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Agroforestry for biodiversity and ecosystem services

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Agroforestry for biodiversity and ecosystem services

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Editorial: Agroforestry for biodiversity and ecosystem services

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Editorial on the Research Topic
Agroforestry for biodiversity and ecosystem services

Introduction

The 21st century presents humanity with a converging triad of crises: unprecedented biodiversity collapse, escalating climate disruptions, and deepening food insecurity, with over 800 million people enduring chronic hunger (IPBES, 2023; IPCC, 2023; FAO et al., 2024). These challenges are exacerbated by widespread soil degradation, affecting 33% of the Earth's land surface, threatening agricultural systems worldwide (FAO et al., 2018). While agroforestry—the intentional integration of trees with crops and/or livestock—offers a promising, nature-based solution to harmonize ecological resilience with human prosperity, its potential remains significantly underutilized (Roy et al., 2025; Mlambo and Mufandaedza, 2025).

Despite its ancient roots and evolution into a cornerstone of nature-based solutions, agroforestry faces persistent barriers to widespread adoption (Tranchina et al., 2024). Policy fragmentation, including conflicting land-use regulations, weak financial incentives for long-term investments, and gaps in locally adapted knowledge, continues to hinder its implementation (Venn et al.). Addressing these barriers is essential to unlock agroforestry's dual promise: safeguarding planetary health while advancing equitable development.

This Research Topic directly addresses this critical need by exploring agroforestry's role in harmonizing biodiversity conservation, ecosystem services, and sustainable development across diverse landscapes — from semi-arid tropics to temperate woodlands. The nine articles in this Research Topic address three interconnected dimensions: policy frameworks, ecological impacts, and socio-economic dynamics. Through policy analyses, geospatial modeling, and on-the-ground case studies, they provide actionable insights for scaling agroforestry effectively.

This editorial synthesizes key findings, underscoring agroforestry's dual capacity to strengthen agricultural productivity and ecological resilience. By integrating native trees with food crops, these systems mitigate habitat fragmentation, sequester carbon, and sustain livelihoods—a critical balance in regions facing land-use conflicts. Collectively, these studies equip farmers, policymakers, and conservationists with evidence-based strategies to mainstream agroforestry. Their methodologies offer replicable pathways to align food security with planetary health, ensuring agroforestry transitions from a niche practice to a cornerstone of sustainable land-use policy.

Policy and governance: bridging gaps for scalable solutions

Agroforestry's potential to reconcile biodiversity conservation, climate resilience, and rural livelihoods is well-documented (Mlambo et al., 2024; Yashmita-Ulman and Singh, 2024). However, systemic policy and governance challenges continue to hinder its widespread adoption. A cross-continental narrative review by Venn et al. dissects agroforestry policies in the EU, India, Brazil, and the U.S., revealing stark contrasts in governance frameworks. While Brazil leads in jurisdictional integration—notably through its ABC+ Plan aligning agroforestry with low-carbon agriculture—the EU and U.S. lag due to misaligned financial incentives (Venn et al.). For instance, the EU's Common Agricultural Policy prioritizes monoculture subsidies, inadvertently disincentivizing tree-crop integration. In India, agroforestry relies on *ad hoc* initiatives like the Sub-Mission on Agroforestry, which struggles to harmonize with state-level forest laws, and in Brazil, despite progress, dedicated legislation remains absent. These fragmented approaches often relegate agroforestry to jurisdictional gaps between disconnected agricultural, forestry, and environmental policies, stifling its capacity to enhance carbon sequestration, soil health, and biodiversity at scale.

Complementing this analysis, Singhal et al. underscore agroforestry's dual role as both an ecological safeguard and an economic lifeline in times of crisis. Their research demonstrates that agroforestry aligns with green economy principles by generating diversified income streams (e.g., timber, fruits, non-timber forest products) while mitigating risks during global shocks, such as pandemics or climate extremes. By addressing deforestation drivers, supporting green recovery, and reducing zoonotic spillover risks through habitat restoration, their work provides a compelling case for policymakers to prioritize agroforestry. Integrating their recommendations—financial incentives, policy coherence, and community empowerment—could accelerate the transition to resilient, multifunctional landscapes that benefit both people and the planet. Together, these studies highlight the urgency of context-specific frameworks to align agroforestry with global climate and biodiversity agendas, bridging the gap between its proven potential and fragmented implementation.

Sustainable management and ecosystem services

Small forest patches embedded in agricultural landscapes serve as vital biodiversity refugia, sustaining ecological networks within human-dominated environments (Decocq et al., 2016). A study by Karamdoost Marian et al. in Iran's mixed temperate broadleaf forests demonstrates how sustainable management practices can amplify these benefits. Their research found that the single-tree selective harvesting method—targeted removal of individual trees rather than clear-cutting—led to an increase in tree species richness and diversity in managed than unmanaged patches. Crucially, this approach maintained critical ecosystem services such as carbon sequestration, with harvested patches retaining most of their baseline carbon storage capacity. These findings challenge the assumption that minimal intervention is always optimal for biodiversity, revealing that carefully designed harvesting can enhance ecological resilience without compromising agricultural productivity. By balancing human needs with conservation goals, the study underscores the potential of adaptive management to transform small forest patches into multifunctional assets within working landscapes.

Kebebew and Ozanne's study in southwest Ethiopia examines the conservation potential of coffee agroforestry systems, emphasizing their role in preserving woody plant diversity. Their research demonstrates that these systems not only sustain higher native tree species richness compared to monoculture coffee farms but also act as refuges for endangered plant species. By mapping ecological corridors and prioritizing keystone species, their findings provide actionable strategies to align agricultural productivity with biodiversity conservation in human-modified landscapes.

In contrast, Comolli et al. shift the focus to economic scalability, analyzing integrated agroforestry systems for cultivating *Ilex paraguariensis* (yerba mate) in Argentina. Their model combines this high-value crop with native timber trees and forage plants, enhancing carbon sequestration and soil organic matter, while diversifying farmer income streams. By addressing challenges like shade tolerance and market access, the study offers a replicable blueprint for balancing ecological resilience (e.g., reduced pesticide use) with profitability—proving that biodiverse agroforestry systems can outperform conventional monocultures in both environmental and economic outcomes. Together, these studies underscore agroforestry's dual capacity to safeguard biodiversity and drive sustainable development. Kebebew and Ozanne highlight its conservation value in ecologically sensitive regions, while Comolli et al. demonstrate its viability as a scalable, income-generating alternative to extractive land use. Their combined insights reinforce the need for context-specific frameworks that harmonize species preservation, climate goals, and rural livelihoods.

Climate resilience: mitigating risks and enhancing stability

In the face of increasingly volatile climate conditions, Dobhal et al. provide a compelling synthesis of global data, reaffirming agroforestry's dual role in safeguarding agricultural productivity while enhancing ecosystem resilience against extreme weather events. Their meta-analysis underscores four critical findings that position agroforestry as a cornerstone of climate adaptation strategies. First, agroforestry systems significantly mitigate vulnerability to droughts, floods, and heatwaves, offering stability in regions disrupted by climate-induced pressures. Second, during heavy rainfall, agroforestry landscapes reduce surface runoff by 20–50% and enhance soil water infiltration, bolstering flood resilience and improving long-term soil health. Third, agroforestry moderates microclimates by enhancing soil moisture retention, providing shade, and reducing wind exposure—key factors in sustaining crop yields under climatic stress. Finally, tree shelterbelts function as natural bio-shields, protecting coastal regions from high wind speeds and storm surges while reducing landscape degradation and infrastructure damage. These insights reinforce agroforestry's pivotal role in climate adaptation, demonstrating how nature-based solutions can foster resilient agricultural systems. Dobhal et al.'s findings offer actionable insights for policymakers, conservationists, and practitioners seeking to integrate agroforestry into sustainable land-use strategies, paving the way for a climate-resilient future

Ghanbari et al. assessed the impact of climate change on agroforestry practices in Iran, examining semi-arid, semi-humid, and humid climates. Their study found that farmers in semi-arid regions relied more heavily on climate-resilient species compared to those in humid environments, highlighting the urgent need for adaptation in response to the climate crisis.

Soil health: the foundation of sustainable systems

Studies by Rathore et al. and Uthappa et al. provide critical insights into the synergistic effects of agroforestry and conservation practices in enhancing soil quality and ecosystem resilience in India's semi-arid regions. Together, their research underscores the transformative potential of integrating ecological stewardship into sustainable land management. Rathore et al. demonstrate that conservation-focused agroforestry systems outperform conventional non-conservation approaches in improving soil quality. Key interventions include microsite improvements (e.g., removing boulders to optimize planting pits), integrated nutrient management that combines organic and inorganic fertilizers, mulching with crop residues and tree leaf litter to retain moisture and suppress weeds, and incorporating deep-rooted nitrogen-fixing species to enhance soil stability and nutrient cycling.

Building on this framework, Uthappa et al. analyze soil quality indices across diverse tree-based land-use systems. Their findings reveal that agroforestry significantly enhances key soil health parameters, including soil organic carbon (critical for fertility in arid regions), nutrient retention (particularly nitrogen and phosphorus), and microbial biomass, which drives nutrient mineralization and overall soil health. This work highlights agroforestry's role in mitigating the harsh conditions of semi-arid climates, where soil degradation poses a significant threat to food security. Together, these studies reinforce agroforestry's dual capacity to restore degraded landscapes and sustain agricultural livelihoods. Their complementary findings advocate for policy frameworks that incentivize conservation agroforestry, particularly in regions vulnerable to climate-induced desertification.

Conclusion

Collectively, the nine articles in this Research Topic highlight the multi-functionality of agroforestry—not merely as a farming practice but as a holistic strategy for ecological and socioeconomic resilience. These studies underscore its fundamental role in fostering biodiversity, enhancing ecosystem services, and strengthening agricultural landscapes in the face of environmental challenges. Moving forward, embracing agroforestry offers a tangible pathway to a more sustainable future—one that integrates agricultural productivity with ecological integrity. The evidence presented in this Research Topic demonstrates that through proactive policy-making, community engagement, and innovative research, agroforestry can significantly contribute to biodiversity conservation and the provisioning of critical ecosystem services.

We hope this Research Topic inspires further inquiry and collaboration in agroforestry, driving the development of scalable, effective solutions that support both food security and environmental sustainability. By bridging science, governance, and practice, agroforestry can evolve from a promising concept into a cornerstone of sustainable land-use strategies worldwide. As editors, we urge policymakers, farmers, and researchers to recognize agroforestry as a vital nexus between conservation and productivity. Beyond policy and economic factors, agroforestry adoption is significantly influenced by socio-cultural contexts. Integrating gender-sensitive approaches, addressing resistance to change, improving training, and incorporating indigenous knowledge are essential for its sustainable success, supported by quantitative assessments.

Author contributions

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact of conservation practices on soil quality and ecosystem services under diverse horticulture land use system

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The 20-year study investigated the effects of conservation practices (CPs) and farmers' practices (FPs) on various soil quality parameters, yield, and economics of horticultural land use systems. CPs demonstrated significant improvements in soil organic carbon (SOC), available nitrogen (N), phosphorus (P), and potassium (K), compared to FPs. Horticultural systems exhibited higher SOC and available N and P contents than FPs, with substantial variations among different fruit species. CPs also enhanced soil quality index, functional diversity, culturable microbial populations, enzyme activity, and soil microbial biomass carbon (SMBC) compared to FPs. It was observed that the SMBC values were 25.0–36.6% and 4.12–25.7% higher in 0–15 cm and 15–30 cm, respectively, under CPs compared to FPs for all the land use systems. In CPs, dehydrogenase activities (DHAs) in surface soils were 9.30 and 7.50 times higher under mango- and citrus-based horticultural systems compared to FPs. The CPs adopted in aonla, guava, mango, litchi, and citrus-based horticultural systems increased SOC by ~27.6, 32.6, 24.4, 26.8, and 22.0%, respectively, over FPs. Canopy spread, fruit yield, litter yield, and soil moisture were significantly higher in fruit-based horticultural systems under CPs. Economic viability analysis indicated higher net present values (NPVs), benefit-cost ratio (BCR), and shorter payback periods (PBPs) for horticultural land use systems under CPs. Principal component analysis (PCA) revealed that CPs had a more positive influence on soil parameters, particularly DHA, acid and alkali phosphatase activity, available N, P, and K contents, soil microbial load, and organic carbon. The maximum ecosystem services were contributed through mango-based land uses among all land uses. Mango-based horticultural systems exhibited the least impact from both CPs and FPs, while peach-based systems were most affected by CPs. Overall, the findings highlight the benefits of conservation practices in improving soil quality, microbial populations, enzyme activity, and crop productivity in horticultural systems.

KEYWORDS

fruit yield, land degradation, rehabilitation, soil organic carbon, soil quality index

Introduction

The land is a vital and non-renewable natural resource of Mother Earth that provides essential resources such as food, shelter, and fiber. Land degradation is an emerging global issue that is caused by both anthropogenic and climatic factors (Singh et al., 2023). This phenomenon is negatively impacting agricultural productivity, with approximately 20% of agricultural land, 30% of forests, and 10% of savannas worldwide (Zhang et al., 2019). Moreover, it is projected that the percentage of degraded land will increase in future, particularly in low- and middle-income nations of tropical and subtropical regions (Chen et al., 2019). The loss of productive capacity due to natural processes or human activities is causing a decline in on-site and off-site native environmental services, which has long-term effects. Land degradation is a significant driver of food insecurity and climate change, resulting in a yearly loss of 6.0 million hectares (M ha) of productive land globally (Lal, 2015). Additionally, soil degradation is accelerating, causing a decline in SOC and fertility, which is promoting soil erosion problems, resulting in the loss of nutrients and SOC within the root zone, and reducing crop productivity (Singh et al., 2022; Jinger et al., 2023). Land degradation is affecting the lives of nearly 1.5 billion people, with approximately 15 BT of soil lost each year due to desertification and drought. Moreover, approximately 12 M ha area is lost annually owing to these phenomena. The biodiversity loss caused by land degradation amounts to approximately 27,000 species each year, with around 110 countries being under potential risk, affecting the lives of 250 million people and putting 1 billion individuals at risk. The global cost of desertification is estimated at USD 42 million (Hamdy and Aly, 2014). El-Swaify and Dangler (1982) noticed that the degradation of land reduces the availability of plant nutrients present in the soil along with the reduction in SOC, which is the cause of lowering crop productivity. Moreover, the reduction in crop productivity is due to the initiation of land degradation in the rooting zone of crops (El-Swaify and Cooley, 1981).

The United Nations Convention to Combat Desertification (UNCCD) at COP 14 in 2019 aimed to bring 350 M ha of degraded land worldwide into cultivation by 2030. India has approximately 120.7 M ha of degraded land, with a significant portion of it being physically degraded due to water erosion, characterized by poor soil physico-chemical properties that make it unsuitable for field crops (Gupta et al., 2021a,b; Jinger et al., 2022). Recently, India committed to the restoration of 26 M ha of degraded land in the country to achieve land degradation neutrality through prevention, mitigation, and rehabilitation techniques (Dhyani et al., 2023). The degraded lands in India can be restored through the application of various techniques, such as micro-site improvements, the addition of organic manures, forest litter, crop residues, and perennial deep-rooted fruit tree species (Rathore et al., 2014). Rainfed agriculture, which makes up approximately 80% of the world's produce and over 60% of the world's food, is particularly important for developing countries, as it is the backbone of marginal or subsistence farming (Singh et al., 2021). However, poor yields and high water losses are major issues in rainfed agriculture, exacerbated by climate change and monsoon variability. To improve productivity, *in-situ* moisture conservation strategies should be given more attention. Additionally, innovative interventions are needed to restore degraded or wastelands and enable them remunerative, ecologically benign for sustainable agriculture production systems, particularly in India, which supports a large proportion of the world's human and livestock populations on limited land area.

