*Trifolium vesiculosum*); Chicory (*Cichorium intybus*); Tall fescue (*Festuca arundinacea*); White clover (*Trifolium repens*), Hairy vetch (*Vicia villosa*); Red clover (*Trifolium pratense*)	Poudel et al. [72]; Kumi et al. [73]; Nyakatawa et al. [38]
4.	Missouri (N = 18)	Red oak (*Quercus rubra*); Black walnut (*Juglans nigra*), Pecan (*Carya illinoinensis);* Honey locust (*Gleditsia triacanthos*); White oak (*Quercus alba*); Post oak (*Quercus stellata*); Black oak (*Quercus velutina*); Hickory (*Carya* spp.)	Tall fescue (*Festuca arundinacea*); Orchardgrass (*Dactylis glomerata*); Red clover (*Trifolium pratense*); Marion lespedeza (*Kummerowia striata*)	Kallenbach et al. [74]; Powelson [75]
5.	Arkansas (N = 16)	Pecan (*Carya illinoinensis*); Northern red oak (*Quercus rubra*); Bristly locust (*Robinia hispida*); Eastern black walnut (*Juglans nigra*); American sycamore (*Plantanus occidentalis*); Cottonwood (*Populus deltoides*); Pitch/loblolly pine (*Pinus rigida* × *Pinus taeda*)	Tall fescue (*Festuca arundinacea*); Big bluestem (*Andropogon gerardii*); Little bluestem (*Schizachyrium scoparium*); Indiangrass (*Sorghastrum nutans*); Orchardgrass (*Dactylis glomerata*)	Dold et al. [76]; Burner and Burke [77]; Niyigena et al. [78]; Gurmessa et al. [79]; Smith et al. [80]; Amorim et al. [81]

Cool-season forages such as tall fescue (*Schedonorus arundinaceus syn. Lolium arundinaceum syn Festuca arundinacea*) and orchardgrass (*Dactylis glomerata*) occur most commonly in silvopasture studies, reflecting the greater research output from states within the North–South transition zone where these species predominate. Several other cool-season species may have a future interest in silvopasture systems including meadow fescue (*Schedonorus pratensis*), an introduced forage that has been identified in an oak savanna, and smooth brome (*Bromus inermis*), a species that also remains productive in shaded environments [82–84]. Warm-season forages such as bahiagrass and native warm-season grasses were more common at more southern latitudes. Cattle, goats, and sheep are the most commonly used animal species in silvopasture research, as observed across the studies reviewed in this manuscript.

4. Challenges and Barriers to Silvopasture Adoption in the United States

Several factors may affect the decision to adopt silvopasture practices. Policy constraints, perceived costs, economic incentives, land tenure issues, and cultural preferences may all play significant roles in influencing silvopasture adoption. A survey of Virginia (USA) producers indicated that only 8% were interested in planting trees (48% were very uninterested), while about 25% were very interested in thinning woodlands for silvopastures [33] (Table 2). Forfeited pasture was a constraint for planting for about half (48%) of respondents, while 27% considered thinning a means to expand pasture acres.

Table 2. Silvopasture establishment preferences among livestock producers surveyed in Virginia. Adapted from Wilkens et al. [33].

Opportunities	%Frequency	Constraints	%Frequency
Planting		Planting	
Shade for livestock	64	Forfeit pasture	48
Pasture diversification	16	Costs and time	24
Improved farm health	12	Land class	14
Increased productivity	8	Tree mortality	14
Thinning		Thinning	
Pasture expansion	27	Maintenance requirements	32
Shade for livestock	21	Residual tree health	26
Improved farm health	15	Environmental impacts	21
Improved forestland	13	Establishment costs	11
Increased production	13	Land suitability	5
		Livestock performance	5

Increasing silvopasture adoption will entail demonstrating that the systems' benefits (economic, environmental, social) are worth the added inputs and management requirements. Expanding the adoption of silvopasture more broadly in a geographic sense will likely require increasing research and demonstration beyond those few states that have had active silvopasture programs. As noted above, sustaining agroforestry efforts can be difficult in the face of personnel changes and fluctuating budgets. Sustained commitment by researchers and institutions to long-term silvopasture programming would likely be greatly facilitated by the assurance of federal (or other) support for these programs. An individual researcher's passion for these practices is unlikely to sustain a program or a career (which depends on continued short-term funding success) if there is little guarantee that the needed resources and investment will be available long-term. At the same time, targeted interventions, incentives, and engagement will aid the advancement of knowledge on both the academic and farm levels. This approach should not only involve academics, technical service providers, and farmers, but should also engage business, finance, and other community members in efforts that create a more supportive environment for the adoption of silvopasture practices. Some of the most common challenges and barriers to silvopasture adoption in the United States include the following:

1. Policy and regulatory hurdles: Policies and regulations related to land-use, zoning, and agriculture may not support or acknowledge the integration of trees, livestock, and crops on the same land [85]. This can make it difficult to establish and maintain silvopasture systems and may discourage landowners from adopting these practices.
2. Lack of knowledge and awareness: Many producers and landowners may not be familiar with the benefits of silvopasture or may lack the technical knowledge and skills needed to establish and maintain these systems. Managing the complexity of the system could be challenging for the land manager with limited knowledge, resources, or support [65,66].
3. Economic constraints: Establishing and maintaining silvopasture systems can require significant upfront investments, such as purchasing seedlings, fencing, and other infrastructure, or payment for thinning and clearing costs if these are not bid out to the forestry industry. These costs can be a barrier for producers, particularly small-scale producers with limited resources [85].
4. Land tenure: Increasingly, land in the USA is not being farmed by the landowners but rather is held by absentee landowners. Without secure land tenure or control over the land, producers may be hesitant to invest in long-term land management practices like silvopasture. New social models based on multi-party agroforestry may be one way forward in addressing these sorts of issues [86].

