Trees, Forests and People 26 (2026) 101394

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Review Article

An assessment of commonly grown agroforestry trees across the tropics: A scoping review

Apollinaire William [a,b,*], Katharina Löhr [a,c], Stefan Sieber [a,d], Vicky M. Temperton [b]

[a] Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[b] Institute of Ecology, Faculty of Sustainability, Leuphana Universität Lüneburg, Universitätsallee 1, Lüneburg, 21335, Germany
[c] Eberswalde University for Sustainable Development (HNEE), Forest Campus, Alfred-Möller-Str. 1, Eberswalde, 16225, Germany
[d] Department of Agricultural Economics, Humboldt Universität zu Berlin, Berlin, 10099, Germany

ARTICLE INFO

Keywords:
Native trees
Biodiversity
Livelihoods
Restoration
Shade trees
Land use systems

ABSTRACT

Agroforestry (AF) is increasingly promoted in tropical regions for its ecological, economic, and social benefits, yet the specific composition and uses of tree species in AF systems are underexplored. This review synthesizes literature on commonly grown AF tree species across the tropics, examining species composition and primary uses. Findings show that trees in AF systems are mainly used for fruit/food, fuelwood/charcoal, and shade, supporting local livelihoods. Fruit trees, especially for domestic consumption, are most prevalent. While many common AF tree species are native to tropical Asia and the Americas, AF systems in tropical Africa are largely dominated by exotic species, except in home gardens and coffee or cocoa systems, where indigenous species are more prevalent. These results underscore the importance of AF in sustaining both livelihoods and tree diversity while also highlighting opportunities to increase indigenous species outside home gardens and cash crop systems. Balancing livelihood needs with long-term ecosystem resilience is essential for guiding species selection in tropical AF.

1. Introduction

Restoring the world's depleted forests and landscapes is crucial for preserving ecological processes and ensuring sustainable livelihoods. Past and current restoration efforts seek to support ecosystem recovery processes along what ecologists have described as “the ambitious ecosystem restoration continuum” (Gann et al., 2019). This restoration continuum process is defined as the range of activities and interventions that can improve environmental conditions, reversing ecosystem degradation and landscape fragmentation. The aim is to follow a sequence of objectives: reducing societal impacts, improving ecosystem management, repairing ecosystem functions, and restoring native ecosystems (Gann et al., 2019).

Since 2020, restoration has become a key focus for global and national policies, especially since the launch of the UN Decade on Ecosystem Restoration (2021–2030). Addressing ecosystem degradation and its impacts on biodiversity, food security, and livelihoods is now a strategic goal for many countries (Gupta et al., 2023). Major initiatives include the Bonn Challenge, aiming to restore 350 million hectares of degraded land worldwide by 2030, and AFR100, which targets 100 million hectares in Africa. In densely populated African countries, efforts mainly center on planting trees on farms through AF and, to a lesser extent, silvopastoral systems. AF, which integrates trees with crops or livestock on the same land, is increasingly seen as vital for climate change adaptation, particularly for smallholder farmers (Masebo and Menamo, 2016; Watts et al., 2022). AF systems are diverse but share the common feature of combining trees with crops or grasslands. They are believed to help reverse land degradation, restore soil fertility and carbon stocks, as well as reduce labor and chemical input costs (Masebo and Menamo, 2016; Sileshi et al., 2020).

AF is situated on the “rehabilitation” side of the restoration continuum; it contributes to the rehabilitation of ecosystems (ES), such as improving soil health, enhancing soil fertility, conserving biodiversity, and providing climate change mitigation and adaptation (Gupta et al., 2020; Masebo and Menamo, 2016). Transitioning from rehabilitation to reclamation, defined as the process of assisting the recovery of severely degraded ecosystems to benefit native biota through the establishment of habitats, populations, communities, or ecosystems similar, but not identical, to naturally occurring ones (Gerwing et al., 2022), encompasses the recovery of native ecosystems. This transition

* Corresponding author at: Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany.
E-mail address: apollinaire.william@zalf.de (A. William).

https://doi.org/10.1016/j.tfp.2026.101394

Available online 6 July 2026

requires greater emphasis on integrating native tree species into current AF systems (Abella and Chiquoine, 2019). Understanding which land use setups best accommodate this process helps to customize AF systems that can sustainably meet ecological and human needs and goals.

The global area under AF systems is estimated at 1.6 billion hectares, with roughly 78% in the tropics and 22% in the temperate regions (Nair et al., 2022). Other literature reports 1.012 billion hectares of global land with at least 10% cover with trees, corresponding to 46% of the total global 22.2 billion hectares of agricultural land (Mahmud et al., 2021). The AF practice started to emerge significantly only during the last century and is presently intensifying in the tropical regions (Mahmud et al., 2021). Latest research shows more tree coverage in southern America, western Africa, and southeastern Asia, while eastern and southern Africa exhibit less cover (Brandt et al., 2023) (Fig. 1).

The layer of tree cover can identify forest hotspots and opportunities for restoration, particularly places with substantially poor tree cover. However, it does not support describing spatial arrangements of different AF systems, hotspots of biodiversity conservation within different agricultural land use settings. Current widely used monitoring systems for restoration are mostly based on the use of remote sensing technologies and do not allow for the segregation of those different aspects. Consequently, there is currently no monitoring platform that accurately assesses the progress and impacts of AF implementation or, even more problematically, the taxonomic composition of trees in agricultural landscapes (Mugabowindekwe et al., 2023). This challenge impedes the understanding of restoration priorities in terms of optimizing tree planting that responds to social, economic, and ecological needs, along the restorative continuum trajectory. There have been attempts to define the importance of some AF systems to enhance livelihoods and ecosystem recovery. The most prominent among these include home gardens (HG) and shade systems (coffee and cocoa).

We define home-gardens as one specific type of AF systems where farmlands are located close to the household's premises, containing a high plant diversity, fully or partially committed to vegetables (Kumar and Nair, 2004) and mainly cultivated using family labor (Ferdous et al., 2016) primarily for domestic consumption (Issahaku et al., 2023). Several studies focus on the critical role of home gardens in promoting biodiversity conservation and supporting local community livelihoods. For example, home gardens are also defined as small-scale traditional AF systems that contain several edible plant species (domesticated and semi-domesticated) and animals (González, 2022). Homestead AF is a unique area for maintaining both plant diversity and productivity (Begum et al., 2012). Home gardens are perceived to be highly sustainable in both biophysical and socioeconomic terms (Kumar and Nair, 2004). Smallholder farmers in many developing tropical countries are increasingly adopting fruit-tree-based AF. Fruit-tree-based AF in home gardens is suited to meet the nutritional needs (Abebaw et al., 2025; Duffy et al., 2021). In addition, AF trees have the potential to increase cash-crop yields by improving soil fertility (Sileshi et al., 2020) and to support the health of both humans and livestock, especially when indigenous, medicinally valuable species are incorporated (Njenga et al., 2015). For example, in Chagga home gardens in Tanzania, native species make up roughly 72% of all trees (Fernandes et al., 1984). In Rwanda, by contrast, the limited research emphasizes the socio-economic roles of home gardens rather than their social–ecological functions (Byiringiro et al., 2024; Dusingizimana et al., 2025; Issahaku et al., 2023).

Historically, Rwandan home gardens have incorporated fruit trees, including bananas, alongside a wide range of native species around homesteads (Van Damme et al., 2014). These gardens, in most cases, contain medicinal native trees such as *Markhamia lutea, Polyscias fulva, Ricinus communis, Vernonia amygdalina*, and *Tetradenia riparia*, along with fruit trees like *Myrianthus holstii* and *Carica cundinamarcensis*. Yet, in many areas, home gardens are poorly managed and are losing their functional capacity, mainly due to the limited AF technological support available to smallholder farmers (Mukundente et al., 2019).

Shade coffee AF systems are also sufficiently documented across tropical zones as a refuge for biodiversity recovery (Perfecto et al., 1996) and for mitigating the effects of climate change (Gomes et al., 2020). Shade coffee enhances the conservation of biodiversity, including pest control species (Perfecto et al., 2014). In tropical AF systems, intercropping multifunctional shade tree species with commercial crops, like coffee, helps reduce the use of chemical pesticides on those crops and promotes biodiversity, including antagonists of pests and diseases and pollinating bees and midges, thereby improving coffee and cacao yields (Tscharntke et al., 2011). In many tropical countries, coffee exports play a significant role in the national economy. Coffee is frequently intercropped with fruit and native tree species, some of which improve soil fertility and, in turn, support higher coffee yields.