In India's Nationally Determined Contribution to the Paris COP 21 agreement in 2015, India committed to sequester an additional 2.5 to 3 billion tons of CO2eq through additional planting of trees or fruit trees by 2030 (MOEFCC, 2015). Therefore, growing fruit crops on degraded lands is a natural way to enhance soil fertility and promote biological activities by adding organic matter such as litterfall and root decay to the soil, leading to an increase in soil organic carbon, soil fertility, nutrient recycling, and biological transformations in the rhizosphere (Rathore et al., 2014). Commercial fruit species, such as mango, guava, aonla, bael, litchi, lemon, kagzi lime, pumelo, and grapefruit, are commonly cultivated, but there is limited information on utilizing degraded lands under rainfed conditions (Rathore et al., 2021). Thus, it is important to cultivate fruit crops with deep roots and low water requirements on degraded lands. Mango (*Mangifera indica* L., Anacardiaceae), litchi (*Litchi chinensis* Som.; Sapindaceae), peach (*Prunus persica* L.; Rosaceae), aonla (*Emblica officinalis*; Phyllanthaceae), and mandarin (*Citrus reticulata* L; Rutaceae) are commercially significant subtropical fruit crops that provide a good source of vitamins, minerals, and antioxidants. These crops cover an area of 3.6 M ha, accounting for 53.5% of the total area under fruits in India and producing approximately 36.7 MT of fruits, which is 37.0% of India's total fruit production. Their average productivity ranges from 7.60 to 15.0 t ha^{-1} (NHB, 2021). Fruit-based land use systems are economically viable for class V and VI soil types as they use various resources judiciously and cater to multiple needs simultaneously. These systems are most suitable for areas that require soil moisture conservation, soil erosion reduction, and sustainable production and income (Rathore et al., 2018). They provide a self-sustainable system where solar energy is harvested at different heights, resulting in higher economic returns even under stressed growing conditions than annual crops (Saroj et al., 2000). Furthermore, they offer opportunities for ancillary industries such as fruit processing (preserves, jam, jelly, etc.), essential oil extraction, employment generation, improved soil organic carbon, and enhanced biological activity for rhizospheric environment stability (Rathore et al., 2014). Cultivation of these fruit crops under conservation practices imparts good quality production of fruits and crops with higher productivity, ultimately leading to achieving the SDG of zero hunger (SDG no. 2) and no poverty (SDG no. 1). Moreover, employment generation through digging pits for planting of saplings, pruning, harvesting of fruits and crops, sustainable production of the fruit production system, and mitigation of GHGs would achieve SDG of decent work and economic growth (SDG no. 8), responsible consumption and production (SDG no. 12), and climate action (SDG no. 13), respectively.

Furthermore, the valuation of ecosystem services in different horticultural land use systems is important because it provides a quantifiable measure of the benefits to the farmers and human wellbeing. Ecosystem services include services such as water purification, climate regulation, and nutrient cycling, which are crucial for sustaining agricultural productivity and maintaining ecological balance (Orlandi et al., 2023). By assigning economic values to these services, policymakers, land managers, and stakeholders can make informed decisions regarding land management, conservation efforts, and resource allocation. Valuation helps in recognizing the contributions of ecosystems, guiding sustainable practices, and promoting the conservation and restoration of horticultural systems for long-term environmental and socio-economic benefits. After considering these things, the monetary value of regulating (carbon sequestration) and supporting ecosystem service (nutrient augmentation) of different horticultural land use systems has been estimated in this study (Pandey et al., 2021).

We put forth a hypothesis that by restoring degraded land and implementing an ecological approach that integrates deep-rooted fruit-based land uses, with or without intercropping, and applying crop residues for *in-situ* moisture retention, integrated nutrient management, we can substantially enhance fruit yields, soil fertility (including SOC and available N, P, and K contents), microbial populations, and enzyme activity, thereby improving nutrient recycling and valuation of ecosystem service. There is still a lack of comprehensive information on soil enzymatic activities, microbial biodiversity, and available nutrients in degraded lands restored through horticulture land use systems. To validate the above hypothesis, our objectives were to (a) assess the effect of CPs and farmers' practices (FPs) on long-term fruit productivity, (b) evaluate the changes in soil fertility parameters, including SOC and nutrient availability, (c) ascertain the soil microbial populations and soil enzyme activities, and (d) valuate ecosystem services under horticultural systems.

Materials and methods

Experimental site

The study was conducted at the research farm of the ICAR-Indian Institute of Soil and Water Conservation in Selakui, Dehradun, Uttarakhand, India from 1995 to 2015 under the subtropical climate of the Indian Himalayas. The site is located at 30° 21′ N latitude, 77° 52′ E longitude, and 517 m above mean sea level with an annual rainfall of 1,600 mm. The mean maximum and minimum temperatures ranged between 19.0 and 37.6°C and between 3.6 and 24.0°C in summer and winter, respectively. In general, May–June were the hottest (45°C), while December–January were the coldest (2°C). The experimental site was a bouldery riverbed situated at Asan River, a tributary of River Yamuna. Sieve analysis of 1 m^3 soil profile conducted at soil working time indicated that 1.27% to 79.46% of the material was found to be <2 mm, and the remaining were gravels and boulders (weight basis). The soil gravel ratio observed in the 1 m^3 pit is mentioned in Table 1. The soil was neutral in reaction (pH 6.5–7.0) with low organic carbon (0.5–0.6%), total N (0.06–0.065%), available P (24.49–25.00 kg ha^{-1}), available K (116.42–117.56 kg ha^{-1}), high Ca (0.195–0.197%), and Mg (0.14–0.15%).

Treatment details

Five horticulture species were used, *viz.* mango, litchi, peach, aonla, and mandarin, along with farmers' practices (control) for study. Two practices were selected for the study, *viz.* (1) conservation practices (CPs) which include microsite improvement (removal of boulders from the pit), integrated nutrient management (farm yard manure + inorganic fertilizers + NPK-consortia of biofertilizer), and mulching (crop residue and leaf litter of trees); and (2) farmers' practices (FPs) includes normal planting with fertilizers without mulching. The varieties of different fruit species and planting geometry are mentioned in Table 1. The methodology of how conservation practices in different horticulture land use improve the ecosystem services has been mentioned in a graphical format in Figure 1.

Soil sampling and analysis

Soil samples were collected using a randomized quadrat sampling experimental design from different land use types. Three quadrats, each of 10 × 10 m for CPs and FPs land use types, were taken as samples with two different soil depths (0–15 and 15–30 cm) in three replications from each quadrat. Pooling of samples was done, and a composite sample was created with a total of 12 samples. The samples were sieved with a 2-mm sieve and stored at ambient temperature for further analysis. SOC was determined using the $K_2Cr_2O_7$-H_2SO_4 wet oxidation method (Walkley and Black, 1934). The soil moisture was determined using the gravimetric method (Reynolds, 1970). Soil mineral N and available P and K contents were measured using standard procedures of Hanway and Heidel (1952), Olsen et al. (1954), and Bremner and Keeney (1965), respectively.

Enzyme activity-based index calculation

Soil quality index

The geometric mean (GMea) of the assayed enzymes was calculated for each sample as:

$$\text{GMea} = \frac{(\text{DHA} \times \text{AP} \times \text{ACP} \times \text{BOD} \times \text{URE})}{5} \quad (1)$$

where DHA, AP, ACP, BGD, and URE stand for dehydrogenase, alkali phosphatase, acid phosphatase, β-D-glucosidase, and urease, respectively. GMea is an integrative approach for combining a large number of enzyme activities related to different soil functions and nutrients. Hence, it can imitate soil quality index (Paz-Ferreiro et al., 2011). In addition, its sensitivity to soil management (García-Ruiz et al., 2008; Paz-Ferreiro et al., 2012) makes it an eligible early indicator of soil quality changes.

Soil functional diversity

It was determined using the

TABLE 1 Description of subtropical fruit species, intercrops, and site characteristics.

Land uses	Fruit species			Intercrops		Soil	
	Scientific names	Cultivars	Planting geometry (m)	Intercropping of different crops/grasses		Soil (%)	Gravel (%)
				1995–2010	2011–2015		
Aonla	*Emblica officinalis L.*	NA7	7 × 7	Blackgram-Toria	Natural grasses	52.7	47.3
Peach	*Prunus persica L.*	Pratap	7 ×7	Blackgram-Toria	Natural grasses	45.8	54.2
Mango	*Mangifera indica L.*	Mallika	8 × 8	Cowpea—Toria	Natural grasses	56.8	43.2
Litchi	*Litchi chinensis Sonn.*	Rose Scented	8 × 8	Cowpea—Toria	Natural grasses	54.3	45.7
Citrus	*Citrus reticulata*	Kinnow	5 ×5	Sunhemp-Toria	Natural grasses	59.2	40.8

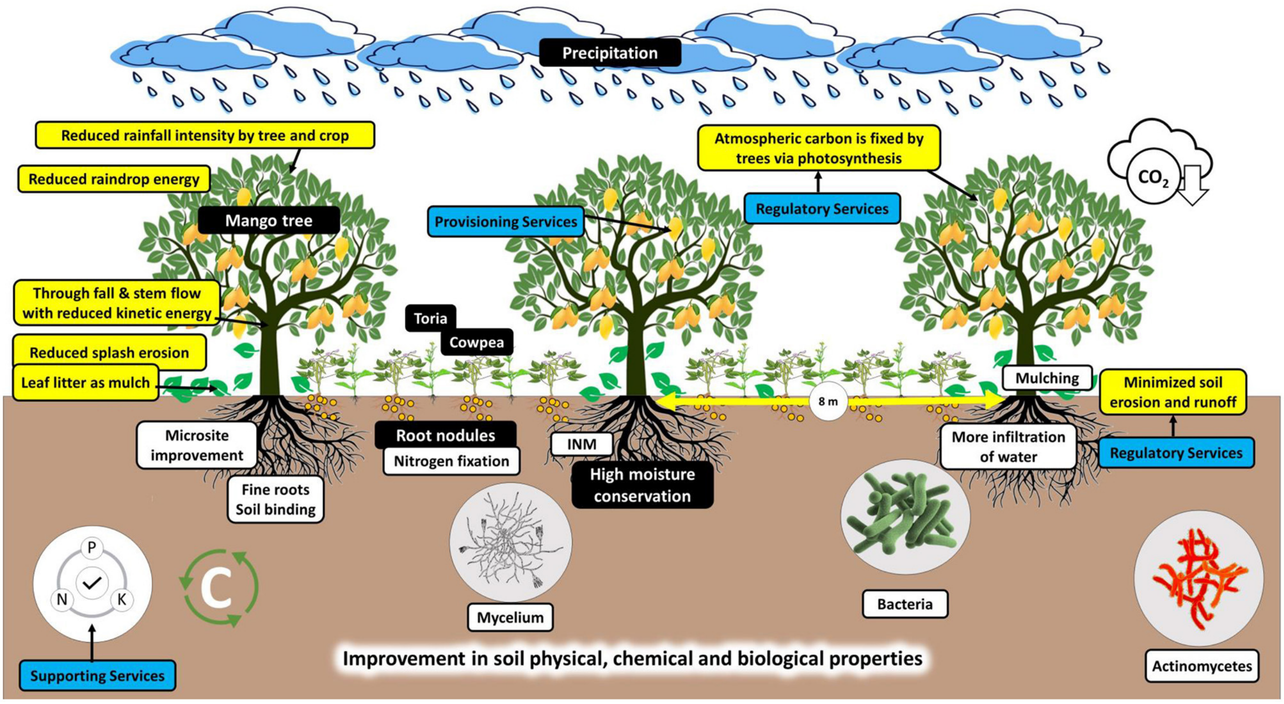

FIGURE 1
Methodology or conservation practices in mango-based land use improve the ecosystem services (This model is similar to other fruit crops of this experiment).

(i) Shannon's diversity index (H)

$$H = -\sum_{i=1}^{5} Pi \times \ln (Pj) \quad (2)$$

(ii) Simpson–Yule index (SYI)

$$SYI = \frac{1}{\sum_{i=1}^{5} P_i^2} \quad (3)$$

where Pi is the ratio of each enzyme activity to the sum of all enzyme activities for a particular sample. In all cases, enzyme activities were expressed as microgram products formed per gram of soil per hour.

Microbial population count

The stored soil samples at 4°C were used for the analysis of microbial count, *viz.* bacteria, fungi, and actinomycetes population in the respective treatments along with control in three replications. The autoclaved readymade potato dextrose agar media (38 g l^{-1}) with pH 7 was used for bacterial and fungal population count using the serial dilution method. The suspension of serially diluted samples from each treatment was spread in plates using a spreader and incubated at 25 ± 2°C and 32 ± 2°C for fungus and bacteria, respectively. The bacterial and fungal populations were recorded in 48 h and 72 h, respectively, after incubation. For actinomycetes, autoclaved actinomycetes isolation agar media with pH 7 was used to ascertain the actinomycetes population in treatments. The

TABLE 2 Data requirement and valuation methodologies for ecosystem services.

Ecosystem service	Data	Valuation method
Carbon sequestration (t/ha)	Carbon stock in tree, increase in soil organic carbon, carbon price, exchange rate of INR	Avoided cost method (Gulati and Rai, 2014)
Nutrient augmentation in soil (kg/ha)	Increase in the soil nutrient availability, fertilizer price	Market price method (Wilson and Carpenter, 1999)

serially diluted samples were inoculated in plates, and reading was taken after 3 days of incubation (25 ± 2°C) (Vance et al., 1987). The population of fungi and bacteria was calculated in terms of colony forming units (CFU) per gram oven dry weight basis (Rolf and Bakken, 1987; Sepehri and Sarrafzadeh, 2018).

Soil enzyme activities

Five soil enzymes were estimated, which include β-glucosidase activity (BGD), urease activity, alkaline phosphatase (AP), acid phosphatase activity (ACP), and DHA. β-glucosidase activity was determined using a procedure adopted by Eivazi and Tabatabai (1977, 1988). In β-glucosidase activity, p-nitrophenyl-β-D-glucoside was used as the substrate. The activity was expressed as µg PNG g^{-1} dwt h^{-1} at 37°C. Similarly, urease activity and acid phosphatase activities were determined using the protocol described by Tabatabai and Bremner (1969). Urease activity was expressed as NH_3-N g^{-1} h^{-1} at 37°C and AP was expressed as µg p-NPP g^{-1} h^{-1} at 30°C (Tabatabai and Bremner, 1969). DHA was determined using a spectrophotometer and expressed as µg TTC g^{-1} h^{-1}.

Soil microbial biomass carbon

Soil microbial biomass carbon (SBMC) was calculated by fumigating fresh soil of known mass (35 g) with 2 mL of ethanol-free $CHCl_3$, and the extract was taken with 140 ml of 0.5 M K_2SO_4 after 1-day ambient temperature incubation. However, unfumigated soil extract was taken directly. SBMC was calculated from the difference in the carbon of fumigated and unfumigated soil using a conversion factor (0.38) described by Vance et al. (1987).