5. Cultural attitudes and values: Existing knowledge and practice frameworks can be a significant barrier to implementing silvopasture. In some regions, traditional land-use practices may not recognize the integration of trees, livestock, and crops, which can make it difficult to introduce new practices like silvopasture. As a producer told one of the authors, "the biggest challenge was changing my mindset".

Independently or in conjunction, these challenges and barriers can make it difficult to implement and scale up silvopasture systems in such a way that can have a rapid and significant positive impact on local ecosystems or global climate systems. Addressing these challenges will require a combination of policy changes, education and outreach, technical support, and financial incentives to encourage adoption and investment in these practices.

5. Future Prospects of Silvopastures in the United States

Silvopasture has the potential to be an effective climate change mitigation and adaptation strategy. A recent analysis by Greene et al. [67] suggested that silvopastures could expand by up to 25.3 million ha in the Eastern United States and would increase global silvopasture acreage by 6% with an anticipated CO_2 capture of up to 25.6 Tg CO_2e yr.$^{-1}$. However, such potential benefits can only be realized if silvopasture is scaled up and widely adopted by farmers and landowners. The authors have highlighted some prospects that can help scale up the adoption of silvopastures among farmers and landowners, which are discussed below.

1. Research: There is still much to learn about silvopastures, including best practices for their establishment and management as well as optimization for ecosystem services (such as soil health, water quality, carbon sequestration, biodiversity conservation) for production functions (livestock and tree production), and their economic output. More research is needed to better understand strategies for scaling up these systems in different contexts and landscapes.
2. Policy: Policies that directly incentivize the adoption of agroforestry practices or provide financial support for farmers to establish silvopasture systems can help to overcome some of the economic barriers to adoption. However, existing programs in this space are not overly prescribed and more work is needed to encourage producer adoption. Policies that promote conservation agriculture and integrated land-use planning can also create a more supportive environment for silvopasture. Financial subsidies, tax incentives, or grants can assist in covering the upfront costs associated with establishing silvopasture systems, although it is unclear if this approach will sufficiently motivate producers to adopt such practices. Subsidies may make the adoption more feasible for small-scale or limited-resource producers who might face economic constraints.
3. Investment: Silvopasture investments can come from a range of sources, including government programs, private sector banking and businesses, and philanthropic organizations. Investments, particularly from carbon trading programs that capture the carbon sequestration benefits of silvopasture systems, may help motivate producers to adopt these systems [87]. Recent advances in technology offer the promise of relatively easy onsite monitoring, which would reduce scale-based barriers to entry [88]. Whether current payment rates and structures are sufficient to entice adoption remains unclear.
4. Education and outreach: Education and outreach can also play a key role in promoting the adoption of silvopasture. The lack of available demonstrations and actively managed sites on farms has been a limitation for advancing these systems; as kinesthetic learners, farmers place great value on sight and touch in learning [89]. Programs to train the trainers and train the technical service providers will also help build capacity, and public awareness campaigns may help in highlighting the benefits of silvopasture systems.

In summary, scaling up silvopasture as a climate change mitigation and adaptation strategy will require a combination of research, policy, investment, and education and outreach approaches. By working together, stakeholders from across different sectors can help to create a more supportive environment for the adoption of silvopastures and realize its full potential as a viable and resilient land-use practice.

6. Conclusions

This review paper outlines the current state of silvopasture research in the United States, highlighting key trends, geographic distributions of studies, and the challenges and opportunities for silvopasture adoption, along with emphasizing the need for targeted studies to enhance its development and application. Silvopasture systems synergistically integrate trees, forage, and livestock, enhancing animal welfare, biodiversity, soil health, and overall agricultural sustainability. The increasing interest in silvopasture and recognition of this practice, especially in the Southeastern United States, underscore the growing potential of silvopasture as a socially acceptable land management practice with desirable environmental impacts. The variety of tree and forage species discussed in this review reflects the diverse climatic conditions and soil types across different states, offering a valuable comparative resource for both practitioners and researchers. However, it is important to note that the range of tree species discussed in this paper is not comprehensive. Furthermore, this review underscores the critical need for additional research on silvopasture to address region-specific challenges, bridge knowledge gaps, and promote the broader adoption of silvopasture practices for more viable and resilient agricultural production systems. Moving forward, a concerted effort among researchers, policymakers, and practitioners will be key to advancing the scientific and practical application of silvopasture across varied landscapes. This review also addresses barriers to silvopasture adoption and proposes solutions such as carbon trading programs and government incentives to make silvopastures more feasible, especially for small-scale producers. Overall, this review provides a foundation for understanding the current status of silvopasture research in the United States.

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