In a changing climate, where shifts in temperature and precipitation are reshaping the ecological niches of tree species (Appelt et al., 2023; Grüter et al., 2022; Nath et al., 2018), various impacts can be expected, including phenological changes, range contractions, and range shifts. There is an increasing consensus about the high likelihood of biological niches shifting spatially as an adaptation strategy; however, there is still little evidence on the direction and the intensity of this impact (Camenen et al., 2016). Therefore, the urgent need for proactive forest management and conservation strategies to address the impacts of

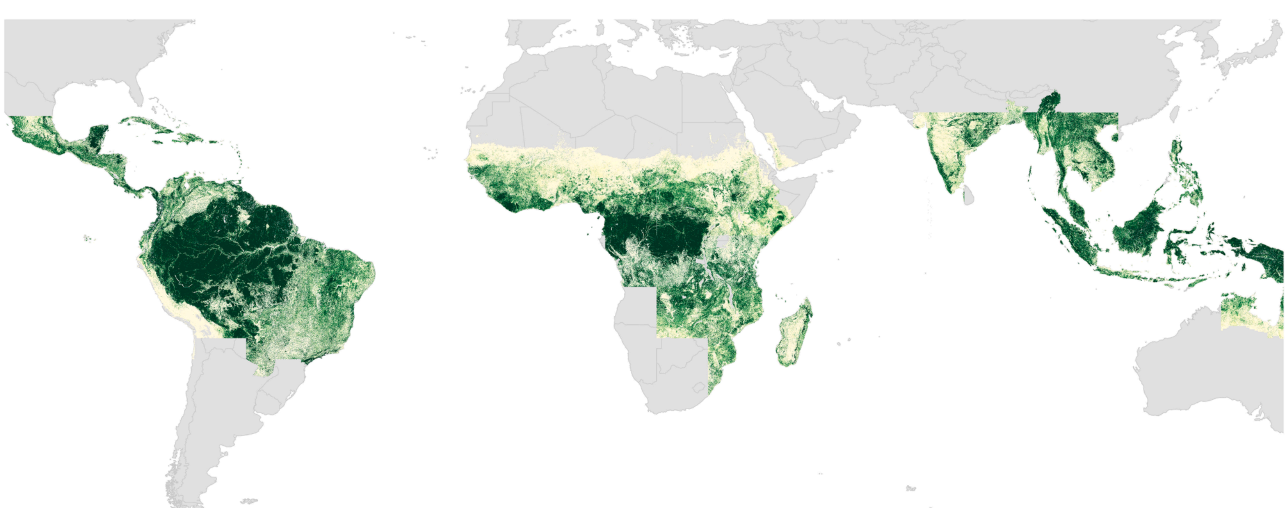

Fig. 1. Map showing tree cover across tropical regions. Data source: https://www.arcgis.com/home/item.html?id=a72920c18d854bd1b622c6d1ee44e2f5#data.

climate change on tree species and preserve ecological functions by mitigating climatic mismatches is critically meaningful (Xu et al., 2024). While restoration, especially with native species, offers a viable pathway to address environmental and social challenges, it also supports local communities (Djiofack et al., 2025). However, the knowledge of how to select suitable tree species under various socio-economic and environmental contexts, both in research and in practice, is lacking.

Most importantly, understanding which tree species, considered "generalists" because their distribution is ubiquitous across the tropics, could provide equivalent ecosystem services as a surrogate for native species, which could experience a shift in distribution following uncertain future climate change scenarios, is key to the management of AF systems under various climate change scenarios. Thus, the overall objective of this paper is to synthesize the existing literature on the composition and primary uses of tree species in tropical AF systems, to identify patterns in species selection and use, and to highlight opportunities for enhancing both livelihood support and ecosystem resilience through informed species choices. For this purpose, this study performs a scoping review to answer the following questions:

1. What are the most commonly researched AF tree species in the tropics and how variable are these across different tropical regions?
2. What are the main functions/uses of the most common AF tree species across the tropics and how are AF tree uses modulated across regions?
3. What proportion of local native trees are found across the different tropical regions under different AF systems?
4. How variable is the species richness of the most commonly used AF species in the tropics?

In this study, we hypothesize that the most common AF tree species in the tropics are largely region-specific (i.e., native to that region) and that the predominance of native species depends on the type of AF system. Despite regional differences in diversity, tropical areas with larger remnants of natural forest tend to support a wider variety of AF tree species, including a greater share of native species. Finally, we hypothesize that the importance local communities place on the benefits of native tree species varies among tropical regions and that this variation may be linked to the extent of remaining natural forests.

This review identifies the most commonly researched AF tree species used across tropical regions and highlights their economic, social, and ecological roles. Commonly researched species are species that appear frequently in the scientific literature, often because they are easy to study, economically important, or historically popular model systems, but may or may not be dominant or common. The construct "Commonly researched" describes human attention and use, which may or may not align with a species' real influence on ecosystems. We estimate AF tree species richness across the tropics and quantify the proportions of native and non-native species in each region. We then contrast these broader tropical patterns with the context of western Rwanda in sub-Saharan Africa, where land resources are increasingly limited, averaging approximately 0.4 hectares per household of 4.8 members. This region experiences severe land degradation, including frequent landslides, soil erosion, and mounting pressure on natural forests driven by high population density and subsistence farming. AF plays a crucial role in Rwanda, supporting rural livelihoods, enhancing food security, and helping address environmental challenges, thereby forming a key pillar of the country's sustainable development strategy. Additionally, this study is embedded within the broader research project "A Social-Ecological System Approach to Inform Ecosystem Restoration in Rural Africa" (https://ecosystemrestoration.net/). The project investigates social-ecological restoration in Western Rwanda and integrates a Living Lab component that implements restoration activities in close co-creation with local communities. As part of the exploration of potential AF trees for the live restoration implementations, the question of which kinds of trees are generally planted in the tropics – whether native or not – and their general uses has emerged. For this reason, we also compare our global findings on tropical trees used in AF with the specific situation in Western Rwanda.

2. Methodology

2.1. Literature search

To identify commonly researched AF tree species in the tropics and their related uses, we conducted a systematic literature review of publications on AF tree species in tropical agricultural landscapes across the three continents: America, Asia, and Africa, sourced from the Scopus and Google Scholar databases. As an interdisciplinary science, AF is comprehensively covered by Scopus and Google Scholar, both of which provide access to publications from a variety of fields, including AF (Pancholi et al., 2023), agriculture (Goertzen, 2019) . The identification screening and in-/exclusion process of the systematic literature review followed the Preferred Reporting Items for Scoping reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021) (Fig. 2) PRISMA is a reporting guideline designed and recommended to enhance the quality of scoping reviews by providing a standardized framework to ensure clarity, completeness, and reliability of the reporting of a review. It also provides a structured workflow to support the identification, screening and inclusion stages of the systematic literature review process.

2.2. Query formulation

The query for relevant documents was constructed to identify AF trees in the tropical areas based on existing literature on tropical AF. It was developed to include various synonyms, related terms, and alternative spellings, while maintaining the focus on our main topic elements "AF" and "tree species."

TITLE-ABS-KEY (AF OR agro-forest* OR agroecosystem* OR agrosilviculture OR agrosilvicult* OR agrosilvipast* OR agrosilvopast* OR silvopast* OR homegarden* OR "home garden*" OR "shade tree*") AND TITLE-ABS-KEY (tree* OR "tree species" OR "woody plant*" OR species OR "plant species" OR "crop species") AND TITLE-ABS-KEY (tropical OR tropics). There was no time scale restriction on the search for this study. For Google Scholar, we used the search string "agroforestry" AND "tree" AND "species" AND "Ethiopia", each time replacing *Ethiopia* with the name of each tropical country of interest. This search string was used on April 28, 2025, to compile an additional list of tropical AF tree species.

The query yielded 2798 results in the Scopus database on April 28, 2025. The research results file, in IRIS format, was then exported and imported into the EndNote 21 software. Subsequently, 3 duplicate records were removed, and the remaining number of records was 2795. Ninety additional records from Google Scholar search were also added, thus totaling 2885 records.

2.3. Title and abstract screening

Titles and abstracts from the collected references were screened and included if they suggested AF tree species in tropical regions using observed data or referencing other literature on tropical AF tree species. They were excluded if they did not mention AF species in the tropics of if they were published in a language other than English. Additional papers were excluded at a later stage during the full-text screening if they were only recommending species that are not explicitly documented on the ground. The screening yielded 400 records that were subjected to content screening.

2.4. Content screening

Following the screening of titles and abstracts to check their relevance to the topic under investigation, the 400 retained papers were

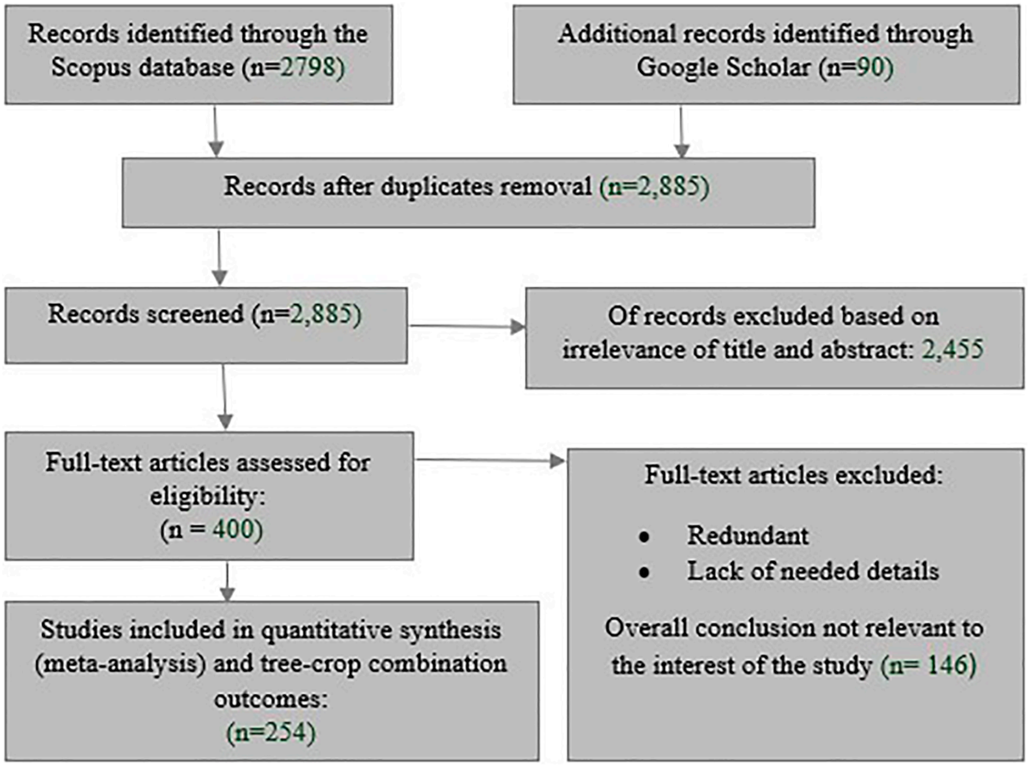

Fig. 2. PRISMA illustrating the flow diagram showing the identification, screening and inclusion process of the literature review.