Growth, yield, and litter production estimation

The canopy spread of all the fruit species was measured with the help of a measuring tape in north–south and east–west directions during the first year and final year. The values of canopy spread in both directions were averaged and expressed in meters (m). The four trees of all treatments were marked for recording data on fruit yield. The fruits of all five fruit species were harvested at maturity stages, weighed with the help of electronic balance every year after the initial fruit-bearing year, and expressed in t ha^{-1}. Litterfall of all fruit species was collected annually with the help of litter traps of 1 × 1 m size placed in four directions under the tree during a litterfall period of 12 months each year (January–December) and weighed by electronic balance after drying in oven and expressed in t ha^{-1}.

Economic analysis

The agriculture inputs such as fertilizers and manures, seeds, intercultural operations, etc., and fruit yields were recorded annually. The monetary values of these inputs and outputs were calculated based on current economic values. During the study, the average price of inputs and outputs was worked on based on yearly price fluctuations. Minimum support prices of fruits and intercrops for every year were taken into account for calculating the economy (DFPD, 2015; NHB, 2015). Total returns were calculated annually, and the benefit:cost ratio was inferred. Based on the economic life of 20 years for five fruit species utilized for estimating the benefit:cost ratio (BCR), net present value (NPV), and payback period (PBP) were calculated at a discounted rate of 8%.

The equivalent yield of crop X [t ha^{-1}] =

$$\left[\frac{\text{Yield of crop Y(t ha}^{-1}) \times \text{Selling price of crop Y(Rs t}^{-1})}{\text{Selling price of crop X (Rs t}^{-1})}\right] \quad (4)$$

Tree and soil carbon sequestration

The calculated tree biomass was multiplied with the constant factor of 0.50 for the computation of carbon stock (IPCC, 2003). The calculated carbon stock was used for calculating CO_2 sequestration by multiplying the carbon stock with a constant factor of 3.67 (IPCC, 2003). Based on SOC and bulk density, the soil carbon sequestration was calculated (Lenka et al., 2013; Paul et al., 2016; Yadav et al., 2018). Equation 5 has been used for calculating soil carbon sequestration:

$$\text{Soil carbon sequestration } \left(\text{t}-^{1}\right) = \frac{\text{SOC} \times \text{BD } \left(\text{Mg m}-^{3}\right) \times \text{soil depth } (\text{m}) \times 10000}{100} \quad (5)$$

Ecosystem services valuation

The unit coefficients of these ecosystem services (carbon sequestration and nutrient augmentation) were calculated. After that, the avoided cost principle or the market price method was used to compute monetary values associated with these ecosystem services. The data requirements and valuation methodologies used for these services are summarized in Table 2. The per hectare quantity of nutrients augmented by the different land use was multiplied by the economical price (market price and subsidies) of chemical fertilizers, as shown in Equation 6. The data on prices of fertilizers in terms of nutrients were taken from the Department of Fertilizers, Ministry of Chemicals and Fertilizers, Government of India (GoI).

$$MV_{NS} = Q_N P_N + Q_P P_P + Q_K P_K \quad (6)$$

where MVNS is the monetary value (Rs ha^{-1}) of nutrients saved due to retained soil that otherwise would have been lost; Q_N, Q_P, and Q_K are unit coefficients of saved N, P, and K, respectively, and P_N, P_P, and P_K are the economical prices for N, P, and K, respectively. Similar to the nutrient augmentation service, the monetary value of the carbon sequestration was estimated by multiplying the avoided cost per ton of CO_2 by the per hectare carbon sequestration potential of fruit trees and soil. The damage avoided cost of CO_2 was taken from the published literature (Ricke et al., 2018; GOI, 2021). In most of the studies, carbon sequestration has been reported in the form of SOC; hence, it was converted into CO_2 equivalent using the conversion coefficient of the Intergovernmental Panel on Climate Change (Mekuria et al., 2011).

Statistical analysis

To assess the impact of land use on various parameters, including soil moisture, soil N, P, K, SOC, organic carbon of bacteria, organic carbon of fungi, organic carbon of actinomycetes, β-glucosidases, ureases, acid phosphatase, and DHA, factorial (ANOVA) was carried out. Three factorial designs were used for conducting the experiment (tree × conservation practices × depth of soil). The statistical significance was determined and compared using Duncan's multiple range test (DMRT) at a significance level of $P < 0.05$. The statistical analysis was performed using OPSTAT (Sheoran et al., 1989). Principal component analysis (PCA) was used to assess the relationship between multivariate data using R Studio (version 3.5.1).

Results

Soil organic carbon, total N, and P

The analysis of variance showed that most of the characters taken in the study showed significance. However, organic carbon of fungi (OCF), organic carbon of actinomycetes (OCA), SMBC, organic carbon, P content, N content, and dehydrogenase enzyme activity (DHA) showed non-significant effect of interactions (tree × conservation practices × depth of soil). However, other parameters showed no significant interaction. With respect to AP, CP has a non-significant effect, although tree species, soil depth, and interactions do have significant effects. In relation to DHA, the interaction between tree species and soil depth was non-significant. The total P content showed a non-significant interaction between tree species and CP. The SOC, available N, P, and K were significantly improved in CP among horticultural land use systems (Table 3). Significant improvements in the chemical composition of soil (0–15 and 15–30 cm) were observed after 20 years of

TABLE 3 Fertility status under different horticultural land uses.

Land uses	Gravel (%)	SOC (%)				Available N (kg ha^{-1})				Available P (ppm)				Available K (ppm)			
		CP	CP	FP	FP	CP	CP	FP	FP	CP	CP	FP	FP	CP	CP	FP	FP
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Aonla	47.3	0.62	0.50	0.48	0.40	150.00	97.50	115.50	78.98	5.80	6.41	4.47	5.19	53.73	31.53	41.37	25.54
Peach	54.2	0.84	0.48	0.61	0.38	127.50	120.00	98.18	104.40	8.09	5.75	6.23	5.00	59.47	41.07	45.79	35.73
Mango	43.2	0.86	0.60	0.67	0.50	187.50	157.50	144.38	137.03	26.65	19.75	20.52	17.19	139.03	98.70	107.06	85.87
Litchi	45.7	0.83	0.54	0.63	0.45	195.00	195.00	161.85	175.50	16.79	15.88	13.94	14.29	85.30	79.87	70.80	71.88
Citrus	40.8	0.90	0.54	0.73	0.45	191.25	202.50	151.09	174.15	15.77	7.66	12.46	6.59	131.30	117.15	103.73	100.75
Fallow	66.2	0.61	0.44	0.49	0.37	123.75	78.75	99.00	66.94	5.96	6.49	4.76	5.52	45.75	34.70	36.60	29.50

CP, Conservation practice; FP, Farmers' practice.

TABLE 4 Soil quality index under different horticultural land uses.

Treatments	H		SYI		GMEa	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Aonla	5.98	5.32	12.05	8.01	124.14	325.37
Peach	5.51	4.87	11.28	7.49	121.27	288.00
Mango	6.31	5.64	12.91	8.60	142.22	374.19
Litchi	5.01	4.39	9.69	6.39	100.33	201.82
Citrus	4.50	3.91	8.10	5.29	80.46	211.12
Fallow	2.76	2.24	5.74	3.67	36.77	96.87

H, Shannon's diversity index; SYI, Simpson–Yule index; GMEa, geometric mean of enzyme activities.

horticultural system involvement (Table 3). Despite soil depth, marked improvement in SOC was noted in all fruit-based land use systems under CPs as against FPs. The peach-based land use system with CPs recorded the highest increment in SOC, i.e., 37.70% and 26.32% at 0–15 cm and 15–30 cm soil layer, respectively, as compared to FPs, while citrus-based land use noted the lowest increment (23.29%) in SOC at 0–15 cm soil layer. Interestingly, mango, litchi, and citrus-based land uses recorded the equivalent 20% increase in SOC at 15–20 cm soil layer in CPs as against FPs. In fallow land, SOC increment in CPs was 24.49% and 18.92% when compared to FPs.

Between practices, ∼23.29–37.70% at 0–15 cm depth and 18.92–26.32% at 15–30 cm depth, more SOC was noticed among all horticultural land use systems and fallow land use. The CPs adopted in aonla, guava, mango, litchi, and citrus-based horticultural systems increased SOC by ∼27.6, 32.6, 24.4, 26.8, and 22.0%, respectively, over FPs. Approximately 3.03–57.5% and 23.8–157.1% higher available N at 0–15 cm and 15–30 cm soil depth, respectively, were recorded under CPs in horticultural land use systems over fallow land. A similar trend was also found in FPs over control. Between practices, 20.4–29.8 and 11.1–23.4% more available N at 0–15 cm and 15–30 cm depth, respectively, were registered in CPs over FPs among land use systems. The mean plant available N observed was 15.6–27.2% higher in the case of CPs than FPs among horticultural land use systems. The horticultural systems improved P availability by ∼1.36–4.47 times and K availability by 1.17 to 3.04 times over control at the 0–15 cm soil layer. A similar trend was also found in sub-surface (15–30 cm) soil.

Soil quality index and functional diversity

In surface soil, the geometric mean of enzyme activities (GMEa) of the horticultural systems of mango and aonla was 3.87 and 3.38 times higher than the control, respectively. The subsurface soil revealed similar findings (Table 4). Surface soil had a GMEa that was around 4% higher than subsurface soil. In both soil layers, Shannon's diversity index (H) was greater in mango- and aonla-based horticultural systems than in other treatments. Intriguingly, the H value in the 0–15 and 15–30 cm soil layers of the mango-based horticultural system was 2.29 and 2.52 times higher than the control, respectively. The H values of citrus- and litchi-based horticultural systems, however, were comparable. Mango- and aonla-based horticultural systems in both soil layers had SYI values that were noticeably greater than litchi- and citrus-based horticultural systems. SYI levels were greater in both soil layers than in H, in contrast. Notably, horti-pasture adoption produced more soil functional diversity in surface and sub-surface soil layers than in control land.

Culturable microbial population

The microbial populations of bacteria, fungi, and actinomycetes were significantly improved in CPs among horticultural systems (Table 5). The microbial counts of bacteria were 14.2–47.0% and 20.4–92.4% more in CPs than FPs at soil depths of 0–15 and 15–30 cm, respectively. Similarly, approximately 27.4–53.8 and 10.4–46.6% higher fungal population was recorded in CPs over FPs at a soil depth of 0–15 and 15–30 cm, respectively. Similarly, actinomycetes counts were also 20.4–51.5% and 15.5–40.4% higher under CPs compared to FPs at soil depths of 0–15 and 15–30 cm, respectively. Among the different horticultural land use systems, higher densities of bacteria, fungi, and actinomycetes were recorded in the aonla, mango, and citrus land use systems, respectively, over the rest of the land use systems under both CPs and FPs.

Soil enzyme activity

CPs across horticulture land use systems substantially increased the enzymatic activity (Table 6). The enzymatic activities of ACP and AP were 94.5–175.2% and 155.8–319.4% and 64.3–144.3% and 30.6–133.2% higher under CPs over FPs at 0–15 cm and 15–30 cm soil depth, respectively. CP and surface soil depth (0–15 cm) had more enzymatic activities compared to FPs and sub-surface soil depth (15–30 cm). Similarly, urease and BGD enzymatic activities were also 130–139.0% and 50.1–279.1% and 13.6–47.0% and 37.1–252.3% higher under CPs over FPs at 0–15 and 15–30 cm soil depth, respectively. DHA was also 128–1,090% and 118.7–1,076.5% more under CPs over FPs at 0–15 and 15–30 cm soil depth, respectively. Among the different horticultural land use systems, higher activity of ACP, AP, DHA, and BGD was observed in the kinnow land use system, respectively, over the rest of the land use system under both CPs and FPs. However, the mango land use system recorded

TABLE 5 Culturable microbial population status under different horticultural land uses.

Land uses	Gravel (%)	Bacteria (CFU × 10^6 g^{-1} dry soil)				Fungi (CFU × 10^4 g^{-1} dry soil)				Actinomycetes (CFU × 10^5 g^{-1} dry soil)			
		CP		FP		CP		FP		CP		FP	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	15–30 cm	0–15 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Aonla	47.3	153.00	81.67	123.93	67.80	9.30	4.67	3.80	7.30	189.67	154.67	144.15	120.00
Peach	54.2	65.33	29.67	50.31	23.80	8.00	4.00	3.20	6.00	75.00	20.67	57.00	17.21
Mango	43.2	62.67	27.00	48.25	14.00	16.70	11.00	8.40	12.00	77.00	43.00	53.90	32.94
Litchi	45.7	46.33	28.67	40.54	21.40	5.00	3.00	2.50	3.90	76.33	37.00	63.36	32.02
Citrus	40.8	104.33	80.67	70.95	60.90	5.33	3.67	2.50	3.47	202.67	127.67	133.76	90.92
Fallow	66.2	38.67	23.67	28.61	12.80	4.00	2.23	2.02	2.72	59.33	15.33	42.13	12.48

CP, Conservation practice; FP, Farmers' practice.

TABLE 6 Enzymatic activities of microbes under different horticultural land uses.

Land uses	Acid phosphatase (μg p-NPP g^{-1} h^{-1})				Alkali phosphatase (μg p-NPP g^{-1} h^{-1})				Urease (NH_3-N g^{-1} h^{-1})				DHA (μg TPF g^{-1} h^{-1})				BGD (μg PNG g^{-1} dwt h^{-1})			
	CP		FP		CP		FP		CP		FP		CP		FP		CP		FP	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Aonla	185.8	124.0	143.1	98.0	76.7	23.2	60.6	18.5	15,602.6	11,005.8	11,545.9	8,364.4	21.5	7.2	16.8	5.7	70.19	44.85	53.35	37.12
Peach	211.9	102.6	158.9	73.9	133.3	55.4	100.0	41.0	11,500.8	6,011.2	8,165.6	4,568.5	98.6	35.9	73.9	27.6	134.34	52.26	98.07	40.36
Mango	220.5	124.6	158.7	92.2	88.8	31.4	66.6	23.9	16,937.4	14,409.2	11,517.5	10,086.4	104.3	13.8	76.2	10.6	121.33	75.13	84.93	57.63
Litchi	250.6	124.8	213.0	109.5	81.4	37.0	70.0	32.9	14,117.5	12,897.6	12,282.2	11,349.9	95.0	8.0	83.6	7.1	134.33	63.02	111.5	54.21
Kinnow	346.7	212.1	214.9	140.0	135.5	65.2	86.7	43.7	8,202.9	4,867.1	5,003.7	3,309.6	129.3	33.5	81.5	23.5	312.18	82.34	206.0	58.48
Fallow	150.9	93.0	113.2	68.8	39.3	18.7	28.3	13.6	6,762.4	3,188.0	4,395.5	2,167.8	13.9	6.1	9.9	4.5	60.36	40.22	42.86	31.25

CP, Conservation practice; FP, Farmers' practice; DHA, Dehydrogenase activity.

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the higher activity of urease both in CPs and FPs over other land use systems.

Soil microbial biomass carbon

The data show that the SMBC values for different land uses under CPs and FPs at two soil depths (0–15 cm and 15–30 cm) were significantly improved after 20 years of plantation (Table 7). Among horticultural land use systems, mango followed by litchi had the highest SMBC values with the lowest value in peach under both CPs and FPs and soil depths. Approximately 11.1–56.7% and 28.2–57.1% more SMBC values were recorded in horticultural land systems established under CPs compared to fallow land at 0–15 cm and 15–30 cm soil layers, respectively. Similarly, 1.69–43.9 and 8.54–32.0% higher SMBCs were observed in horticultural land systems established under FPs over fallow land at 0–15 cm and 15–30 cm layer, respectively, among horticultural land systems established under FPs. It was observed that the SMBC values were 25.0–36.6% and 4.12–25.7% higher in 0–15 cm and 15–30 cm, respectively, under CPs compared to FPs for all the land use systems. The data also revealed that 14.3–31.8% and 2.89–21.6% higher SMBCs were registered under CPs and FPs, respectively, in the surface soil layer (0–15 cm) in comparison to the sub-surface soil layer (15–30 cm). The average values of SMBC (0–30 cm) recorded were 15.0–31.4% more under CPs than FPs among all horticultural land use systems and fallow land. Finally, the fallow land use has the lowest SMBC values under both CPs and FPs, with a more considerable difference between the two practices in the 0–15 cm surface soil than in the 15–30 cm sub-surface soil.

Canopy spread, fruit yield, litter yield, and soil moisture

Canopy spread, fruit yield, litter yield, canopy spread, and soil moisture were observed significantly more in fruit-based horticultural systems established with CPs over FPs on degraded land (Table 8). The mean canopy spread of different fruit species observed was mango (6.05 m and 7.95 m), litchi (5.82 and 7.46), aonla (5.48 and 7.00), peach (5.56 and 7.00), and citrus (3.93 m and 5.00 m) in different fruit species established under FPs and CPs, respectively. The long-term data on fruit yield have shown an increasing trend in fruit yield with the progressive years except for litchi and kinnow. There was a declining trend in fruit yield of kinnow and litchi after 12 years of plantation in both CPs and FPs (Figure 2). The mango fruit yield and mango equivalent fruit yield (MEFY) of litchi, aonla, peach, and citrus were calculated for comparison of systems using Equation 4. Among the horticultural systems, the maximum mango fruit yield was recorded (10.1 and 15.0 t ha^{-1}) followed by mango equivalent fruit yield (MEFY) of litchi (7.76 and 10.9 t ha^{-1}), MEFY of peach (6.92 and 10.0 t ha^{-1}), MEFY of aonla (6.23 and 8.41 t ha^{-1}), and MEFY of citrus (6.11 and 8.13 tha^{-1}) under FPs and CPs, respectively, of 20 years plantation. Similarly, mean litter yields of mango, litchi, aonla, peach, and citrus were observed at 3.02 and 4.05, 2.85 and 3.78, 5.46 and 7.48, 5.56 and 7.25, and 6.05 and 8.35 t ha^{-1} in FPs and CPs, respectively during 20 years of life span. Similarly, mean soil moisture in mango, litchi, aonla, peach, and citrus under FPs and with CPs were 10.5 and 13.6, 10.15 and 13.1, 10.12 and 13.5, 12.6 and 14.5, and 13.4% and 15.2%, respectively, during 20 years of life span in degraded lands.

Economic viability

The net present values (NPVs), benefit-cost ratio (BCR), and payback period (PBP) were analyzed for mango, litchi, aonla, peach, and citrus fruit species based horticultural land use systems with CP and FP conditions (Table 9). The values of NPV, BCR, and PBP of all fruit species in the case of CPs were higher than FPs. The highest NPVs were realized in mango (607,201.8 and 900,032 Rs ha^{-1}) followed by litchi (465,514 and 654,524 Rs ha^{-1}), peach (415,166 and 604,832 Rs ha^{-1}), aonla (374,002 and 504,464 Rs ha^{-1}), and citrus (366,786 and 487,982 Rs ha^{-1}) established under FPs and CPs, respectively. Similarly, the highest BCR was also realized in mango (2.93 and 3.90), followed by litchi (2.81 and 3.14), aonla (2.24 and 3.05), peach (2.11 and 2.95), and minimum in citrus (2.05 and 2.88) in FPs and with CPs, respectively. Similarly, the minimum PBP (4.0 and 3.2 years) was observed with peach, followed by citrus (4.2 and 3.5), mango (5.0 and 4.0), litchi (5.4 and 4.2), and the highest PBP with aonla (5.5 and 4.4 years) (Table 9).

Principal component and DMRT analysis

PCA biplots were compared for both CP and FP. The total variation was 72.6% and 74.5%, respectively. In the scree plot, the Y axis shows PC components while the X axis shows the variances. By comparing both FPs and CPs, more correlation in the values of BGD, DHA, ACP, AP, N, K, soil microbial load, and organic carbon was found in CPs compared to the FPs. However, urease, organic carbon fungi, P, organic carbon bacteria, and organic carbon actinomycetes were less related, which is similar in both cases. This showed that the CPs improved most of the soil enzymatic properties holistically when applied compared to FPs. The PCA biplot showed a better response by mango was least affected by both CPs and FPs; however, peach was most affected by CPs (Figure 3). The DMRT was also done to compare the different treatments (Table 10).

Ecosystem services

The carbon sequestration (trees + soil), nutrient augmentation, and total ecosystem services of horticultural land use system under conservation and farmers' practices have been assessed in Tables 11–13. The monetary value of C-sequestration ranged from Rs. 29,291.99 to 45,508.45 ha^{-1} under conservation practice, which is 8.33% to 15.94% more than monetary values observed under farmer practice. Similarly, the monetary value of nutrient augmentation ranged from 808.6 to 11,414.5 and 377.4 to 9,411.1 in conservation practice and farmer practice, respectively (Table 12). The highest monetary valuation of the total ecosystem services

TABLE 7 Soil microbial biomass carbon (μg g^{-1} soil) in different fruit species established with conservation and farmers' practices.

Horticultural land use systems	Soil microbial biomass carbon (μg g^{-1} soil)			
	Conservation practices		Farmers' practices	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Aonla	475.23	364.45	348.12	296.34
Peach	410.80	359.34	300.56	292.12
Mango	579.45	440.23	425.32	355.50
Litchi	568.65	435.66	420.91	346.84
Kinnow	565.34	429.32	415.23	341.45
Fallow	369.56	280.23	295.56	269.14

TABLE 8 Average growth parameter, fruit and litter yields, and soil moisture in different fruit species.

Horticultural land use systems	Conservation practices				Farmers' practices			
	CS (m)	FY (t ha^{-1})	LY (t ha^{-1})	SM (%)	CS (m)	FY (t ha^{-1})	LY (t ha^{-1})	SM (%)
Aonla	7.00	20.18	5.58	13.54	5.48	14.96	4.46	10.82
Mango	7.95	15.00	6.35	13.68	6.05	10.12	5.02	10.5
Litchi	7.46	9.35	6.78	13.12	5.82	6.65	5.12	10.15
Peach	7.00	12.60	7.25	14.56	5.56	8.65	6.0	11.65
Kinnow	5.00	19.52	8.35	14.24	3.93	14.67	7.05	11.42
Fallow	-	-	-	-	-	-	-	-

CS, Canopy spread; FY, Fruit yield; LY, Litter yield; SM, Soil moisture.

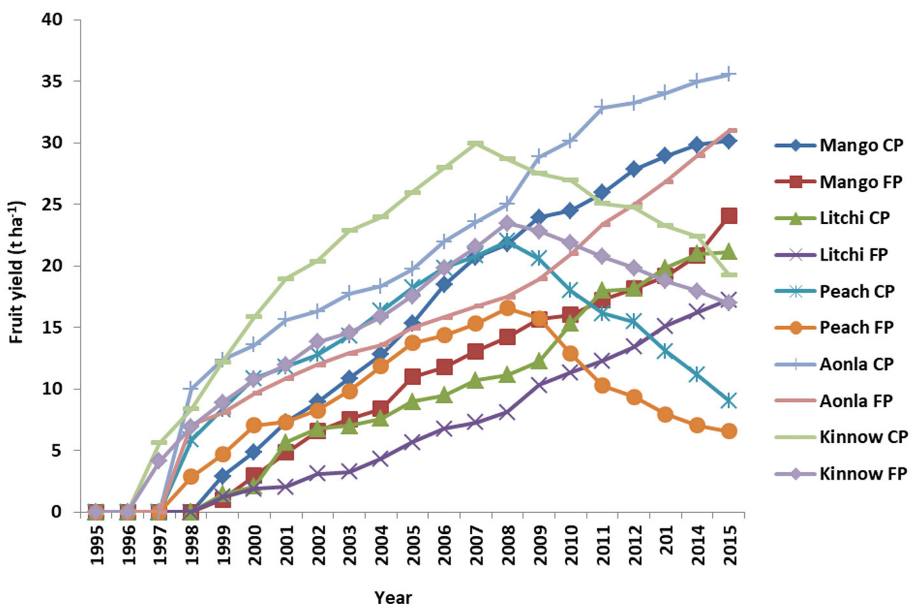

FIGURE 2
Fruit yield (t ha^{-1}) of different fruit crops from 1995 to 2015.

(regulating service + supporting service) among different fruit-based land uses with conservation practice is Rs 56,907 ha^{-1} in the mango-based land use system among all land uses (Table 13). The conservation practice realized 9.6% to 16.4% of additional benefits in the form of ecosystem services in different horticultural land use systems.

TABLE 9 Economics of different horticultural land uses.

Particulars	Mango		Litchi		Aonla		Peach		Citrus	
	FP	CP	FP	CP	FP	CP	FP	CP	FP	CP
NPV (Rs ha^{-1})	607,202	900,032	465,514	654,524	374,002	504,464	415,166	604,832	366,786	487,982
BCR	2.93	3.9	2.81	3.14	2.24	3.05	2.11	2.95	2.05	2.88
PBP (years)	5.5	4.3	5.9	5.0	6.4	5.5	5.7	4.5	5.8	4.5

CP, Conservation practice; FP, Farmers' practice; NPV, Net present value; BCR, Benefit cost ratio; PBP, Payback period.

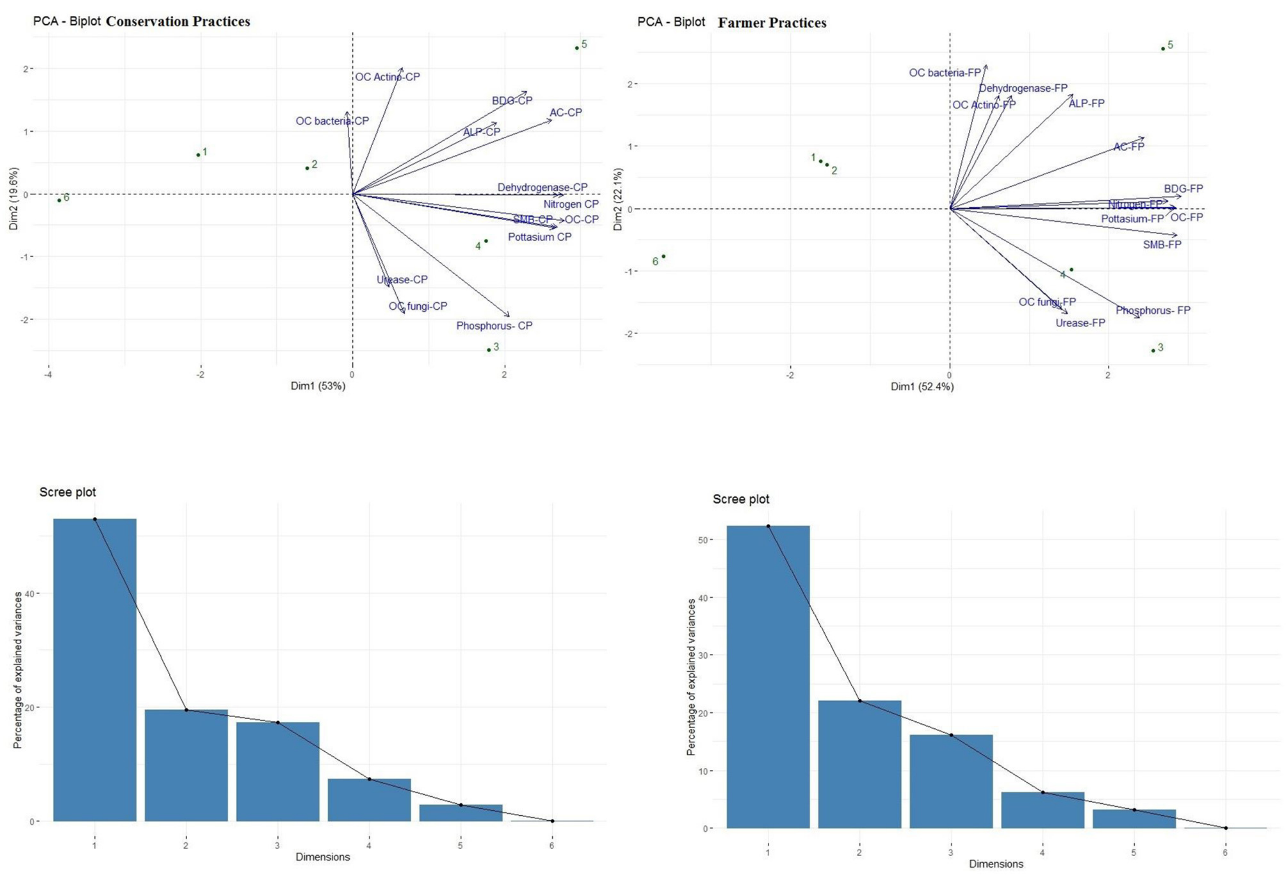

FIGURE 3
PCA biplot and screen plot for conservation practices **(Left)** and farmers' practice **(Right)**.

Discussion

C, N, and P in soils

The carbon, N, P, and soil quality index have been influenced significantly by various fruit-based land uses (Tables 3, 4). According to Ghosh et al. (2016), there may be a positive association between microbial population and SOC in both soil layers, which may account for the significantly higher DHA in the kinnow- and mango-based horticulture systems. According to Kumar et al. (2019), kinnow and mango-based agricultural systems with higher levels of glucosidase activity than others may have higher microbial biomass turnover and adequate C availability because of higher litterfall, root biomass, and rhizodeposition. Urea and similar compounds are hydrolyzed by urease. Due to increasing SOC and a microbial population that promoted urease secretion in mango- and litchi-based horticulture systems, its activity increased (Chang et al., 2007). According to Chakrabarti et al. (2004), the reduced urease activity in the control group may be caused by insufficient C and energy. Kinnow- and peach-based horticulture systems have much greater ACP than fallow. According to Dodor and Tabatabai (2003), SOC can specify phosphatase activity. It is possible that the presence of phospholipids and inositol phosphates in litters promoted phosphatase activity. Improved animal-based and horticulture-based system + conservation practices were found to reduce soil erosion (34%−48%) and loss of SOM (26%−51%), N (33%−45%), P (19%−54%), and K (27%−51%) compared to the traditional shifting cultivation system in Nagaland, India. It might be due to the improved physical, chemical, and biological properties of soil due to integrated nutrient management in this production system (Chatterjee et al., 2021).