screened for relevance to the expected details, particularly with respect to tree species in AF systems. Papers that did not mention AF species in a specific tropical region were excluded. In this study, we included both review articles and empirical research articles that used observational, survey-based, or experimental data and reported tree species used in agroforestry systems within the same area investigated. In total, we examined 217 empirical studies and 37 review papers. The empirical studies comprised 97 observational studies, 53 survey-based papers, 44 mixed-methods studies combining surveys with field observations, and 23 experimental studies. Each tree species was recorded only once, even if it was mentioned multiple times within a single paper. The tropical countries represented in the included studies were grouped into seven regions. North and Central America comprised the Dominican Republic, Cuba, Mexico, Nicaragua, Guatemala, Panama, Costa Rica, Honduras, and El Salvador. South America included Colombia, Venezuela, Ecuador, northern Peru, Brazil, Bolivia, and Suriname. West Africa included Nigeria, Ghana, Côte d'Ivoire, Sierra Leone, Togo, Benin, Guinea, Guinea-Bissau, and Gambia. Central Africa comprised Cameroon, the Democratic Republic of Congo, and Gabon. East Africa included Kenya, Tanzania, Uganda, Rwanda, Burundi, South Sudan, Somalia, Ethiopia, and Madagascar. Southern Africa comprised Mozambique, Zambia, and Malawi. South Asia included Bangladesh, Sri Lanka, southern India. Finally, Southeast Asia included Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Cambodia, Papua New Guinea, Laos, and Myanmar. This process yielded 254 papers that were retained into the EndNote program and finally selected for analysis. Out of the 254 papers included in this literature review and published since the 1980s, we found that about 66% were published since 2016. Publications on AF tree species have increased since 2013. Of the 254 papers analyzed, 22% (n = 56) were related to East Africa, 16% (n = 41) to Southeast Asia,14.6% (n = 37) to West Africa, 12.5% (n = 26) to North and Central America, 12.5% (n = 26) to South America, 9% (n = 24) to South Asia, 7.9% (n = 20) to Central Africa, and 6.3% (n = 16) to Southern Africa.

2.5. Data extraction, entry, cleaning and consolidation

When extracting tree species and their uses from agroforestry literature, explicit decision rules are needed to ensure consistency and reproducibility. What counts as "trees" are woody perennials, excluding annuals and non-woody plants, matching to accepted Latin names for tree species identity, harmonizing tree uses based on broad categories (Example, fuel, firewood, cooking energy fall into the category of fuelwood), one record for species to avoid duplications in counting various uses (Rigal et al., 2022; Zhang et al., 2023). For species name standardization, species names were verified using the World Checklist of Vascular Plants, an expert-reviewed global database of known vascular plant species.

Tree species were manually extracted from papers. Manual extraction of tree species from research papers is often considered more important than automatic extraction due to the need for high accuracy, deep contextual understanding of complex ecological data and the limitations of current automated systems in handling nuanced or unstructured academic text. Data on tree species were recorded in an Excel spreadsheet according to the tropical countries in which the species were recorded and then organized by tropical region. Tropical regions were identified based on the recorded data. Excel functions were used to check the consistency of the names of the tree species, as some were referred to by their common English names, while others were documented using their scientific names. Counts of papers for each species of AF tree were made, and a list of the most common tree species in AF systems for each region was generated using a filter.

Three categories of AF systems were investigated from the literature are shade-based (Coffee plantations, home gardens) and non-shade-based AF systems. In this study, we define shade trees as woody species that are regularly intercropped with either Coffea, cocoa (Esquivel et al., 2023) or banana plantations.

In this literature review, we acknowledge that "commonly observed" or "important" tree species in published studies often reflect where scientists work and which species they choose to study, rather than their true ecological prevalence. Factors such as accessibility, infrastructure, and security tend to concentrate research in wealthier, more temperate, or otherwise easily reached regions. As a result, substantial publication bias arises, and much of the tropics and other remote, biodiversity-rich areas remain undersampled (Culumber et al., 2019; Hughes et al., 2021; Troudet et al., 2017).

3. AF Tree composition

A total of 3285 AF tree species were identified in the literature across tropical zones worldwide, showing notable differences among countries. The highest number of species is found in tropical North and Central America with 738 species, followed by East Africa with 519 species, then South America with 483 species, Southeast Asia with 444 species, West Africa with 351 species, South Asia with 351 species, Central Africa with 238 species, and, lastly, Southern Africa with 117 species.

3.1. Diversity of AF species across the tropics

Considering the botanical diversity of commonly researched AF tree species for each tropical region across different zones, South Asia, Central Africa, and Southeast Asia exhibit the highest diversity; East Africa shows the lowest species diversity (Fig. 3). Note that the number of individuals recorded represents a count of individuals per species rather than a count of species or diversity level.

We cannot determine with high confidence whether observed differences in species richness reflect true ecological patterns or uneven research effort across regions. However, based on this review, studies reporting agroforestry trees and/or their uses appear to be disproportionately concentrated in certain tropical regions, while other tropical regions remain comparatively underrepresented. This highlights the need to intensify research efforts in underrepresented regions.

3.2. Most commonly researched AF tree species in the tropics

The most commonly researched AF tree species are defined here as those that are reported to occur in all global tropical regions, even if they do not occur at the same frequency across these regions. While variation across continents exists, we find 20 common species reported across all tropical regions; thus, they are representative of the tropics overall (Fig. 4). The 20 most commonly researched species in the tropics include mango (*Mangifera indica*), avocado (*Persea americana*), guava (*Psidium guajava*), papaya (*Carica papaya*), orange (*Citrus sinensis*), Grevillea (*Grevillea robusta*), leucena (*Leucaena leucocephala*), Gliricidia (*Gliricidia sepium*), kapok tree (*Ceiba pentandra*), jackfruit (*Artocarpus heterophyllus*), lemon (*Citrus limon*), neem (*Azadirachta indica*), coffee (*Coffea arabica*), fig trees (Ficus spp.), cashew nuts (*Anacardium occidentale*), soursop (*Annona muricata*), eucalyptus (*Eucalyptus* spp.), coconut tree (*Cocos nucifera*), oil palm (*Elaeis guineensis*), and Moringa (*Moringa oleifera*) (Fig. 3).

Species unique among the top 20 AF tree species in America include Wax laurel (*Myrica pubescens*), Spanish elm (*Cordia alliodora*), Ice-cream-bean (*Inga* sp.), Coral tree (*Erythrina poeppigiana*, Brazilian teak (*Dipterix micrantha*), *Stilt palm* (*Iriartea deltoidei*), Mamey sapote (*Pouteria sapota*), Spanish cedar (*Cedrela odorata*), Lipstick tree (*Bixa Orellana*), Golden spoon (*Byrsonima crassifolia*), Spanish lime (*Melicoccus bijugatus*), Yellow mombin (*Spondias mombin*), Big-leaf mahogany (*Swietenia macrophylla*), Cacao tree (*Theobroma cacao*), and Gumbo limbo (*Bursera simaruba*). Species unique to Africa include African baobab (*Adansonia digitata*), Pigeon pea (*Cajanus cajan*), African locust bean (*Parkia biglobosa*), Australian pine (*Casuarina equisetifolia*), Tamarind (*Tamarindus indica*), African fan palm (*Borassus aethiopum*), Yellow mombin (*Spondias mombin*), Antiaris (*Antiaris* sp.), African cactus (*Euphorbia tirucalli*), Red Calliandra (*Calliandra callothyrsus*), Nile tulip (*Markhamia lutea*), Woodland waterberry (*Szyigium guineense*), Acacia (*Acacia* sp.), Fish-poison pea (*Tephrosia vogelii*), Velvet bushwillow (*Combretum molle*), Lucky bean (*Erythrina abyssinica*), Apple-ring acacia (*Faidherbia albida*), and African teak (*Milicia excelsa*). Species only reported in Asia include Brown salwood (*Acacia mangium*), Rubber tree (*Hevea brasiliensis*), Big-leaf mahogany (*Swietenia macrophylla*), Teak (*Tectona grandis*), Northern black wattle (*Acacia auriculiformis*), Arecanut palm (*Areca catechu*), Rambutan (*Nephelium lapaceum*), Indian rosewood (*Dalbergia sissoo*), Hummingbird tree (*Sesbania grandiflora*), Beach almond (*Terminalia bellirica*), Bengal quince (*Aegle marmelos*), and Breadfruit (*Artocarpus altilis*). The results obtained demonstrate a variation in tropical AF species across continents. Fig. 4 summarizes the 20 most commonly researched species identified on each continent. It is evident that commonly researched species across all tropical regions are not necessarily the most common for each continent.

3.3. Variations among the most commonly researched AF tree species: natives vs exotics

Although continental patterns in common AF species vary, examining the subtler differences among tropical regions helps clarify how these species are distributed. The 20 most commonly researched AF tree species present variations across different tropical zones (Fig. 5). For example, overall, most of the common tropical AF tree species are more predominant in the East African region than in other tropical zones, except for a few species such as the Coconut tree, Oil palm tree, Cashew nut tree and kapok tree. On the other hand, Grevillea and Eucalyptus are more common in East Africa than in the rest of the tropics.

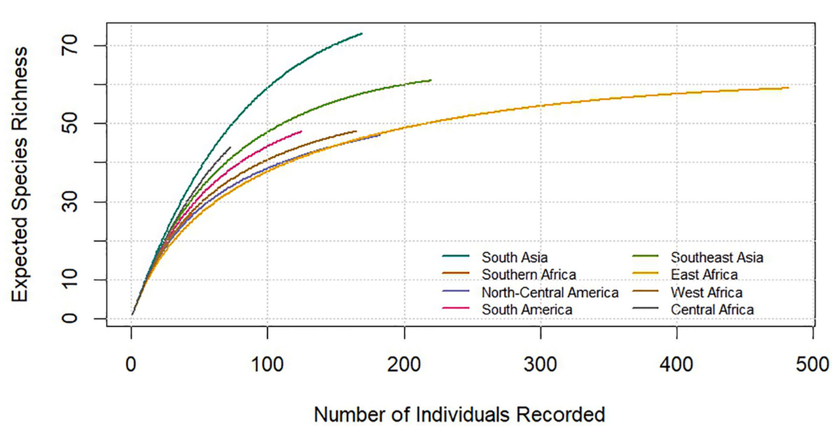

Fig. 3. Rarefaction curve of AF species identified in papers and documents across global tropical zones. Rarefaction is based on species recorded in published papers.

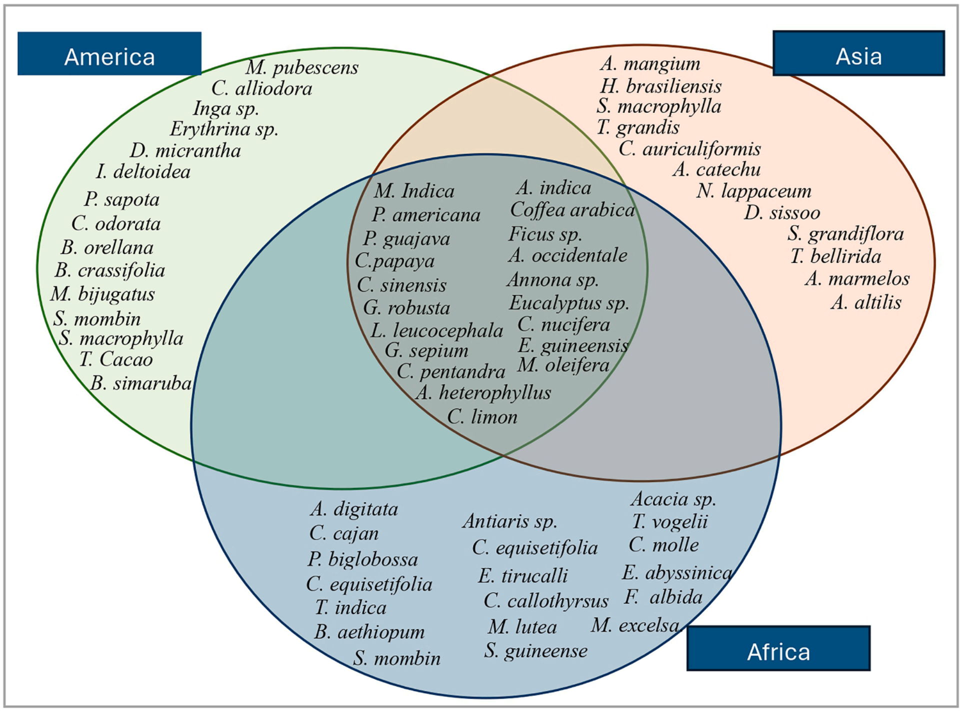

Fig. 4. The 20 most commonly researched AF tree species in the tropics are shown within the intersection of the three circles. The list in the top-left circle shows the most common tropical American AF tree species. The list in the top-right circle shows the most common tropical Asian AF tree species. The list from the bottom circle shows the most common species of tropical African AF trees. For clarification reasons, we simplified the 8 tropical regions in Fig. 1 into 3 continents. Species occurring across tropical zones were classified as the most common, while continent-specific species were considered most common within their own continents.

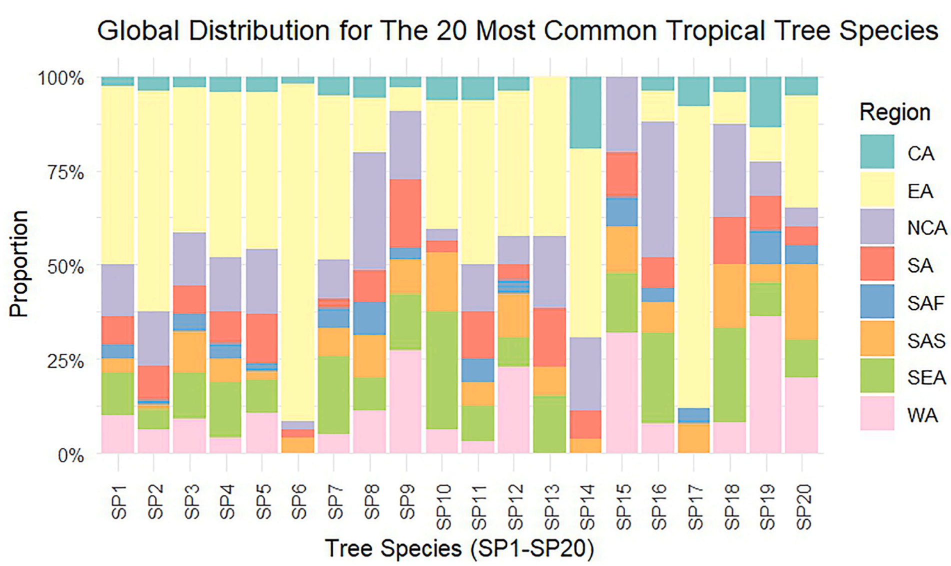

Fig. 5. The 20 most commonly researched AF tree species across tropical regions (CA: Central Africa, EA: East Africa, NCA: North & Central America, SA: South Asia, SAF: Southern Africa, SAS: South Asia, SEA: Southeast Asia, WA: West Africa). The bars indicate the percentage frequency of species occurrence in each tropical region. As the graph shows, the most commonly researched species are SP1: mango fruit, SP2: avocado fruit, SP3: guava fruit, SP4: papaya fruit, SP5: orange fruit, SP6: Grevillea, SP7: Leucaena, SP8: Gliricidia, SP9: kapok tree, SP10: jackfruit, SP11: lemon, SP12: neem, SP13: coffee, SP14: *Ficus*, SP15: cashew nuts, SP16: soursop, SP17: eucalyptus, SP18: coconut tree, SP19: oil palm, and SP20: Moringa.

4. Main functions/uses of the most commonly researched AF tree species across the tropics

Across tropical agroforestry, most trees are in fact highly multi-functional, but this is only partly captured in formal studies. Studies typically predefine a small number of broad uses/functions. The present study captured only the uses/functions reported in the published literature on agroforestry. The most commonly researched AF trees across tropical regions are predominantly used for fruit/food for domestic consumption (32.7%), fuelwood and charcoal (15.9%), and shade (13.7%), despite differences in diversity (Fig. 6). Percentages are proportional to the number of counts for each use.

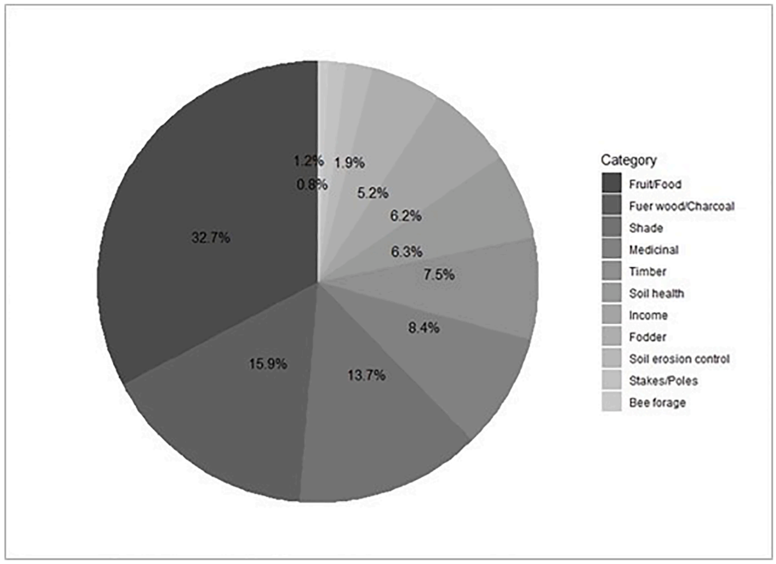

Fig. 6. Main uses of the most commonly researched AF tree species across the tropics.

4.1. Variation in uses among the most commonly researched AF tree species across different tropical zones

The predominant use of the most commonly researched AF tree species is for fruit and food, with the highest proportions occurring in the Americas and Asia. The least important use is "bee forage" (Fig. 7). Percentages for each use type were calculated based on total counts of all uses.

4.2. Variations among the most commonly researched AF tree species per tropical region: natives vs exotics

Native vs exotic status is determined by a combination of reconstructed historic range, mode and timing of arrival, and the spatial scale chosen for assessment, often supplemented by genetic evidence. For widely naturalized trees such as Mangifera indica and Grevillea robusta, most contemporary schemes still classify populations outside their original biogeographic ranges as exotic to capture long-standing or intra-country introductions. In most of the literature reviewed, trees species were regionally classified as exotic or native.

The highest proportion of the most common native trees in different tropical zones is found in tropical Asia and lowest in Africa, particularly in West and East Africa. Coffee plantations exhibit similar global tropical native tree predominance trends (Fig. 6). West Africa: 89%, South Africa: 83%, Southeast Asia: 71%, South Asia: 89%, South America: 75%, North & Central America: 89%, and East Africa: 66% (Fig. 8).