TABLE 10 DMRT to compare the different treatments of parameters taken in the study.

Sl. No.	Parameters	Statistically at par (DMRT)
1.	Acid phosphatase	Mango CP and Peach CP Litchi FP and Aonla FP
2.	Alkaline phosphatase	Peach CP and Kinnow CP Mango CP-Litchi CP-Aonla CP Kinnow FP-Peach FP Litchi FP-Fallow CP
3.	Actinomycetes	Kinnow-Aonla CP Litchi-peach-mango-CP
4.	Beta dehydrogenase activity	Kinnow-Mango FP Aonla CP-Litchi FP Aonla FP-Fallow FP
5.	Dehydrogenase activity	Kinnow CP-Mango CP-Peach CP-Litchi CP Peach FP-Mango FP-Aonla CP-Fallow CP-Litchi FP-Aonla FP-Fallow FP
6.	Potassium	Kinnow-Mango CP Kinnow FP-Mango FP Aonla CP- Peach FP- Fallow CP Aonla FP-Fallow FP
7.	Nitrogen	Kinnow CP-Litchi CP Mango CP-Litchi FP- Kinnow FP Mango FP-Aonla CP- Peach CP Peach FP-Fallow CP-Aonla FP
8.	Phosphorus	Peach CP-Fallow CP-Aonla CP Peach FP-Fallow FP-Aonla FP
9.	Organic carbon	Mango CP-Litchi CP- Kinnow CP Kinnow FP- Mango FP Aonla CP- Litchi FP-Fallow CP Aonla FP- Fallow FP
10.	Organic carbon bacteria	Aonla FP- Kinnow FP Peach FP-Litchi FP Mango FP- Fallow FP
11.	Organic carbon fungi	Litchi CP-Kinnow CP Peach FP- Fallow CP- Kinnow FP
12.	Urease	Mango FP-Litchi FP Peach CP-Aonla FP Fallow FP-Peach FP
13.	SMBC	Mango CP-Litchi CP- Kinnow CP Aonla CP-Mango FP-Peach CP, Litchi FP-Kinnow FP Fallow CP-Fallow FP, Aonla FP, Peach FP

Soil functional diversity is controlled by the kind, amount, and accessibility of the substrate to microbes (Ghosh et al., 2019). As a result, agroecosystems that get organic C, N, P, and S from various sources may have an impact on how microbial communities in soils operate and change organic matter (Hu et al., 2011; Ghosh et al., 2020). Horticultural systems based on kinnow and peach had the most litterfall. However, the larger Shanon's diversity index (H) in these plots than others was brought on by strong urease activity in mango and aonla (Table 4). Although some systems received varied amounts of litterfall, this measure was unable to distinguish between the functional varieties of the soil in those systems. We created the Simpson–Yule index (SYI), a dominance indicator that gives more weight to common or dominant species, to distinguish between them. Thus, a distinct distinction between litchi and citrus was discovered. SYI fared better in this investigation at detecting changes in soil functional diversity. The biggest C availability, in this case, was accounted for by mango- and aonla-based horticulture systems, which were notably different from the others due to catabolic diversity (Ghosh et al., 2023) and led to increased soil functional diversity. Mango- and aonla-based horticulture systems may deliver organically bound N, P, and S slowly but gradually thanks to equilibrium between labile and recalcitrant pools of SOM. It is evident from GMEa values that horticulture systems enhanced soil health. Utilizing horticulture methods ensured a larger above-ground biomass production, which in turn led to a higher litterfall and SOC status. In mango-based horticulture systems, these events increased microbial population and enzyme activity over control. Through increased root biomass and higher litterfall, horticultural systems also made sure that enzymes had access to the substrate. Improved nutrient cycling, availability, and soil carbon sequestration were all made possible by increased soil enzyme activity.

Culturable microbial population

Substrate quantity, quality, and microbial accessibility control soil functional diversity (Bending et al., 2002). Therefore, the agroecosystems receiving organic C, N, P, and S from different sources can affect the microbial transformation of organic matter and the functional diversity of microbial communities in soils (Sall et al., 2006). The microbial populations of bacteria, fungi, and actinomycetes were significantly improved in different horticulture land use systems under CPs over FPs (Table 5). The population of bacteria, fungi, and actinomycetes increased under all horticultural systems over control, with the mango- and aonla-based systems having the greatest population than others. Interestingly, topsoil has a substantially greater population of culturable microbes than sub-surface soil. In CPs, microsite improvement, mulching, and integrated nutrient management all together might have improved SOC and soil moisture regime, which served as a source of nutrients and supplied hydrogen and oxygen to the microorganisms, and it served as a solvent and carrier of other food nutrients to the microorganisms (Jat et al., 2023). Thus, soil moisture and SOC helped in improving the soil bacterial, fungal, and actinomycetes density. In turn, it might have influenced the nutrient dynamics to improve nutrient availability to fruit crops (Sahu et al., 2017). Soil microorganisms mineralize litter and facilitate the release of nutrient elements and their continual recycling (Kumar et al., 2019). Dead plant residues and plant nutrients become food for the microbes in the soil. The decomposition of SOM imparted energy for growth and provided carbon for the formation of new cells. In the process, N, P, and K were recycled and helped improve soil health (Smith, 2018).

Soil enzyme activity

Our study revealed that CPs had higher activity of AP, ACP, urease, and BGD over FPs both in surface and sub-surface soil depths (Table 6). In both soil layers, horticulture systems had

TABLE 11 Carbon sequestration regulatory ecosystem services (t ha^{-1}) and monetization (Rs ha^{-1}) under different horticultural land use systems.

Horticultural land use systems	Carbon sequestration (t ha^{-1})						Monetization of C-sequestration (Rs ha^{-1})		% Benefits (CP over FP)
	Conservation Practices			Farmers' practices					
	Tree CS	Soil CS	Total	Tree CS	Soil CS	Total CS	CP CS	FP CS	
Aonla	113.0	5.8	118.8	108.0	1.7	109.6	34,084.46	31,463.88	8.33
Peach	106.9	22.3	129.2	100.7	10.7	111.5	37,091.61	31,991.58	15.94
Mango	124.7	33.9	158.6	118.2	25.6	143.8	45,508.45	41,257.37	10.30
Litchi	121.6	26.4	148.0	114.2	18.2	132.4	42,484.45	37,985.85	11.84
Citrus	69.9	32.2	102.1	64.7	26.4	91.1	29,291.99	26,147.92	12.02

CS, Carbon sequestration; CP, Conservation practice; FP, Farmers' practice.

TABLE 12 Supportive ecosystem services (nutrient augmentation with fertilizer equivalent of N, P, and K) in different horticultural land use systems.

Horticultural land use systems	Nutrient augmentation (kg ha^{-1})						Monetization of saved nutrients (Rs ha^{-1})		% Benefits (CP over FP)
	CP			FP					
	Urea	SSP	MOP	Urea	SSP	MOP	CP	FP	
Aonla	97.8	−1.5	8.0	62.0	−3.9	1.3	808.6	377.4	114.2
Peach	97.8	8.7	33.5	79.7	5.9	25.7	1,654.1	1,290.8	28.1
Mango	309.8	212.2	262.1	251.0	171.4	211.4	11,398.5	9,201.6	23.9
Litchi	407.6	126.4	141.2	372.6	112.2	127.6	7,664.1	6,936.2	10.5
Citrus	415.8	68.6	280.0	346.3	54.8	230.6	11,414.5	9,411.1	21.3

CP, Conservation practice; FP, Farmers' practice; SSP, Single super phosphate; MOP, Murate of potash.

TABLE 13 Total ecosystem services (TES) from different horticultural land use systems (Rs ha^{-1}).

Horticultural land use systems	CP			FP			% Benefits (CP over FP)
	Regulating services	Supporting services	TES	Regulating services	Supporting services	TES	
Aonla	34,084.5	808.6	34,893.1	31,463.9	377.4	31,841.3	9.6
Peach	37,091.6	1,654.1	38,745.7	31,991.6	1,290.8	33,282.4	16.4
Mango	45,508.4	11,398.5	56,907.0	41,257.4	9,201.6	50,458.9	12.8
Litchi	42,484.5	7,664.1	50,148.6	37,985.9	6,936.2	44,922.0	11.6
Citrus	29,292.0	11,414.5	40,706.5	26,147.9	9,411.1	35,559.0	14.5

CP, Conservation practice; FP, Farmers' practice; TES, Total ecosystem services.

considerably greater activities of C-cycling enzymes such as BGD. In both soil layers, horticulture systems based on mango and guava produced considerably greater levels of N and P cycling enzymes such as phosphatase and urease. Significantly higher activities of BGD, AP, ACP, and DHA under CPs might be due to greater SMBC and SOC over FPs. Mijangos et al. (2006) have reported that SMBC or SOC had a positive correlation ($P < 0.05$) with soil enzyme activity in both soil layers. Mulching, microsite improvement, and INM in CPs contributed a good amount of litterfall, root biomass, and rhizodeposition and eventually enhanced carbon availability (Hu et al., 2011). Dodor and Tabatabai (2003) reported that SOC could stipulate AP and ACP activity. The presence of inositol phosphates and phospholipids in litters might have encouraged phosphatase activity. The decomposed part of the litterfall worked as the substrate for BGD and improved its activity (Ghosh et al., 2019).

Soil microbial biomass carbon

The SMBC significantly improved by different fruit-based land uses (Table 7). Rathore et al. (2021) also observed a higher soil microbial population in the upper layer of soil because of more SOC present in the layer. The results on SMBC values under CPs, FPs, and soil depths were significantly varied among various land uses. This indicates that mango followed by litchi had the highest SMBC values, whereas the lowest values of SMBC in peach were recorded under both CPs and FPs at two depths. The higher SMBC under CP as well as in the upper soil layer is due to differences in the root exudates of different plants, SOM content, litter yields, and microbial community composition as compared to the lower soil layer of degraded lands (Ghosh et al., 2019). The SMBC values decreased with increasing soil depth, which is in line with the fact that microbial biomass is highest in the topsoil layers, where the SOM content is highest. Additionally, the difference in SMBC values between CPs and FPs is more pronounced in the 0–15 cm soil layer than in the 15–30 cm soil layer. This finding suggests that CPs may have a more significant impact on microbial biomass in deeper soil layers. Additionally, better soil structure, stabilized microclimate, and higher nutrient recycling potential of CPs might have also enhanced SOC and SMBC (Moore et al., 2003).

The horticultural land use systems enhanced the SMBC because of the addition of leaf litter and root exudates, which increased SOM and created favorable conditions for microbial growth. The degradation of organic substances provides both energies for growth and carbon for the creation of new cells of soil microbial bacteria. SMBC and SOC in fruit-based land use systems had grown in the degraded land, with CP accumulating higher SMBC and SOC than farmer practice. Verma et al. (2010) also reported that conservation practice improved SOC in apple orchards with continuous application of farm yard manure. Furthermore, the difference between SMBC values under CPs and FPs is more prominent in the 15–30 cm soil layer than in the 0–15 cm soil layer, suggesting that conservation practices have a more significant impact on the microbial biomass in deeper soil layers. Finally, the fallow land use has the lowest SMBC values under both CPs and FPs, with a more considerable difference between the two practices in the 0–15 cm soil layer than in the 15–30 cm soil layer. Overall, the data highlight the positive impact of conservation practice on SMBC, which varies among different land uses and soil depths.

Canopy spread, fruit yield, litter yield, and soil moisture

The growth and fruit production have been significantly varied under different fruit-based land uses (Table 8). Among the fruit species planted with CPs and FPs, canopy spread was positively correlated with fruit yield ($r = 0.95$) and litter yield ($r = 0.92$). This indicated that higher plant spread would capture more sunlight and convert more solar energy into food material (photosynthates) for the production of more fruit yield under both situations on degraded lands. The mean canopy spread was recorded higher under CPs in mango followed by litchi, aonla, citrus, and peach as compared to FPs. Mango attained maximum canopy spread followed by litchi and aonla among all other fruit species because of its very deep rooting pattern and ability to draw more nutrients and moisture from deeper soil layer, which supplied the required amount of moisture along with nutrients to the plant under CPs as compared to FPs. Similarly, among the fruit species established with CPs, the mango produced higher MEFY, litter yield, and soil moisture than FPs on degraded lands, followed by litchi, peach, aonla, and citrus. Mango produced more canopy spread and fruit yield as compared to all other fruit species with CPs due to the mulching effect and its suitability to edapho-climatic conditions, which favored attaining more canopy spread, fruit yield, and soil moisture (Chavan et al., 2023). *Melia dubia* + dragon fruit and *Melia dubia* + lemon grass cultivation along with soil moisture conservation practices has resulted in better fruit yield of dragon fruit and biomass yield of *Melia dubia* and lemon grass compared to control besides conservation of soil and water in Mahi ravines of Central Gujarat (Jinger et al., 2020, 2021; Kakade et al., 2020).

Economic viability

The economic profitability was assessed in different fruit-based land uses (Table 9). Benefit–cost analysis of horticultural land use systems (mango, litchi, peach, aonla, and citrus) established with CPs and FPs for 20 years of life span indicated that fruit species established with CPs were more economically viable and profitable than fruit species planted under FPs on degraded land (Table 7). The NPVs of 900,032, 654,524, 504,464, 604,832, and 487,982 Rs ha^{-1} were observed in mango, litchi, aonla, peach, and citrus land use systems, respectively, planted with CP, whereas these NPVs were lower among fruit species planted in FP analyzed for 20 years of lifespan. Among horticultural land use systems, approximately 37.51–84.43% and 30.44–65.56% higher NPVs were observed in mango land use under CPs and FPs, respectively, over other land use systems. Similarly, the BCR of horticultural land use systems was maximum in mango, followed by litchi, aonla, peach, and lowest in citrus under CPs and FPs, respectively. The PBP observed in different horticultural land use systems planted with FPs and CPs was recorded minimum in mango followed by peach, citrus, and litchi and highest PBP in aonla for 20 years. A comparison of the horticultural land use systems under CPs with FPs indicated that NPV of horticultural land use systems with CP ranged from Rs 487,982 to 900032 ha^{-1}, which were more profitable than FP (366,786–607,202 Rs ha^{-1}) calculated for 20 years of lifespan. The benefit analysis of various fruit species for 20 years was observed beneficial, which indicated that practicing INM, organic mulching, and allowing natural grasses in different fruit species provided more economic benefits than without INM and organic mulching. Moreover, the fruit yield of various fruit species under CP was higher because of more canopy spread, the availability of more soil moisture in the soil profile helped in attaining more vegetative growth, and the adsorption of more moisture along with nutrients from deeper layers of soil helped in more fruit production under degraded land condition (Chavan et al., 2022). Between the two practices (CP and FP), fruit species established with CPs were the most profitable (487,982–900,032 Rs ha^{-1}) in 20 years, and the difference of their respective NPVs was significantly 33.06–48.22% more of different fruit species over clean cultivation. Overall, fruit species established with CPs were a higher discounted profit earner over FPs. Thus, fruit species established with CPs observed higher BCRs than those established with FPs. In terms of PBP, fruit species established with CPs had the shortest and fruit species with FPs the longest (5.5–7.0 years). Thus, the utilization of inter-tree space by suitable crops can provide extra returns, leading to higher economic benefits even in a shorter period than sole litchi (Rathore et al., 2014).

Ecosystem services

The carbon sequestration in trees and soil under conservation and farmers' practices have been assessed in horticultural land use systems (Table 11). It is observed that additional monetary benefits accrued due to the adoption of CP over FP vary between 8.33% and 15.94% for carbon sequestration. This comparison highlights the advantage of adopting conservation practices in terms of enhanced carbon sequestration and the associated economic benefits. Similarly, the highest additional benefits due to the adoption of conservation practices are observed (114.2%) in the aonla-based horticultural land use system, whereas in the other systems, additional benefits vary between 10.5% and 28.1%. This can be inferred that conservation practices augment the nutrient content of soil and reduce the requirement for external fertilizer application (Table 12). The monetary quantification of the total ecosystem services (regulating service + supporting service) in different fruit-based land uses with conservation and farmers' practices has been computed, which revealed that the highest monetary value of total ecosystem services (56,907 Rs ha^{-1}) assessed was in mango-based land use system among all land uses with CPs (Table 13). The total ecosystem services of mango under conservation practice is approximately 12.8% more than mango-based land use established with farmer practice (Pandey et al., 2021). By adopting CPs, farmers can gain additional benefits in the form of ecosystem services varying from 9.6% to 16.4% in different horticultural land use systems. The conservation practice used in fruit-based land uses attained more tree biomass and produced higher fruit yield, which realized more returns ha^{-1} as compared to farmer practice due to higher moisture availability and nutrition supplied through integrated nutrient management. Additionally, fruit-based land uses contributed to more litterfall into the soil, increasing porosity and preserving more soil moisture, which improved the vegetative growth of fruit trees (Kumar et al., 2018; Rathore et al., 2020). The higher ecosystem services or benefits of fruit trees have also been reported in the literature (Orlandi et al., 2023).

Conclusion

The study compared existing farmers with conservation practices based on deep-rooted fruit species in terms of the chemical and biological characteristics of the soil, including the organic carbon, N, and P contents, enzyme activities, and microbial population, as well as economic analyses. The results of the analysis of variance revealed that most of the parameters studied were significantly affected by the CPs and horticultural land use systems. The SOC and available N, P, and K contents were significantly improved in the CPs adopted in horticultural land use systems. The results showed that the CPs improved the soil enzymatic properties holistically when applied compared to FPs. Furthermore, the horticultural systems substantially increased the enzymatic activity and microbial population of bacteria, fungi, and actinomycetes in the soil. Moreover, SYI of mango- and aonla-based horticulture systems showed notable differences from the others due to higher catabolic diversity and led to increased soil functional diversity. Among the horticultural systems, the canopy spread, fruit, and litter yield was recorded highest in mango, followed by litchi. A similar trend was also observed for NPV, BCR, and PBP. Overall, the study provides evidence that CPs, such as the adoption of horticultural land use systems, have a positive effect and lead to improved SOC, nutrient availability, enzymatic activity, microbial population, yield, and BCR.

Constraints of the study area

The investigation site is situated in the North-Western Himalayas. The soil of the study site is prone to land degradation (soil erosion) owing to steep slopes. Cultivation of arable crops is very difficult due to high boulder content, low infiltration rate, and poor soil organic matter, leading to crop failure. Moreover, establishing fruit trees on these lands is also difficult as the root growth is seriously affected. However, CPs played a crucial role in enhancing soil fertility, survival, growth, and yield of the crops. Furthermore, wild animals also cause damage to food crops and fruit trees. However, spiny bamboo fencing reduced the damage caused by the wild animal.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data set will be made available on request. Requests to access these datasets should be directed to AR, rathoreac@gmail.com.

Author contributions

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Comparative analysis of soil quality indexing techniques for various tree based land use systems in semi-arid India

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Inappropriate management of land use systems is one of the main factors that leads to soil quality degradation and its quantification is crucial to their sustainable utilization planning. The objective of the research is to evaluate how various land-use systems, *viz.*, natural forest, tree plantations of *Tectona grandis, Terminalia bellirica, Swietenia macrophylla, Artocarpus hirsutus*, *Melia dubia* based agroforestry system, horticulture (*Mangifera indica*) and agriculture systems impact the soil physicochemical and biological characteristics in semi-arid climatic conditions of India. Principal component analysis followed by linear and non-linear scoring methods was employed to compute the soil quality index (SQI). The soil attributes *viz.,* dehydrogenase activity, acid phosphatase activity, soil available nitrogen, potassium, calcium, porosity, and soil available iron emerged as significant indicators for assessing the soil quality. Among different SQIs, non-linear weighted SQI can efficiently assess soil quality. Based on the non-linear weighted SQI, the order of the systems studied was natural forest (0.973)>*Swietenia macrophylla* (0.756)>agroforestry (0.737)>agriculture (0.556)>*Tectona grandis* (0.416)>*Terminalia bellirica* (0.373)>*Artocarpus hirsutus* (0.343)>*Mangifera indica* (0.208). The study concludes that converting natural forests into different land-use systems deteriorated the soil quality. Identifying soil indicators will help rapidly diagnose soil degradation, assess soil-based ecosystem services, and design appropriate land management practices in the future.

KEYWORDS

tree-based land-use systems, soil degradation, soil indicators, soil quality index, soil health

1 Introduction

Soil is one of the vital component of the terrestrial ecosystem that has an indirect and direct impact on all living forms. Soil health has been one of the critical deciding factors in the success or failure of human civilization. There has been wide-scale deforestation over the years to meet the growing needs of food, fodder, and timber due to the increasing population and urbanization. Continuous deforestation converted natural forests into different land uses like tree plantations, horticulture, agroforestry, agriculture, etc. To meet the production goals, the farming community has opted for improper soil management and land use techniques, such as monoculture, intensive cropping patterns with heavy mechanization, and injudicious usage of agri-chemicals (Chandel et al., 2018). Soil health and sustainability have always been out of context in this due course of development. Unscientific agricultural intensification to achieve self-sufficiency has damaged soils and accelerated its degradation (Jinger et al., 2023). The two main forms of degradation linked with poor soil management practices in semi-arid environments are soil nutrient depletion and soil physical deterioration (Jien and Wang, 2013; Ghaemi et al., 2014; Trivedi et al., 2016; Chemeda et al., 2017; Jinger et al., 2023). Different vegetation types can significantly alter the physical, chemical, and biological aspects of the soil (Tauqeer et al., 2022). They can have long-term effects on soil characteristics (Li et al., 2019), and these changes may be used as a crucial tool to evaluate the changes in soil quality (SQ) (Liu et al., 2018). Therefore, SQ assessments are necessary to understand the state of the soil and create more effective management strategies (Qi et al., 2009).

The soil has to be assessed regularly to monitor the change in different SQ parameters. To assess SQ, it is essential to measure every soil property that indicates a quantifiable soil characteristic impacting the soil's capacity to fulfill a particular function (Karlen et al., 1997). Developing a soil quality index (SQI) with a minimal set of characteristics has been found to indicate the capability of the soil to perform owing to changes in the management techniques, such as land-use changes (Doran and Parkin, 1994; Karlen and Stott, 1994; Raiesi, 2017). There are fewer studies comparing the SQ under various land use systems (LUSs). Rashkow (2014) investigated the SQ of forested, converted, and cropland areas and noted that forested areas exhibited the highest level of SQ, followed by converted and it was least in cropland areas. Chandel et al. (2018) observed that the SQI in the forest was highest than any other LUS in Submontane Punjab. Zou et al. (2021) suggested that SQI was better in primary rain forest followed by rubber based agroforestry and least in monoculture rubber plantations. In another study it was observed that, soil qualities were less affected by the conversion of natural forests into tree plantations than by the conversion of cultivated areas (Zarafshar et al., 2020). A minimum dataset (MDS) of soil indicator as SOC, bulk density, CEC, pH, available potassium, and available phosphorous was developed by Hinge et al. (2019) to determine SQ under various land use and soil management and recorded the highest SQ in dense forest. Based on the MDS values of silt, pH, CEC, exchangeable potassium, and soil organic matter, Mesfin et al. (2023) determined that grassland had higher soil quality in comparison to both natural forest and cultivated land.

The SQIs are developed by different scoring techniques, such as linear and non-linear. A weighted additive SQI using MDS could quantify the adverse impacts of forest conversion to dry farming on SQ (Davari et al., 2020). Dry farming and forest removal lowered the SQ by 44.5%. A non-linear scoring of soil indicators showed a decrease in SQI due to deforestation(Nabiollahi et al., 2018). Sinha et al. (2014) identified the weighted non-linear index as the most sensitive for all agroecosystems and proposed it as a future evaluation index. Research suggests that SQIs are a valuable technique to determine the impact of land degradation and changes in land use on SQ. However, the most robust SQI method suitable to assess the effect of various LUS is still a question to be answered. Therefore, there is a need for further investigation to explore the various SQI indexing techniques in different LUSs. Many studies on SQ indexing focus on short-term effects, but there is limited research on the long-term impacts of land use change on SQ. It is crucial to comprehend the long term viability and sustainability of different LUSs. It is hypothesized that conversion of natural forests to agricultural land will deteriorate SQ. Understanding the significance of SQ, the present study was conducted with the aims (1) to assess the soil physicochemical and biological characteristics across various land-use systems and (2) to develop MDS of soil indicators and compare soil quality indexing approaches to assess SQ under tree-based LUSs.

2 Materials and methods

2.1 Description of the study area

The study was carried out at the research farm, Gandhi Krishi Vigyana Kendra, University of Agricultural Sciences (UAS), Bengaluru, Karnataka, India (Latitude: 13° 05′ North, Longitude: 77° 34′ East and Altitude: 924 msL). The mean annual rainfall of the study region is 920 mm, with a maximum temperature of 29.6°C and a minimum temperature of 18.2°C. The climate of the study region is semi-arid. As per USDA classification, soils are classified as fine, kaolinitic, isohyperthermic, Typic Kandiustalf. The soil texture varied from sandy clay to sandy clay loam. Eight prevalent land-use systems were considered to study their long-term influence on soil characteristics and SQ.

Among the eight different and distinct LUSs studied, seven were tree-based LUSs *viz.*, natural forest, tree plantations of *Tectona grandis, Terminalia bellirica, Swietenia macrophylla, Artocarpus hirsutus*, *Melia dubia*-based agroforestry system (*Melia dubia*-finger millet), horticulture system (*Mangifera indica*) and one agriculture based LUS (finger millet) were considered for the study. These land-use systems (LUSs) were studied under similar climatic conditions with the respective crops for more than 30 years, except for the agroforestry system (around 10 years). The experimental setup provides an unique opportunity to understand the long-term influence of LUSs and management on SQ under disturbed and undisturbed conditions. The forest in the study is classified as a dry deciduous (Champion and Seth, 1968). The tree plantations (*Tectona grandis, Terminalia bellirica, Swietenia macrophylla,* and *Artocarpus hirsutus*) were established in 1986 with a spacing of 2 m × 2 m. The *Melia dubia* – finger millet-based agroforestry system was established 2010 at a spacing of 8 m × 5 m, and mango was planted at a spacing of 10 m × 10 m between 1974 and 1977. Agricultural land was under cultivation of finger millet (*Eleusine coracana*) continuously from 1974 onwards. Area under different land use systems were 1,500, 1,280, 1,600, 640 and 2,000 m^2 for tree plantations, agroforestry, mango, finger millet and natural forest, respectively.

2.2 Soil samples collection and analysis

Representative soil samples from eight different LUSs were collected from 0 to 0.6 m depth following standard protocols using motorised auger. In each land use system, soil samples were collected from three random locations and in each location, soils were collected from three different depths (0–20 cm, 20–40 cm and 40–60 cm). The average value of the three depths was considered in this study. The representative soil sample collected was divided into two subsets. One subset of the sample was air-dried and passed through a 2 mm sieve. The samples were stored in a moisture-free environment for further analysis. The second subset of the sample was placed in refrigerated conditions and utilized to determine the biological properties of the soil.

The physicochemical and biological properties of soil samples were determined using standard analytical procedures. The soil pH and electrical conductivity (EC) were measured using a pH meter and a conductivity meter in 1:2 soil-to-water ratio (Jackson, 2005). The soil organic carbon (SOC) was estimated using the wet digestion method (Jackson, 1967). The soil available nitrogen (N), phosphorus (P), and potassium (K) were determined by the alkaline potassium permanganate distillation (Subbiah and Asija, 1956), Bray's method (Bray and Kurtz, 1945) and ammonium acetate extractant method (Jackson, 2005), respectively. Soil available calcium, magnesium, sulfur, iron, zinc, copper, and manganese were determined using inductively coupled plasma optical emission spectrometry (ICP-OES) (Spectra Genesis, Germany manufacture). The Keen Raczkowski cup method was used to determine the pore space and maximum water holding capacity (MWHC) (Piper, 1966). According to the established protocol, soil dehydrogenase activity (DHA) was measured by converting 2, 3, and 5 triphenyl tetrazolium chloride (TTC) to triphenyl formazan (TPF) (Tabatabai, 1994). Acid phosphatase activity (AcidPhos) was measured using the p-nitrophenyl phosphate technique (Tabatabai and Bremner, 1969). Soil microbial biomass carbon (SMBC) was measured by chloroform fumigation and incubation method (Carter, 1991).

2.3 Soil quality index (SQI)

SQ is assessed in three steps (Andrews et al., 2002): selecting the minimum data set (MDS) using PCA and correlation, scoring soil indicators, and integrating scores to develop SQI (Figure 1). The variables with significant differences ($p < 0.05$) between LUSs were selected for PCA and MDS selection. The PCA was performed to analyze the relationship between these indicators using the varimax rotation technique. The PCs that explained at least 5% of the variation in the data and had eigenvalues greater than one were considered for indicator selection (Brejda et al., 2000).

In each PC, indicators with weighted loading values within 10% of the highest weighted loading were chosen to screen the MDS regardless of sign (Rezaei et al., 2006). A multivariate correlation was utilized to eliminate data redundancy when multiple factors were retained within a single PC. Among the highly-correlated variables (>0.60), one with higher values is only considered for MDS. Each highly weighted variable was considered significant for the MDS when they were not correlated.

For the SQI computation each observation of the MDS indicator was normalized. The normalized indicator value is referred as the "indicator score" (S_i). Both linear (S_L) and non-linear (S_{NL}) scoring functions were employed to compute S_i, so that the indicator values ranged between 0 and 1 (Andrews et al., 2002). In both methods, each indicator was categorized as "more is better," "less is better," or "optimum is better." For "optimum is better," indicator observations were scored as "more is better" up to the threshold level and then scored as "less is better." Linear normalization (S_L) was performed using the maximum (X_{max}) and minimum (X_{min}) for each soil indicator (X) (Eqs 1 and 2).

$$S_L = \frac{X}{X_{max}} \quad (1)$$

$$S_L = \frac{X_{min}}{X} \quad (2)$$

Non-linear scores (S_{NL}) were calculated using the average indicator value (X_0) (Eq. 3)

$$S_{NL} = 1 / \left(1 + \left(\frac{X}{X_o}\right)^b\right) \quad (3)$$

Where, b is the slope assumed to be −10.5 for the positive function and +10.5 for negative function (Sinha et al., 2009; Zhang et al., 2011).