Findings from papers that did not mention shade systems, compared to shade-based AF systems (home gardens and coffee plantations), non-shade-based AF systems have a relatively lower percentage of native tree species. The proportion of native tree species is lowest in Africa, particularly East Africa, and highest in Southeast Asia.

In Rwanda, however, the proportion of native species in home gardens is the lowest reported globally (61%). In shade coffee systems, this proportion is slightly higher (64%). In other AF systems, where studies did not specify home gardens or shade coffee, the proportion is lower than that reported for the rest of the tropics.

From the ecological perspective, the most prominent use of the tropical AF tree is soil health. Besides the integration of native trees and fruit trees, native or not, we also find that there is a tendency to find trees that contribute soil nutrients to the soil, particularly nitrogen-fixing trees (Table 1). We found the most common fruit species can be intercropped with a diversity of N-fixing tree species within home gardens and coffee plantations.

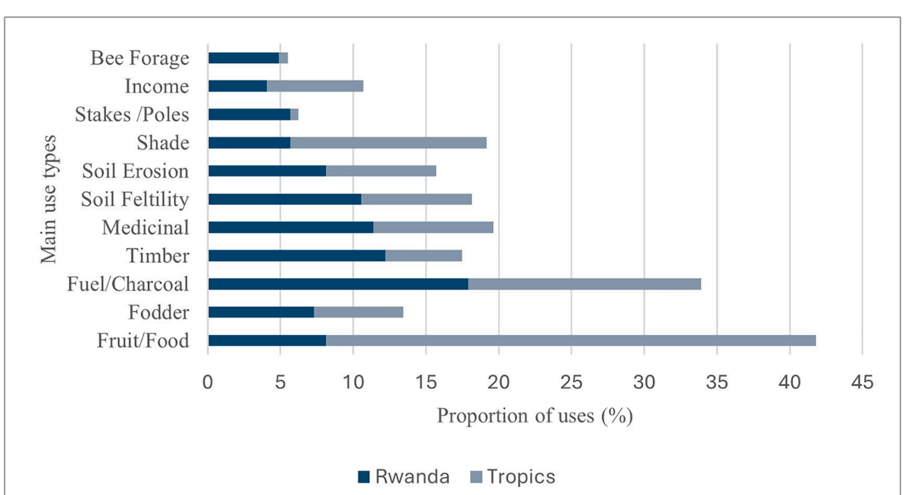

Fig. 7. Histogram showing variations in the uses of the most commonly researched tropical AF trees in Rwanda versus the rest of the tropics.

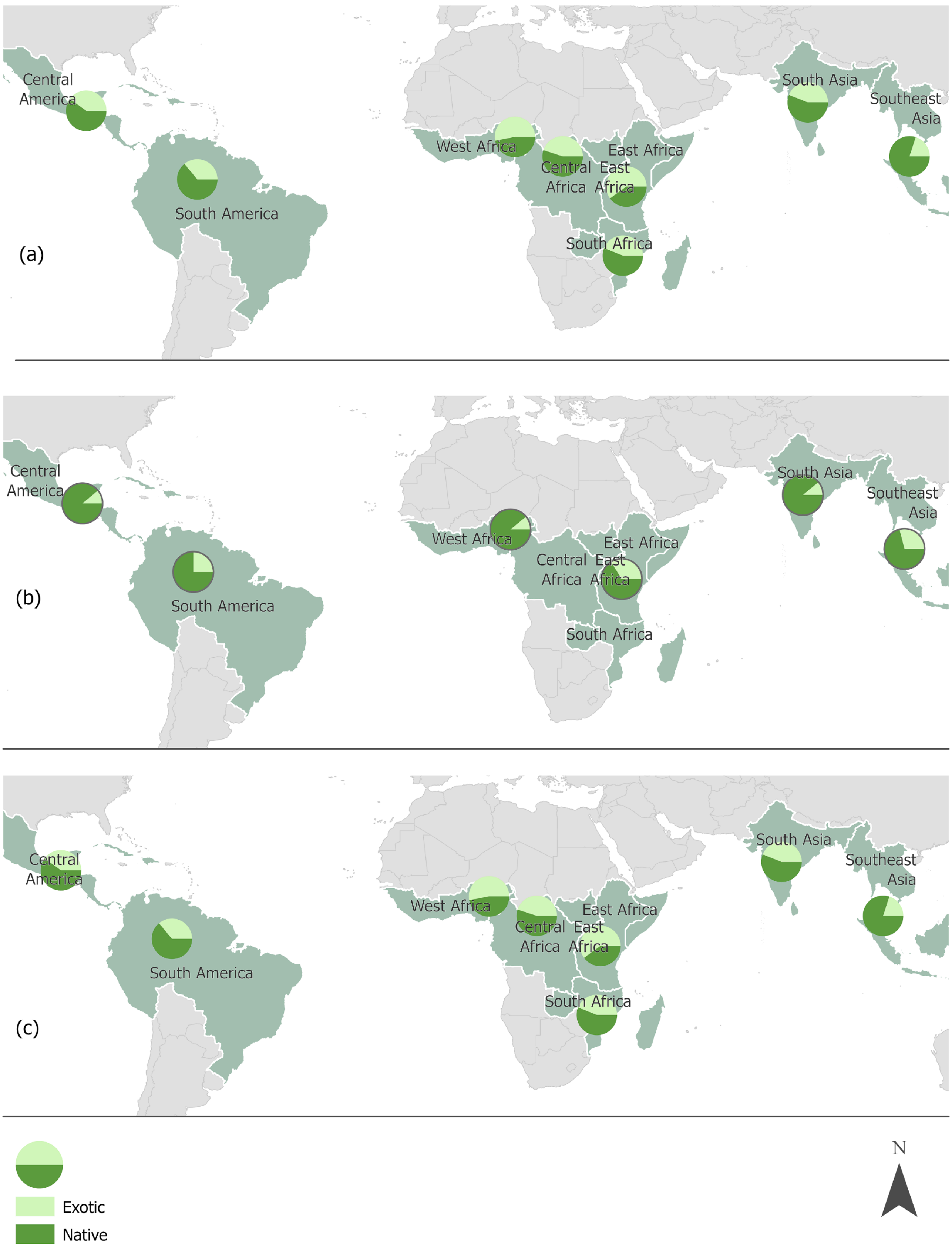

Fig. 8. The pie charts on the map show the proportions of native versus exotic tree species in HG-based AF systems (a), in shade coffee systems (b), and in other systems from papers where neither home gardens nor shade systems were mentioned (c). Native tree species are dark green, while exotic tree species are in light green. These figures are based on published papers on each tropical region globally. Detailed information on the most commonly researched tree species across tropical zones, including their most commonly reported uses and native origin, is found in Table S1.

Table 1
Association of N-fixing AF tree species with fruit species in "shade" systems.

Tropical countries	Fruit trees	Associated N-fixing trees	AF system	References
Cote d'Ivoire	*P. americana, M. Indica, C. papaya, Musa* sp., *Citrus* sp.	*Milicia excelsa*	Coffee	(Herzog, 1994)
	Persea americana, Mangifera indica, Citrus sinensis	*Milicia excelsa, Albizia zygia* and *Gliricidia* sp.	Cocoa	(Kouassi et al., 2023)
Indonesia	*M. indica, Musa* sp.	*Gliricidia sepium, Erythrina* sp.	Coffee	(Martini and Riyandoko, 2017; Suyanto et al., 2005)
Vietnam	*M. indica, Artocarpus heterophyllus, P. americana, Macadamia integrifolia*	*Leucaena leucocephala*	Coffee	(Nguyen et al., 2020), (Rigal et al., 2023)
Uganda	*M. indica, A. heterophyllus, P. americana, C. papaya, Citrus* sp., *P. guajava*	*Albizia chinensis, Albizia coriaria. Milicia excelsa*	Coffee, home gardens	(Gram et al., 2018), (Tabuti et al., 2011), (Oduol and Aluma, 1990), (Kyarikunda et al., 2017)
Brazil	*P. americana, Musa* sp.	*Cajanus cajan*	Coffee	(Gomes et al., 2020), (Zaro et al., 2020)
Peru	*Mangifera indica, Persea americana, Musa* sp.	*Acrocarpus fraxinifolius*	Coffee	(Solis et al., 2020)
Rwanda	*Persea americana, Mangifera indica, Citrus* sp., *Psidium guajava* *Persea americana*	*Alnus acuminata, Calliandra calothrysus, Erythrina abyssinica* *Albizia* sp. *Inga oerstediana*	Home garden, Coffee Coffee	(Ndoli et al., 2021), (Uwera et al., 2022), (Cyamweshi et al., 2021), (Bucagu et al., 2013) (Pinard et al., 2014)
Ethiopia	*Mangifera indica, Musa paradisiaca Psidium guajava*	*Albizia gummifera Millettia ferruginea Acacia abyssinica Cordia africana*	Coffee	(Ayalew et al., 2022), (Teketay and Tegineh, 1991)

5. Discussion

Our review identifies a wide diversity of tree species across continents and regions. Whilst we also find an overlap of species across continents, the most common AF tree species across the tropics are regionally specific, including a large proportion of native species. In tropical areas with substantial natural forest cover or high tree diversity, the surrounding agricultural landscapes tend to exhibit greater taxonomic richness and reduced reliance on exotic tree species (Chazdon and Uriarte, 2016). This practice is traditionally considered an ecosystem recovery strategy, especially in abandoned agricultural lands neighboring forests (Martínez-Ramos et al., 2016). In some tropical regions, natural regeneration occurs, and farmers subsequently implement selective maintenance of the regenerated trees on their farmland (Suryanto et al., 2021). Proximity to natural forests also provides access to planting material for AF (Souza et al., 2014) and contributes to a high diversity in tropical zones, particularly where mature natural forests have a large extent (Zahawi et al., 2021).