After assigning scores to each indicator, the weight was calculated using PCA's output. To compute the weight factor for each soil indicator in a PC, the percent variation explained by the PC with the highest loading was divided by the total variation explained by all the PCs with an eigenvalue greater than 1 (Bhardwaj et al., 2011; Singh et al. 2014). The SQI is computed by multiplying each indicator's value by its weight and integrating the result (Eq. 4).

$$SQI = \sum_{i=1}^{n} W_i S_i \quad (4)$$

In addition, the following equations were utilised to compute the additive SQI (Eq. 5) (Andrews et al., 2002)

$$SQI = \sum_{i=1}^{n} Si / n \quad (5)$$

Where, W_i is the indicator's PCA-based weight, S_i is the indicator's score, and n is the number of indicators. So, in the present study, four SQIs were developed.

2.4 Sensitivity analysis

The following equation (Eq. 6) (Masto et al., 2008) was used to compute the sensitivity of the SQI for detecting the effects of land use change on SQ

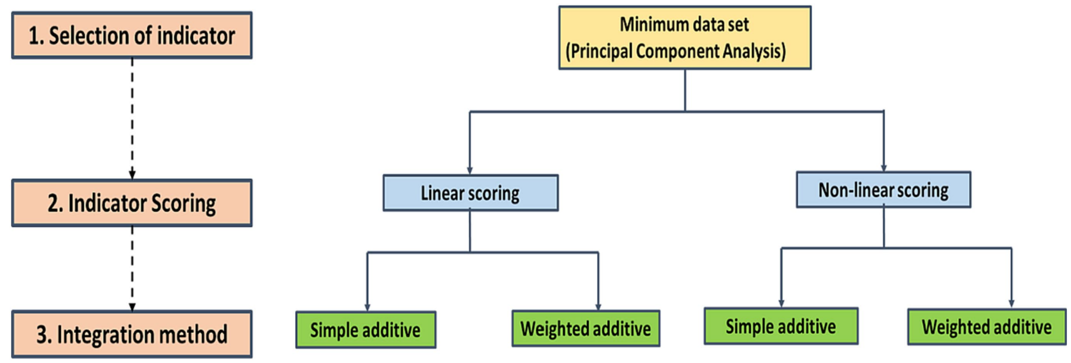

FIGURE 1
Flow diagram for calculating the SQI.

$$\text{Sensitivity}\,(S) = SQI_{max} \,/\, SQI_{min} \qquad (6)$$

Where, SQI_{max} represents the maximum SQI and SQI_{min} represents the minimum SQIs observed under each indexing procedure.

2.5 Data analysis

The statistical analysis of the data pertaining to various soil attributes was conducted using R software version 4.2.2, employing a randomized block design (RBD). Means of the soil properties of different LUSs were compared by using the Tukey HSD procedure (Steel and Torrie, 1960). Pearson's correlation coefficient determined the strength of SQ properties. The PCA was carried out using Statistical software SPSS 20.0 and the results were further used to develop the MDS by PCA for SQI development. Descriptive statistics and one-way analysis of variance (ANOVA) were applied to the SQI under different land uses. A radar plot presents the percentage contribution of each indicator to the SQI in different LUSs.

3 Results and discussion

3.1 Effect of land use systems on soil indicators

3.1.1 Soil chemical properties

The soil pH of natural forest (6.73) and *S. macrophylla* (6.54) was neutral, whereas that of agriculture and agroforestry soils was acidic (4.93 and 5.03, respectively) (Table 1). The soil pH values of other tree-based systems varied between 5.03 and 6.24. The addition of litter in tree-based systems has influenced the soil pH, which aligns with many previous reports (Tang and Yu, 1999; Marschner and Noble, 2000; Xu et al., 2006; Rukshana et al., 2011). It can also be observed that as the tree-based LUSs age, the soil pH is becoming more neutral, which is evident from the order Agroforestry (5.03) < *M. indica* (5.83) < Tree plantation (6.06) < Natural forest (6.73). Hong et al. (2018) stated that afforestation reduces pH in relatively alkaline soil and can also increase in relatively acidic soil leading to neutralization over long durations(Hong et al., 2018). This might be due to the creation of an overall balance of the hydrogen ions generated in the soil during the nutrient cycle and various other processes (litter decomposition, microbial enzyme activities, root exudates, etc.) that occur in the soil ecosystem (De Schrijver et al., 2012; Rukshana et al., 2014). Natural forests recorded significantly higher EC levels (0.09 dS m^{-1}) than other LUS (Table 1). This may be caused by the weathering and decomposition of litter, which results in the enrichment of soil minerals by basic salts. Previous studies (Verma et al., 2001; Alam et al., 2018) have reported a higher EC in tree-based systems than in arable land.

The study revealed that the different LUSs significantly affected soil organic carbon (SOC) levels. The SOC was higher under natural forests (0.98%) and lower in agriculture systems (0.36%) (Table 1). The findings are consistent with prior research studies (Pal et al., 2012; Singh and Sharma, 2012; Nanganoa et al., 2019; Tesfahunegn and Gebru, 2020). The tree-based LUSs are associated with increased SOC levels, which can be attributed to the incorporation of varying quantities of litter and roots, and differential rates of organic matter breakdown added by different tree species. Removing crop residues from cultivated land and frequent soil tillage may reduce SOC. Depleting SOC may decrease soil fertility, land degradation, and potential desertification.

Higher N was recorded in the agriculture system, while P and K was highest under agroforestry (Table 1). The increased availability of N, P, and K in managed agricultural system and agroforestry may be attributed to the consistent and frequent additions of synthetic fertilizers, whereas, in natural forest and tree plantations, there were no such additions. Among the unmanaged tree-based systems, the highest N, P, and K were recorded under natural forests, stating that diversity in litter quality also affects the soil nutrient availability compared to monoculture.

Higher Ca and Mg was recorded in natural forest (Table 1). Earlier studies have reported that natural forests have a higher concentration of exchangeable bases (Ca, Mg) in their soil than other LUSs (Muche et al., 2015; Tesfahunegn and Gebru, 2020). The higher Ca and Mg content in tree-based systems can be ascribed to the addition of a larger quantity of litter and addition of substantial amounts of organic matter and nutrients to the soil. Exchangeable bases vary due to leaching losses, a low concentration in the parent rock, and clay mineral content. According to Muche et al. (2015), the continual cultivation and use of inorganic fertilizers resulted in the depletion of exchangeable Ca and Mg.

TABLE 1 Soil physicochemical and biological properties.

Soil property	Land use systems							
	T. grandis	*T. bellirica*	*S. macrophylla*	*A. hirsutus*	Natural forest	*M. indica*	Agriculture	Agroforestry
pH	$5.70^{bc\$}$	5.76^{bc}	6.54^{de}	6.24^{cde}	6.73^{e}	5.83^{cd}	4.93^{a}	5.03^{ab}
EC	0.07^{a}	0.08^{ab}	0.08^{ab}	0.07^{ab}	0.09^{b}	0.06^{a}	0.06^{a}	0.08^{ab}
OC	0.56^{bc}	0.50^{abc}	0.64^{c}	0.40^{ab}	0.98^{d}	0.37^{a}	0.36^{a}	0.55^{bc}
N	156.79^{ab}	163.84^{b}	208.52^{c}	148.32^{a}	223.4^{cd}	147.30^{a}	261.75^{e}	237.66^{d}
P	15.47^{abc}	12.65^{ab}	13.59^{abc}	11.14^{a}	17.30^{bc}	15.19^{abc}	18.98^{c}	19.06^{c}
K	127.93^{a}	134.04^{a}	137.73^{ab}	131.32^{a}	153.87^{b}	128.35^{a}	153.96^{b}	191.73^{c}
Ca	2.56^{ab}	2.15^{a}	2.65^{ab}	2.57^{ab}	3.08^{b}	2.30^{ab}	2.14^{a}	2.47^{ab}
Mg	0.46^{abc}	0.52^{bcd}	0.45^{ab}	0.53^{bcd}	0.73^{e}	0.34^{a}	0.62^{cde}	0.68^{de}
Zn	0.68^{b}	0.90^{bc}	1.16^{cd}	0.80^{bc}	1.34^{d}	0.22^{a}	0.18^{a}	0.70^{b}
Fe	10.76^{a}	14.07^{ab}	15.90^{ab}	18.15^{b}	12.31^{ab}	10.49^{a}	16.22^{ab}	13.75^{ab}
Cu	1.17^{abc}	1.46^{bc}	0.99^{abc}	1.54^{c}	1.43^{bc}	0.74^{a}	0.85^{ab}	1.10^{abc}
Mn	24.90^{ab}	29.99^{ab}	23.32^{ab}	28.41^{ab}	36.34^{b}	22.28^{a}	25.55^{ab}	27.47^{ab}
DHA	6.38^{a}	8.08^{a}	17.54^{a}	6.96^{a}	40.44^{b}	3.10^{a}	1.61^{a}	5.58^{a}
AcidPhos	123.40^{bc}	108.6^{abc}	77.96^{a}	93.28^{ab}	122.42^{bc}	73.71^{a}	123.02^{bc}	142.53^{c}
SMBC	334.54^{de}	348.12^{e}	364.05^{e}	316.38^{cd}	429.38^{f}	263.28^{ab}	247.85^{a}	292.30^{bc}
MWHC	28.82^{abc}	29.4^{bc}	30.65^{bc}	26.16^{ab}	31.80^{c}	25.54^{ab}	23.76^{a}	28.05^{abc}
Porespace	40.24^{ab}	41.15^{b}	42.33^{b}	37.53^{ab}	41.99^{b}	36.85^{ab}	34.85^{a}	39.5^{ab}

[$] in a row values followed by similar letter indicates non-significance.

Higher Zn content was recorded in natural forest (1.34 ppm), followed by *S. macrophylla* (1.16 ppm), and it was least in agriculture soils (0.18 ppm), which is on par with the horticulture system (0.22 ppm) (Table 1). The highest concentration of iron was recorded in *A. hirsutus* (18.15 ppm), which was on par with agriculture, *S. macrophylla* and *T. bellirica,* while the least was recorded in *M.indica* (10.49 ppm). Cu concentration was higher in *A. hirsutus* tree plantations (1.54 ppm), which was on par with *T. bellirica,* natural forest, *T. grandis,* agroforestry, and *S. macrophylla* while the *M.indica* (0.74 ppm) had the lowest. The highest concentration of Mn was recorded in natural forests (36.34 ppm), lowest was recorded in *M.indica* (22.28 ppm). The variability in micronutrient content among different tree species can be attributed to variations in concentration, litter decomposition rate, the quantity of litter added, and soil organic matter build-up (Dhaliwal et al., 2019).

3.1.2 Soil biological properties

Higher DHA was recorded in natural forest (40.44 μg TPF g^{-1} soil 24 h^{-1}) while agriculture soil (1.61 μg TPF g^{-1} soil 24 h^{-1}) had the least (Table 1). Higher DHA in the natural forest may be attributable to greater substrate availability and higher SOC levels. Błońska et al. (2017) and Yu et al. (2012) also found higher DHA in natural forest. Additional litter biomass, dead root cells, and rhizosphere secretions may boost carbon, nutrient and higher rhizospheric microbial activity (Uthappa et al., 2015; Woźniak et al., 2022). There was a considerable difference in DHA between the tree-based LUSs. Cultivated soils generally have less organic matter, weaker structure, and fewer microbes.

Agroforestrty exhibited higher AcidPhos activity (142.53 μg PNP g^{-1} soil h^{-1}), similar to that of agriculture, *T. grandis, T.bellirica,* and natural forest, and significantly lower phosphatase activity was recorded in *M.indica* (73.21 μg PNP g^{-1} soil h^{-1}) which was comparable to *S. macrophylla, T.bellirica* and *A.hirsutus* (Table 1). The regulation of phosphorus cycling in soil, especially in soils deficient in phosphorus, is significantly influenced by phosphatase activity (Janes-Bassett et al., 2022). Phosphatase activity is associated with SOM, P, and N availability. The highest AcidPhos activity in agroforestry might have increased organic-P hydrolysis into inorganic-P, increasing the available P (Radersma and Grierson, 2004).

The SMBC was the highest in natural forest (429.38 μg g^{-1}), whereas agriculture system (247.85 μg g^{-1}) and *M. indica* (263.28 μg g^{-1}) had the least values (Table 1). The difference in SMBC amongst land uses is due to SOC content, management of the LUS, litter quality, and quantity (Lepcha and Devi, 2020). Continuous and higher organic matter deposition via leaf litter resulted in higher SMBC in natural forest. A strong positive association ($r = 0.857$) was observed between SOC and SMBC. The results are consistent with previously reported studies (Chen et al., 2017; Padalia et al., 2018; Lepcha and Devi, 2020). The imbalanced use of fertilizers and application of fertilizers, particularly N, resulted in a considerable decline in SMBC (Lu et al., 2011; Qiu et al., 2016).

3.1.3 Soil physical properties

Higher maximum water holding capacity was recorded in natural forest (31.80%), which was on par with *S. macrophylla, T. bellirica, T. grandis* and agroforestry while the agriculture (23.76%) was least, which was on par with *M.indica, T. grandis* and *A. hirsutus* (Table 1). *S. macrophylla* recorded the highest pore space (42.33%), which was on par with natural forest (41.99%) and *T. bellirica* (41.15%), and lowest was recorded in agriculture (34.85%) (Table 1). Trees maintain soil structure and minimize soil crust formation by adding organic matter, promoting soil macro and micropores, and retaining moisture. Agricultural soils may have become more compact due to cultivation practices and minimal organic manure additions. The soil pore space is inversely related to soil bulk density. Bizuhoraho et al. (2018) and Zhang et al. (2022) found greater soil porosity in tree-based land use than in cultivated land. Soil organic matter and tree root systems accelerate soil aggregate formation (Jiao et al., 2020) and improve soil structure (Wang et al., 2018).

3.2 Principal component analysis (PCA)

The soil properties that exhibited significant variation among the LUSs were chosen for PCA. The four PCs with an eigenvalue greater than one were selected, which explained 80.53% of the cumulative variance (Table 2). Varimax rotation was performed to optimally distribute the variance in the selected four PCs. PC1 with an eigenvalue of 5.13, explained a variation of about 30.16%. It included DHA with a positive factor loading of 0.918 and Ca (0.858). The PC2 explained a variation of 22.61% and an eigenvalue of 3.84. It included K (0.884), AcidPhos (0.829), N (0.822), and Mg (0.798) with positive factor loading. The PC3 explained 18.80% of the variation with an eigenvalue of 3.20. In this PC, pore space has the highest factor loading (0.864), followed by MWHC (0.846). The PC4 had the highest factor loading of 0.891, contributed by Fe, with an eigenvalue of 1.52 and a variation of 8.96%.

TABLE 2 Soil quality index evaluation using PCA.