5.1. Main uses of tropical AF trees: food, fuel, shade

In tropical regions, AF trees are typically used for fruit, food, fuelwood, and shade. Fruit trees are particularly popular as they have a long lifespan, require minimal maintenance, support biodiversity, and meet growing market demand (Rahman et al., 2016). Consequently, fruit trees dominate many tropical AF systems (Hanif et al., 2018). For example, they represent 61% of the most popular AF trees in Panama (Holmes et al., 2017), at least 70% of the most common shade species in Côte d'Ivoire (Atangana et al., 2021), up to 60% in the Dominican Republic (Notaro et al., 2021), 53% of home garden species in Guatemala (Gillespie et al., 1993), 75% in Indonesia (Rahman et al., 2016), and around 56% in Benin (Sêdami et al., 2016). In contrast, the proportion is lower in East Africa, at around 35% in Tanzania (Mkonda and He, 2017) and 19% in Rwanda (Nansamba, 2010). In several regions, fruit trees also fulfil additional roles, such as providing shade, having medicinal uses (e.g., in Bolivia, Ecuador, El Salvador (Thomas and Van Damme, 2010), Benin (Ouinsavi and Sokpon, 2008) and the Democratic Republic of Congo (Batsi et al., 2020)), and generating income (e.g., in Costa Rica and the Dominican Republic) (Notaro et al., 2020; Salazar-Díaz and Tixier, 2019).

Our findings indicate that, beyond providing fruit and food, a major use of AF trees in the tropics is fuel. In the Philippines, AF trees are mainly valued for fuelwood (Cordero, 2022), while they are primarily used for fuel and timber in Kenya and Laos (Kosaka et al., 2006; Rotich et al., 2017). Fuelwood dependence is particularly high in Africa, where it supplies 58% of energy needs (Specht et al., 2015). For example, in Tanzania, 85% of people rely on it for cooking (Matavel et al., 2023) and, in rural Rwanda, 91% use firewood (Bapfakurera et al., 2024; Ndayambaje and Mohren, 2011). Using diverse native species for fuelwood can enhance biodiversity, nutrient cycling, pollination, and pest control (Armengot et al., 2020; Loguercio et al., 2009; Pumariño et al., 2015), while also reversing land degradation (Steinfeld et al., 2024). Such benefits are especially relevant in coffee-based AF systems, where pollination can significantly increase yields (Centeno-Alvarado et al., 2024), including bean yields in regions like Rwanda (Kingazi et al., 2024). Native species are often preferred for their adaptability, water conservation, and support for wildlife undergrowth (Cordero, 2022).

5.2. Fruit trees are commonly used in AF systems as shade trees, in association with N-fixing trees

Our findings are in line with previous findings showing that shade systems (coffee-based and home garden-based) harbor a diversity of fruit trees (Kumar and Tiwari, 2017). Our findings also highlight the importance of fruit trees in home gardens, as also evidenced in tropical zones such as Southeast Asia (Catacutan et al., 2017), South America (González, 2022), and Central America (Montagnini, 2006), where home gardens are of vital importance to the local subsistence economy and regional food security, especially in regions that still carry the influence of Mayan culture, characterized by the predominance of native species (Montagnini, 2006). In many tropical developing countries, fruit/food items are integrated into home gardens as a strategy to minimize climate change-related risks; home gardens have historically served as a reliable source of food and nutritional stability for their owners during periods of economic hardship and insufficient food supply (Barthel et al., 2015). A study conducted in southern Ethiopia on the role of AF in climate change adaptation came to the observation that home garden AF plays a pivotal role in climate change adaptation through the provision of diverse ecosystem services, including the mitigation of climatic risks such as droughts and erratic precipitation (Gebremariam et al., 2025).

For example, home gardens are claimed to provide an opportunity for food security in Indonesia (Duffy et al., 2021), Ethiopia, and Kenya (Abebaw et al., 2025), where the integration of fruit trees is important. While fruit shade trees improve the quality of coffee, cocoa, etc., and supplement nutrition, N-fixing trees are well integrated with fruit trees (e.g., Table 1), most N-fixing trees do not present significant competition for water and nutrients against fruit trees as these typically have deep rooting systems.

Shade tree species, particularly N-fixing trees, when intercropped with coffee, positively affect the chemical properties of the soil, thus improving coffee productivity (Misgana et al., 2024). Nitrogen-fixing trees are commonly incorporated into tropical AF systems, particularly shade tree systems, to improve soil fertility, particularly in nutrient-poor or degraded soils. This reduces the need for synthetic fertilizers and supports sustainable crop production (Getachew et al., 2023; Munroe and Isaac, 2014). A literature review on the role of tropical N-fixing trees for carbon sequestration in the Congo Basin also highlighted the multifunctionality of these species, including their contribution to climate resilience, soil fertility, fuel wood energy supply, and restoration of degraded soils (Koutika et al., 2021).

In tropical AF, addressing the adverse impacts of climate change lies in intercropping multifunctional shade tree species that provide beneficial socio-economic and ecological outcomes. Future research should explore both quantitatively and qualitatively how various tree combinations within these shade systems generate these benefits.

5.3. Home gardens and shade coffee systems are an AF refuge for native tree species

Our findings emphasize the important role of home gardens in conserving a large number of native tree species (Rooduijn et al., 2018). Tropical home gardens often act as regeneration sinks for native trees (Kumar and Tiwari, 2017), particularly in Tropical Asia, where they are more widespread than other AF systems (Rooduijn et al., 2018). Studies from Bangladesh, Indonesia, and the Eastern Himalayas consistently demonstrate that native species dominate home garden tree communities, accounting for over 50% of all AF trees in some cases (Barbhuiya et al., 2016; Leuschner and Khaleque, 1987; Rahman et al., 2017, 2016). This prevalence is supported by low management intensity and favorable microclimatic conditions that promote the regeneration and survival of indigenous species. Soil fertility is usually maintained using organic methods, such as producing manure on site and composting crop residues. The division of labor within households also shapes home gardens: men typically manage cash crops, fruit trees, and other long-term plantings, while women focus on vegetables, spices, medicinal plants, and harvesting crops for home consumption and local sales (Barbhuiya et al., 2016). Native trees also help to retain soil moisture and fertility, creating conditions that are suitable for leguminous and medicinal species, which are often cultivated in HGs (Lakshmi and Joseph, 2017). Overall, the ecological and social characteristics of home gardens make them particularly effective at sustaining native tree diversity. Tropical home gardens typically maintain high plant richness, often comparable to or exceeding nearby forests, and include many native trees used for food, medicine, timber, and shade, and can raise income and household resilience to shocks. In Southeast Mexico, most native trees in home gardens arrived by natural regeneration and were then spared and managed, making gardens important sinks for wild native trees in fragmented landscapes (Rooduijn et al., 2018). These systems can maintain unique, locally evolved genetic diversity that is valuable for climate adaptation and future breeding (Korpelainen, 2023). Home gardens are ideal places to produce seed and seedlings of native species for wider restoration or enrichment planting (Rooduijn et al., 2018; Suwardi et al., 2023).

In tropical Africa, the proportion of native species in HG is relatively low compared to other tropical regions. Other African research corroborates these results, suggesting that the reduced native species presence stems from prioritizing high-value non-native species through intensive management practices, causing them to dominate in competition for space and resources (Tadesse et al., 2019). Factors underpinning this situation include socio-cultural changes, the Westernization of production systems, and a potential lack of knowledge or support for cultivating indigenous species (Adefila et al., 2024). However, when the practice is well embedded in a culture, the proportion of native species can be very high, as in the Chagga home gardens, on the fertile slopes of Mount Kilimanjaro, where the proportion of native tree species is about 72% (Fernandes et al., 1984). A striking contrast is found in Rwanda, where a survey conducted across the country shows that the emphasis of home gardens is to support nutrition (Issahaku et al., 2023), implying the integration of fruit trees, most of which are exotic.

Although our synthesis indicates that exotic tree species now numerically dominate many contemporary African agroforestry systems, this pattern cannot be attributed solely to recent farmer preferences and risks being overinterpreted if removed from its historical context. Across East and Central Africa, the widespread presence of *Grevillea robusta, Eucalyptus* spp. and other fast-growing exotics reflects a long history of colonial and post-colonial forestry and agricultural policies that actively promoted these taxa as cheap, high-yield sources of timber, fuelwood and poles, and as easily managed boundary or woodlot trees (Anatole et al., 2022; Mbaruku et al., 2024; Melaku, 2021; Mellisse et al., 2024; Ruticumugambi et al., 2024). In Burundi, for example, colonial administrations explicitly selected exotics over “expensive” native forest species, and *Eucalyptus* became the default reforestation species, a status largely maintained in contemporary state and NGO programs (Anatole et al., 2022). Similar trajectories underpin the current dominance of *Grevillea* and *Eucalyptus* in smallholder systems in Rwanda, Kenya and Ethiopia, where extension and project interventions have supplied seed and seedlings, framed these species as modern and profitable, and normalized their use in home gardens, hedgerows and woodlots (Fuchs et al., 2022; Mbaruku et al., 2024; Melaku, 2021; Molla et al., 2023; Ruticumugambi et al., 2024; Tadesse et al., 2019). At the same time, many systems still retain significant native components (e.g. *Faidherbia albida* parklands, or homesteads with high proportions of indigenous perennials), illustrating that exotic dominance is contingent and spatially uneven, shaped by interacting historical, policy and market drivers rather than representing a simple farmer-driven replacement of indigenous agroforestry traditions (Demie et al., 2024; Legesse and Negash, 2021; Tadesse et al., 2019, 2021).

Studies show that invasive alien plants often reduce abundance and diversity of resident species, while increasing primary production and changing nutrient cycling, fire regimes and soil chemistry (Pyšek et al., 2012; Rai and Singh, 2020; Vilà et al., 2011). In Africa, invasive plants and shrubs are highlighted as a major threat to biodiversity, hydrology and regeneration across agroforestry and rangeland systems (Rai and Singh, 2020; Shiferaw et al., 2018; Syngkli and Rai, 2025). These risks are highly species- and context-specific: many exotics have modest or mixed effects, but some cause large, hard-to-reverse changes(Cordero et al., 2023; Pyšek et al., 2012; Shiferaw et al., 2018; Vilà et al., 2011). However, in smallholder and agroforestry systems, exotics can be central to income, energy and food security. Fast-growing exotic timber and fuel species are often the main source of poles and firewood, underpinning household energy self-sufficiency and cash income, even where they entail environmental trade-offs (Rai and Singh, 2020; Reppin et al., 2020; Shiferaw et al., 2018). Tree-based systems (often dominated by exotics) can maintain or increase crop yields while adding income streams and buffering climatic and market shocks, thereby strengthening livelihood resilience (Quandt et al., 2019; Reed et al., 2017; Reppin et al., 2020). Fruit trees, frequently a mix of exotic and indigenous, are associated with improved diet diversity and reduced food insecurity in African smallholder households (Quandt et al., 2019; Reed et al., 2017; Tesfay et al., 2024; Zaca et al., 2025). Therefore, “Exotic” does not automatically mean functionally inferior. Several strands of work show the need to assess traits and functions, not origin alone: in tree biodiversity–ecosystem functioning experiments, exotic trees selected to be functionally equivalent to natives were more productive in diverse mixtures, likely due to enemy release and reduced apparent competition, not superior resource-use traits (Belluau et al., 2021), trait-based studies in agroforestry demonstrate that functional traits (e.g. height, wood density, leaf economics) predict carbon storage, soil fertility and multiple ecosystem services, irrespective of nativeness (Edelstein et al., 2025; Ontong et al., 2023; Reppin et al., 2020) and reviews of exotic species in mutualistic networks show that some exotics can partly substitute or complement native ecological roles (e.g. seed dispersal and regeneration) even while also facilitating invasions, so their net functional effect is often mixed rather than uniformly negative (Cordero et al., 2023; Pyšek et al., 2012).

A stronger discussion can argue that some exotic generalists may act as partial functional substitutes under climate change, but usually at the cost of native biodiversity, and with strong constraints. non-native generalists tend to occupy central positions, interact with many partners, and show high environmental tolerance, thereby bolstering functional resistance (continued pollination/seed dispersal) as conditions change (Aslan, 2019). Also, some exotic trees and shrubs show greater drought resilience, lower mortality, and higher regeneration than co-occurring natives, so their dominance is projected to increase under future aridification (Medina-Villar et al., 2024; Nyssen et al., 2024). Furthermore, many exotic plants exhibit broad tolerance and conservative, stress-resistant trait syndromes, allowing relatively stable performance across strong environmental gradients (Ferrero et al., 2022; Kaushik et al., 2022; Westerband et al., 2021). These patterns underpin the idea that certain exotic generalists can serve as "climate-proof" providers of basic ecosystem functions (e.g., biomass production, some mutualistic services) when vulnerable natives fail. However, reviews of restoration planting show that exotic tree species pose non-trivial risks of invasion, altered phenology, and biotic homogenization, and often underperform for supporting native biotas (de Carvalho et al., 2022; Ennos et al., 2019; Russo et al., 2025).

The findings show that coffee systems typically incorporate fruit trees and a significant proportion of native shade species, which enhance soil fertility and nutrient use (Haggar et al., 2015). Although organic certification has encouraged the use of native shade trees in Central America, Latin America, and Southeast Asia, certified shade coffee remains limited in several regions (Jha et al., 2011; McCook, 2017; Nesper et al., 2017). The integration of native trees varies widely: South Asia traditionally relies on dense natural shade (Naidu, 2018), while Central America has a long history of AF and, therefore, has high levels of native cover (Esquivel et al., 2023). East Africa has lower levels of native cover: for example, Uganda's coffee systems contain approximately 57% native shade trees (Gram et al., 2018), whereas in Rwanda, this figure is only around 22%, with exotics such as Grevillea robusta dominating (Nansamba, 2010). Ethiopia, the center of origin of the crop, has diverse native shade canopies in its Afromontane forests (Ayalew et al., 2022). Overall, outside of home gardens and traditional shade systems, native tree integration remains limited, with western Rwanda specifically showing clear gaps in incorporating native species into expanding coffee production (Reckmann et al., 2025).

Linking our findings to the restoration continuum introduced earlier in this paper, we show that agroforestry AF can operate across all levels, from recovery and regeneration (R.I), through reparation and recuperation (R.II), to full ecosystem recovery at broader policy and international scales (R.III) (Fahad et al., 2022; Giudice Badari et al., 2020; Montagnini, 2020; van Noordwijk et al., 2020). First, AF tree diversity and uses contribute directly to ecological intensification (R. I) and local recovery (R.II). High AF tree diversity in tropical America and Asia, and lower diversity in East Africa, reflects different positions along a continuum of ecological intensification within agricultural land: where tree diversity is high, AF already functions as a biodiversity-enhancing production system; where diversity is low, there is greater scope for intensification through diversification of tree species (Fahad et al., 2022; Giudice Badari et al., 2020; Udawatta et al., 2019). Dominant uses such as food and fuel indicate that AF delivers provisioning services critical for subsistence, consistent with people-centred restoration that starts from livelihood needs and local ecosystem services (food security, energy) (Fahad et al., 2022; Lelamo, 2021; Sistla et al., 2016; van Noordwijk et al., 2020). Fruit trees in home gardens that improve diets and seasonal food security exemplify R.I "restoration from within" existing farming systems, where tree integration enhances soils, microclimate, and nutrition without land-use change (Clara Manasa et al., 2024; Fahad et al., 2022; Lelamo, 2021; Sistla et al., 2016; Udawatta et al., 2019). Fuelwood from AF trees substitutes for woodlot or forest extraction, reducing pressure on natural forests and thus contributing to recovery and regeneration (R.II) at landscape scale by lowering deforestation drivers (Dawson et al., 2013; Lelamo, 2021; Montagnini, 2020; Sistla et al., 2016; Udawatta et al., 2019).

Secondly, the balance between native and exotic species extends impacts from local recovery (R.II) to policy-driven reparation (R.III). Our finding that native shade trees, including nitrogen fixers, remain important in home gardens and shaded cash crops aligns with evidence that traditional multistrata AF and shade coffee/cocoa can retain a large share of forest tree diversity, including endemic species, acting as circa situm and in situ reservoirs (Bhagwat et al., 2008; Dawson et al., 2013; Lelamo, 2021; Montagnini, 2020; Osuri et al., 2025; Rendón-Sandoval et al., 2020; Udawatta et al., 2019). The global prevalence of exotic species in non-shade AF systems, and our recommendation to promote more diverse mixtures including natives on degraded agricultural land, correspond to moving systems along the continuum from simple "tree planting" toward biodiversity-oriented reparation (R.III) that requires supportive policies, extension services, and functional input/seed markets (Dawson et al., 2013; Kimaro et al., 2024; Lelamo, 2021; Udawatta et al., 2019; van Breugel et al., 2025; van Noordwijk et al., 2020). Expanding cash-crop areas under native shade, where socially and ecologically appropriate, represents a restoration option that combines economic incentives with structural and functional diversification, similar to high-diversity shade coffee and cocoa systems used as restoration tools (Bhagwat et al., 2008; Giudice Badari et al., 2020; Montagnini, 2020; Osuri et al., 2025).

Finally, proximity to forests, nurseries, and germplasm resources links AF to landscape-scale recovery and reparation (R.II–R.III). Our finding that AF tree diversity is highest near large natural forests echoes evidence that remnant forest composition and proximity strongly shape natural regeneration and recruitment in restoration plots and secondary forests (van Breugel et al., 2025; Zahawi et al., 2021). Within the continuum, this represents R.II: leveraging existing landscape structure (forest remnants, corridors) to accelerate recovery. Establishing tree nurseries and strengthening AF near natural forests positions these landscapes as sources of native germplasm, enabling circa situm conservation and supplying restoration material elsewhere, thereby bridging R.II (local recovery) and R.III (landscape- and policy-supported reforestation programmes) (Dawson et al., 2013; Osuri et al., 2025; van Breugel et al., 2025; van Noordwijk et al., 2020; Zahawi et al., 2021). Shade agroforests used as nurseries and seed sources for restoration in India and Latin America provide parallel examples (Giudice Badari et al., 2020; Montagnini, 2020; Osuri et al., 2025). Because many rural communities have limited access to forests, AF-based nurseries and seed-rescue systems also address the "Rights" and "Know-how/Markets" bottlenecks in people-centred restoration typologies, making native tree options practically accessible along the restoration continuum (Dawson et al., 2013; Lelamo, 2021; Osuri et al., 2025; van Noordwijk et al., 2020).

5.4. CDM and REDD implications of agroforestry systems

Agroforestry systems across the tropics already provide substantial carbon storage while simultaneously supporting rural livelihoods, making them strong candidates for integration into climate mitigation mechanisms such as the Clean Development Mechanism (CDM) and REDD+ frameworks in tropical Africa (Tschora and Cherubini, 2020), tropical Asia (Singh et al., 2024) and tropical Latin America (Villa et al., 2020). In East Africa, agroforestry systems supply fodder, food, firewood, and household income while storing, on average, 24 Mg C ha^{-1} in aboveground biomass and approximately 99 Mg C ha^{-1} in soils (Muthuri et al., 2023). Accordingly, REDD+ and the UN-REDD Programme increasingly recognize tree-based farming systems as pathways for reducing deforestation and enhancing forest carbon stocks. Fruit- and timber-based agroforestry systems are therefore promoted as approaches that can simultaneously achieve climate mitigation and livelihood objectives (Awazi et al., 2024). For example, the integration of shade trees, including native fruit and timber species, into coffee production systems can enhance carbon sequestration while improving farmers' livelihoods and strengthening climate resilience (Maulana et al., 2025).

Beyond REDD+, carbon credit markets and corporate offset schemes view agroforestry-generated credits as a potential income source for smallholders while aiding corporate emissions targets, yet operational integration into national climate strategies remains limited. Most tropical countries reference agroforestry in NDCs and REDD+ strategies but rarely quantify it in GHG inventories due to technical, institutional, and financial constraints (Atangana et al., 2013; Awazi, 2025; Sharma et al., 2025). Implementation of smallholder-focused projects also faces major economic and governance barriers, including high transaction costs for enforcement, monitoring, and verification, alongside insecure land and tree tenure, as seen in West African cocoa landscapes and Senegal's REDD+ planning, where unresolved tenure, complex registration, and unclear carbon rights impede adoption, carbon accounting, and incentive mechanisms (Kouakou et al., 2026; Kouassi et al., 2021; Rosenstock et al., 2019; Tranchina et al., 2024).

Nevertheless, growing evidence suggests that agroforestry systems designed around species that combine high carbon sequestration potential with locally valued products and services can deliver substantial climate mitigation benefits while remaining socially and economically relevant to farmers (Reang et al., 2021; Sari et al., 2020; Willmott et al., 2023). This alignment between carbon storage objectives and livelihood benefits highlights the strong potential of agroforestry as a practical and socially inclusive component of CDM, REDD+, and broader nature-based climate mitigation strategies.

Agroforestry remains underrepresented in CDM and REDD+ schemes because both mechanisms demand robust, low-cost measurement, reporting and verification, while the absence of harmonized carbon accounting methods for diverse agroforestry systems makes inclusion technically and institutionally challenging. Additional barriers include insecure land tenure, high transaction costs, and limited, often superficial assessment of livelihood outcomes, which together raise the risk that projects prioritize carbon targets over local development and smallholder interests (Atangana et al., 2013; Green and Unruh, 2010; Sharma et al., 2025). Yet, although farmers typically select trees for provisioning and cultural services such as food, timber, fodder and spiritual values, many preferred species also deliver substantial mitigation and regulatory benefits through high biomass and soil carbon storage (Chavan et al., 2023; Hossain et al., 2025). For example, several widely used timber and multipurpose species have high carbon densities or sequestration rates, while in Ethiopian parklands farmers favor species such as Cordia africana, Mangifera indica, Croton macrostachyus and Faidherbia albida because they combine strong economic value with significant carbon stocks, thereby aligning livelihood and climate objectives (Wolde and Desalegn, 2025). Designing agroforestry systems for CDM/REDD+ compatibility, therefore, implies deliberately combining farmer-preferred multipurpose species with high-carbon, deep-rooted, long-lived trees, and promoting functionally diverse mixtures that enhance soil carbon, microclimate regulation and ecosystem resilience. Such designs improve the permanence of carbon stocks and the integrity of carbon credits, while maintaining or improving local livelihood benefits (Atangana et al., 2013; Rosenstock et al., 2019).

Targets that focus only on the number of trees planted, without accounting for tree species composition, risk undermining restoration goals. Large-scale initiatives that prioritize fast-growing monocultures or a narrow suite of species may reduce soil carbon, biodiversity, and pollination, and can even increase local temperatures in some regions, despite formally meeting tree-count targets. Reorienting restoration targets, finance, nursery systems, and planning tools around species composition and functional diversity is therefore essential if restoration is to deliver its anticipated climate and conservation benefits.

5.5. Study limitations and future perspectives

We acknowledge the risk of a potential counting bias in our analysis of species frequency. Our method, which records a species once per paper, effectively equates species frequency with the number of papers in which it appears. However, this does not account for the 'richness' of individual papers. Consequently, our frequency metric is a measure of research attention (or publication prevalence) rather than an absolute measure of ecological or on-farm abundance. This means that species diversity may be overrepresented in regions or agroforestry systems that are the subject of large-scale inventory papers. We also recognize that, as a scoping review of heterogeneous observational, survey, and review-based literature, the goal is to map patterns rather than formally rate the risk of bias. Also, a limitation of this review is the risk of geographic and taxonomic publication bias. The frequency with which AF tree species are reported in the literature often reflects research intensity and accessibility rather than their true ecological prevalence. Factors such as infrastructure, security, and established research networks tend to concentrate studies in wealthier or more accessible regions. Consequently, substantial areas of the tropics and other remote, biodiversity-rich regions remain undersampled, leading to an incomplete picture of species importance (Cooper et al., 2024; Esquivel et al., 2023; Ortolan et al., 2025). In this regard, more field studies are needed on less-studied native trees and locally important species. Also, studies in under-sampled regions need to be intensified to bridge the uneven representation of AF species. Finally, there is a need to intensify research on agroforestry systems that document common AF tree composition, including both native and exotic species, across different system types, particularly in tropical countries and regions where data are scarce.

Methodological literature notes that many scoping reviews rely on a limited number of databases, raising concerns about missed studies (Winn et al., 2025). However, multiple comparisons show that Google Scholar and a major citation index such as Scopus cover most scholarly literature in many fields, including agriculture. For our scoping review, we sourced data from publications in two major literature databases, Scopus and Google Scholar. Although this is not entirely comprehensive and may have omitted some relevant regional literature, since these two databases are some of the largest available and also allow one to analyze patterns in results, we consider our approach solid enough. Scopus and Google Scholar each bring important strengths, where Scopus offers structured, multidisciplinary coverage and is widely treated as a powerful tool to map country-focused searchers and regional research output and Google Scholar offers unmatched inclusiveness (Bramer et al., 2017; Martín-Martín et al., 2021), indicating that searching two databases markedly improves coverage and recall and reduces the risk of missing eligible studies (Ewald et al., 2022). Several scoping reviews on agroforestry or tropical regions rely solely on Scopus for primary searching, including work on ecosystem services in the Asia-Pacific and a global bibliometric review of agroforestry ecosystem services (Charles et al., 2024; Villanueva-González et al., 2026). Furthermore, a significant number of broader or regional reviews employ Scopus, in conjunction with other databases (frequently Web of Science and/or Google Scholar), for agroforestry and food security, climate change impacts, and the integration of local species (Salleh et al., 2023; Shin et al., 2020). It is recommended that future research directions involve a scoping review of multiple databases. The review based on multiple databases should, among other things, investigate whether the loss of certain references results in changes to the conclusion of the current review study.

There is also a high need for research into whether widespread generalist trees can partially substitute the ecosystem functions of shifting natives under future climates without undermining biodiversity. This paper urges both quantitative and qualitative studies to investigate the impact of various fruit–nitrogen-fixing tree combinations on yields, soil health and livelihoods in shaded areas. Further research should also examine the social and ecological suitability of tropical AF tree species across different agroecological zones to better inform landscape restoration policies, research, and practice. Such work can help identify tree options that not just deliver ecological benefits and reliable economic returns while supporting farmers' livelihoods, but also optimize short-, medium-, and long-term outcomes.

6. Conclusion

In this review, the highest reported diversity of AF tree species occurs in tropical regions of the Americas and Asia, while fewer species are reported from Africa, particularly East Africa, noting that these patterns may partly reflect uneven research effort and accessibility rather than true underlying diversity. The most commonly reported uses of AF trees are similar across regions, with the main uses being food (mainly fruit trees) and fuel. This aligns with the expectation that food and fuel occupy an important position in systems geared toward subsistence agriculture. Consequently, fruit grown in home gardens in human-dominated landscapes improves the dietary quality of poor rural communities that rely on a less diverse staple diet, particularly during lean seasons. Fuel derived from AF trees could be useful for rural smallholder farmers who cannot afford alternative sources of fuel and do not have enough land for woodlots. This is the case in western Rwanda, for example, where the average farm size is <0.5 hectares.

We also find that native shade tree species, including N-fixing species, are important for both home gardens and cash crops. Globally, there is a documented prevalence of exotic species in non-shade AF systems in tropical regions. Our results suggest that promoting more sustainable mixtures of diverse species, including native species, in degraded agricultural areas beyond home gardens and cash crops may be beneficial. Additionally, expanding the area allocated to cash crops, where feasible, could provide further opportunities to integrate native tree species.

Finally, we find that the highest AF tree diversity is found in tropical regions that are close to relatively larger natural forests than to regions where the diversity is relatively lower, consistent with evidence that proximity to forests and permeability of the surrounding matrix support the persistence and recruitment of native tree species in agroforestry systems. These results suggest that establishing tree nurseries and enhancing AF in agricultural landscapes near natural forests may ensure the conservation of the germplasm of native species and facilitate their dissemination into other neighboring landscapes, particularly given limited access to forest resources by rural communities from resource-scarce human-dominated landscapes.

CRediT authorship contribution statement

Apollinaire William: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Katharina Löhr:** Methodology, Resources, Writing – review & editing. **Stefan Sieber:** Methodology, Resources. **Vicky M. Temperton:** Methodology, Resources, Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

The authors gratefully acknowledge the financial support provided by the German Research Foundation (DFG) as part of the research project "FOR 5501: A social-ecological systems approach to inform ecosystem restoration in rural Africa" (Project number 496337053). Open Access funding enabled and organized by Projekt DEAL.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2026.101394.

Data availability

Data will be made available on request.

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