Factor	Loading in principal components			
	PC1	PC2	PC3	PC4
PH	0.806	−0.486	0.236	0.078
EC	0.748	0.120	0.290	0.135
OC	0.779	0.300	0.443	−0.050
N	0.074	0.822	−0.137	0.064
P	0.119	0.779	−0.474	−0.222
K	0.022	0.884	−0.001	0.015
Ca	0.858	0.098	0.030	−0.012
Mg	0.332	0.798	0.104	0.288
Zn	0.727	−0.013	0.555	0.259
Fe	−0.080	−0.007	−0.144	0.891
Cu	0.232	−0.072	0.538	0.383
Mn	0.325	0.269	0.263	0.567
MWHC	0.444	0.020	0.846	−0.096
Porespace	0.352	−0.036	0.864	−0.113
DHA	0.918	0.154	0.216	0.016
AcidPhos	−0.132	0.829	0.254	0.015
SMBC	0.754	−0.042	0.586	0.093
Eigenvalue	5.13	3.84	3.20	1.52
Variability (%)	30.16	22.61	18.80	8.96
Cumulative variability (%)	30.16	52.77	71.57	80.53

3.3 Selection of minimum dataset (MDS)

From each PC, indicators within 10% of the highest factor loading were selected for the MDS (Rezaei et al., 2006). If a PC included more than one soil indicator, the correlation coefficient ($r < 0.60$) was utilized to determine whether variables were redundant and should be removed (Legaz et al., 2017) (Figure 2). In the first PC, two indicators were within 10% of the highest factor loading (Table 2). From the PC1, the two indicators were DHA and Ca, with a correlation coefficient of 0.71. Since both are important variable and represents two different aspects of soil, i.e., biological and chemical properties (major secondary nutrients), both were considered.

In PC2, K, AcidPhos, N, and Mg were within 10% of the highest factor loading. The K was positively correlated with N ($r = 0.71$), AcidPhos ($r = 0.63$), and Mg (0.68) (Figure 2). Since the soils of semi-arid tropics have low fertility, particularly N, it was considered essential and retained from a soil fertility point of view. It was also considered because the study area's soils were poor in N and it is a limiting nutrient for growth and plant functions. The AcidPhos represents the P availability in the soil, so AcidPhos was also considered from PC2.

In PC3, pore space and MWHC were within 10% of the highest factor loading. This PC focuses on soil physical parameters based on loading factor pattern and size. Pore space and MWHC were highly correlated ($r = 0.97$) (Figure 2). Therefore, only pore space was selected to represent the PC3 for MDS. In PC4, Fe was selected, representing the soil's available micronutrients. Overall, the MDS comprised of the indicators chosen as K, N, Ca, DHA, AcidPhos, pore space, and Fe, which represented the soil's physical, chemical, and biological properties.

In the current study, DHA and AcidPhos were chosen as indicators of MDS among various soil biological properties. Due to their higher sensitivity, soil enzyme activity has often been used in forest soils to evaluate the consequences of land use change (Lucas-Borja et al., 2010; Bini et al., 2013). DHA was considered one of the important SQ indicator (Mandal et al., 2011; Biswas et al., 2017; Klimkowicz-Pawlas et al., 2019). The DHA reflects soil organic matter quality, nutrient availability, microbial activity related to N cycling, and organic compound oxidation (Bünemann et al., 2018), making it an important indicator of SQ (Chaudhury et al., 2005). Phosphatase activity plays a crucial role in the regulation and maintenance of P cycling in the soil, particularly in phosphorus-deficient soils (Janes-Bassett et al., 2022). According to Lemanowicz (2018) phosphatase activity can indicate soil biological and organic phosphorus mineralization capacity. Mahajan et al. (2021) also identified acid phosphatase as one of the MDS in controlling the SQ.

Among the macro nutrients N, K and Ca were selected for MDS. N is an important nutrient for optimal plant growth and development and it has been selected as MDS to evaluate the SQ by Mahajan et al. (2021). It plays an essential role in several vital activities, including growth, the increase of leaf area, and biomass production (Anas et al., 2020). A lack of N can inhibit plant growth and development. Adequate N supply improves above-ground biomass, grain yields, root development (volume, area, diameter, length, mass), nutrient uptake, nutritional balance, and dry mass production (Good et al., 2004; Diaz et al., 2006). K is also frequently used as an SQ indicator in earlier studies (Bünemann et al., 2018; Shi et al., 2021; Maini et al., 2022; Brar et al., 2023). While evaluating SQ under different land use systems Vashisht et al. (2020) and Shao et al. (2020)

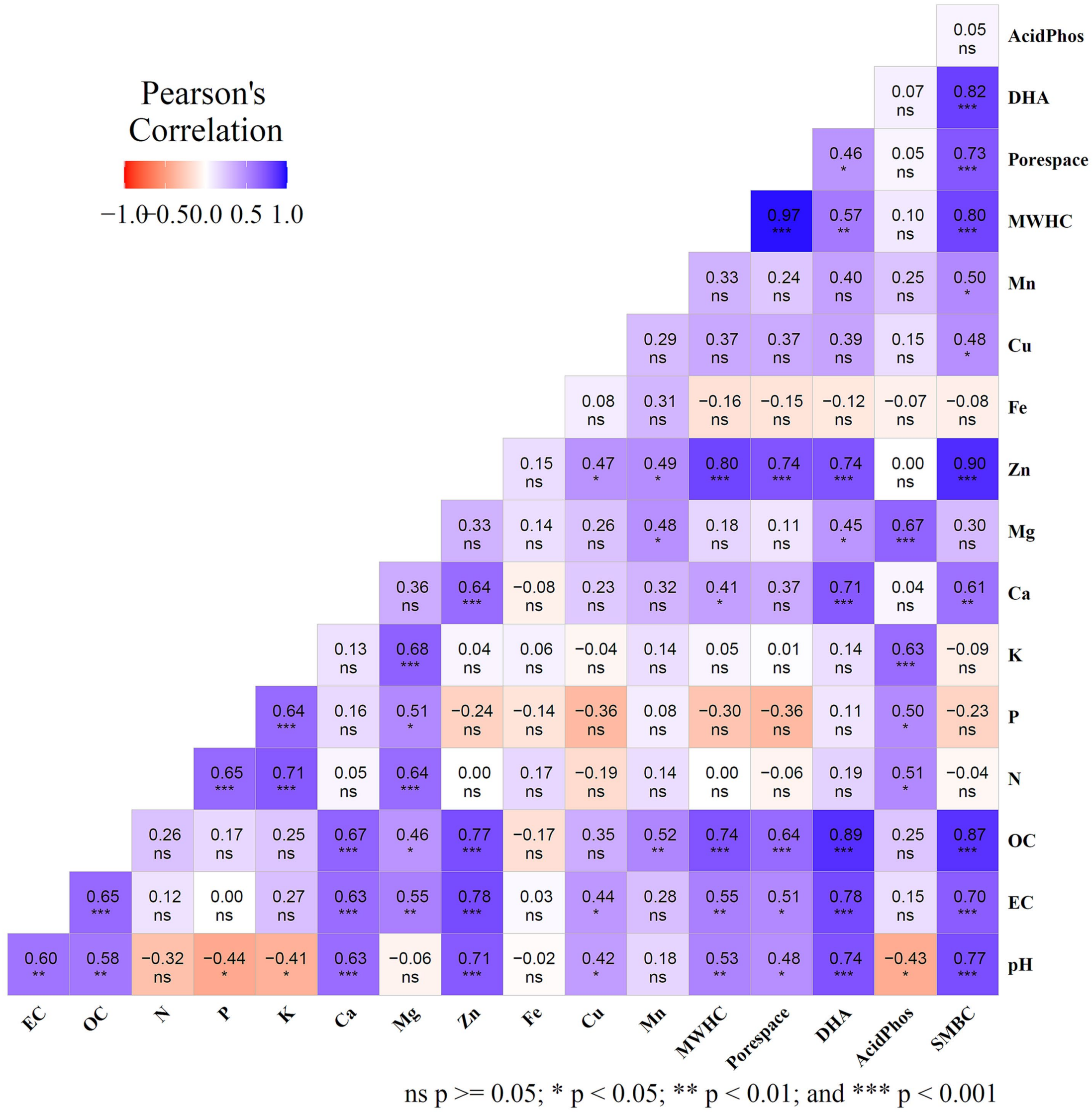

FIGURE 2
Correlation matrix of soil physicochemical and biological properties.

also identified K as one of the MDS. The K is vital in plants' osmotic regulations that help regulate moisture stress. Another study concluded that available K and Fe are the most important parameters to assess soil health (Idowu et al., 2008). According to Phillip and Martin, 2003, Ca is a secondary macronutrient essential to plants, and its concentrations in the shoot can range from 0.1 to 5% dry weight. It functions as a secondary messenger and structural component of cell walls and membranes (Phillip and Martin, 2003). Ca contributes to soil fertility through clay flocculation and good aeration (Norton, 2013) and by improving the physical condition of soils. Calcium-rich soils are often more friable and have better water infiltration capabilities. Studies in different tree based systems also identified Ca as MDS while evaluating the SQ (Mulyono et al., 2019; Leul et al., 2023). Tesfahunegn (2014) included Fe as an important SQ indicator in assessing SQ under different LUSs. Through its involvement in the electron transport chain, iron serves as essential for practically all living species since it is involved in many physiological, biochemical, and metabolic activities (Gyana and Sahoo, 2015). Soil porosity is widely recognized as the best indicator of SQ. Characterization of the pore system helps comprehend water and air retention and movement in the soil, evaluate LUS effects, and measure soil deterioration such as compaction and crusting (Pagliai and Vignozzi, 2006). Cardoso et al. (2013) stated that soil porosity is important parameters for assessing SQ status. The other soil properties had low factor loading; thus, these were excluded from the MDS. The "more is better" approach was followed for DHA, AcidPhos, N, K, and *Ca.* For Fe and pore space "optimum is better" approach was followed.

3.4 Soil quality indexing under different land-use systems

The SQI was developed by transforming soil properties into scores using linear and non-linear scoring methods, and the weights calculated

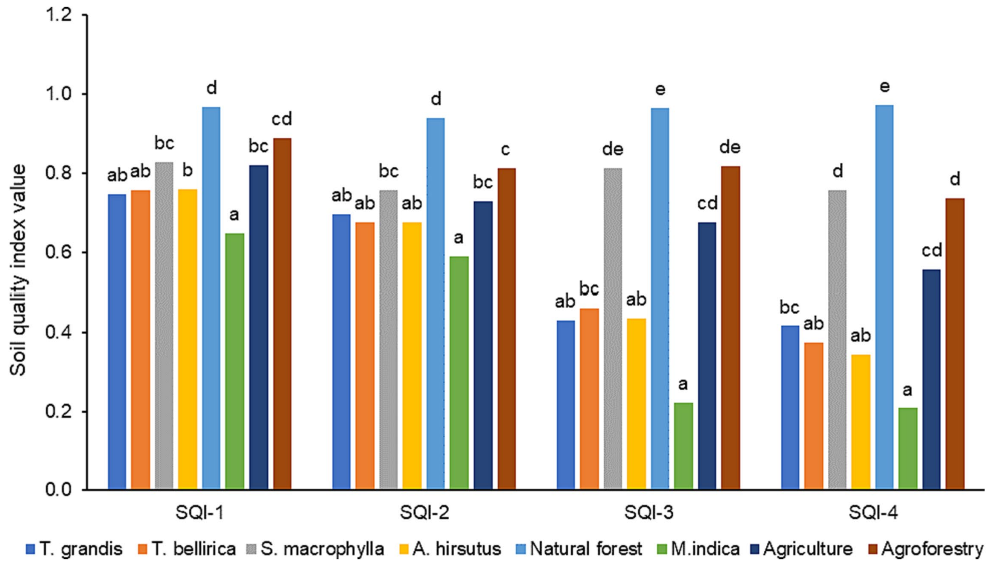

FIGURE 3
Effect of different land use systems on the soil quality index developed using different indexing method.

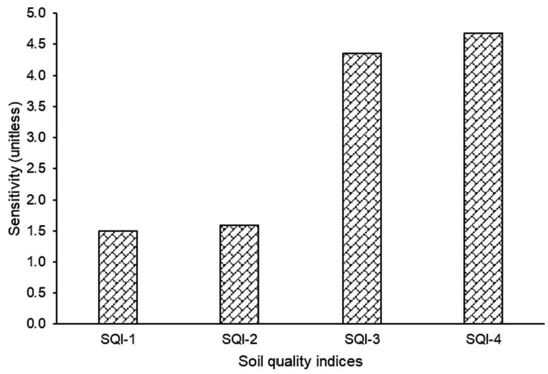

FIGURE 4
Sensitivity values of different soil quality indices developed using different indexing methods.

from PCA are presented in Figure 3. All four SQI: linear additive (SQI-1), linear weighted (SQI-2), non-linear additive (SQI-3), non-linear weighted (SQI-4) were able to identify SQ changes in different LUS, implying that they could be used to monitor SQ. However, a sensitivity test revealed the differences among the SQIs (Figure 4). The SQI-4 had the highest sensitivity to detect SQ changes under different LUSs, while the least sensitive was SQI-1. The order of sensitivity of SQIs tested was SQI-4 > SQI-3 > SQI-2 > SQI-1. Thus, SQI-4 derived through a non-linear weighted method could be successfully used to assess SQ, as it is the most sensitive index for assessing different agroecosystems (Sinha et al., 2014) and represents the system function more accurately than the linear technique (Andrews et al., 2002; Mahajan et al., 2020).

Radar plots illustrate how MDS soil indicators contributed to SQI in various scoring methodologies (Figure 5). In the linear additive method, all the selected MDS indicators had equal contributions except for DHA. In the linear weighted method, all the parameters had equal contributions except for Fe and DHA. In both the non-linear additive and weighted methods, the contribution of all the parameters was significantly different. It also agrees with the sensitivity analysis (Figure 4), where non-linear scoring methods were more sensitive than linear scoring methods.

The SQI calculated for different land uses using the non-linear scoring weighted method was significantly higher under natural forest (0.973), followed by *S. macrophylla* (0.756) and agroforestry (0.737). Significantly lowest SQI was recorded in *M. indica* (0.208). Based on the SQI, the order of the systems studied was natural forest (0.973) > *S. macrophylla* (0.756) > agroforestry (0.737) > agriculture (0.556) > *T. grandis* (0.416) > *T. bellirica* (0.373) > *A. hirsutus* (0.343) > *M. indica* (0.208). The natural forest soils are rich in organic matter, harbours rich soil biodiversity (Bardgett and Van Der Putten, 2014; Uthappa, 2021) and have high biotic activity (Osman and Osman, 2013), which has positive effects on soil physicochemical and biological properties as reflected by the highest SQI. Chandel et al. (2018) found that the SQI was the highest in forest ecosystems, followed by grassland, horticulture, cultivated, and bare land. They also stated that the improved SQI in forested areas is due to the higher organic matter content of the soil. According to Tesfahunegn (2014) natural forest areas have a better SQ than uncultivated marginal land systems and forests maintained higher SQI values than agroforestry and agriculture (Mandal et al., 2013). The *S. macrophylla* based tree plantation and agroforestry system, has emerged as second best LUSs. Practising agroforestry can be viable and sustainable option to maintain soil health (Fahad et al., 2022; Jinger et al., 2023). The monoculture of forest trees, horticulture trees, and agriculture proved to be the third best option compared to natural and agroforestry systems. It is worth mentioning that except in agriculture and agroforestry system, no other systems received fertilizers or soil amendments. The trees (*S. macrophylla, A. hirsutus, T. bellirica and T. grandis*) were also planted at a very closer spacing (2 × 2 m) which would have led to exhaustion of soil nutrients.

The results of the present investigation revealed that the converting natural forests into different LUSs as tree plantations, horticulture, agroforestry and agriculture deteriorates the SQ. However, increasing population and demographic changes exert tremendous pressure on

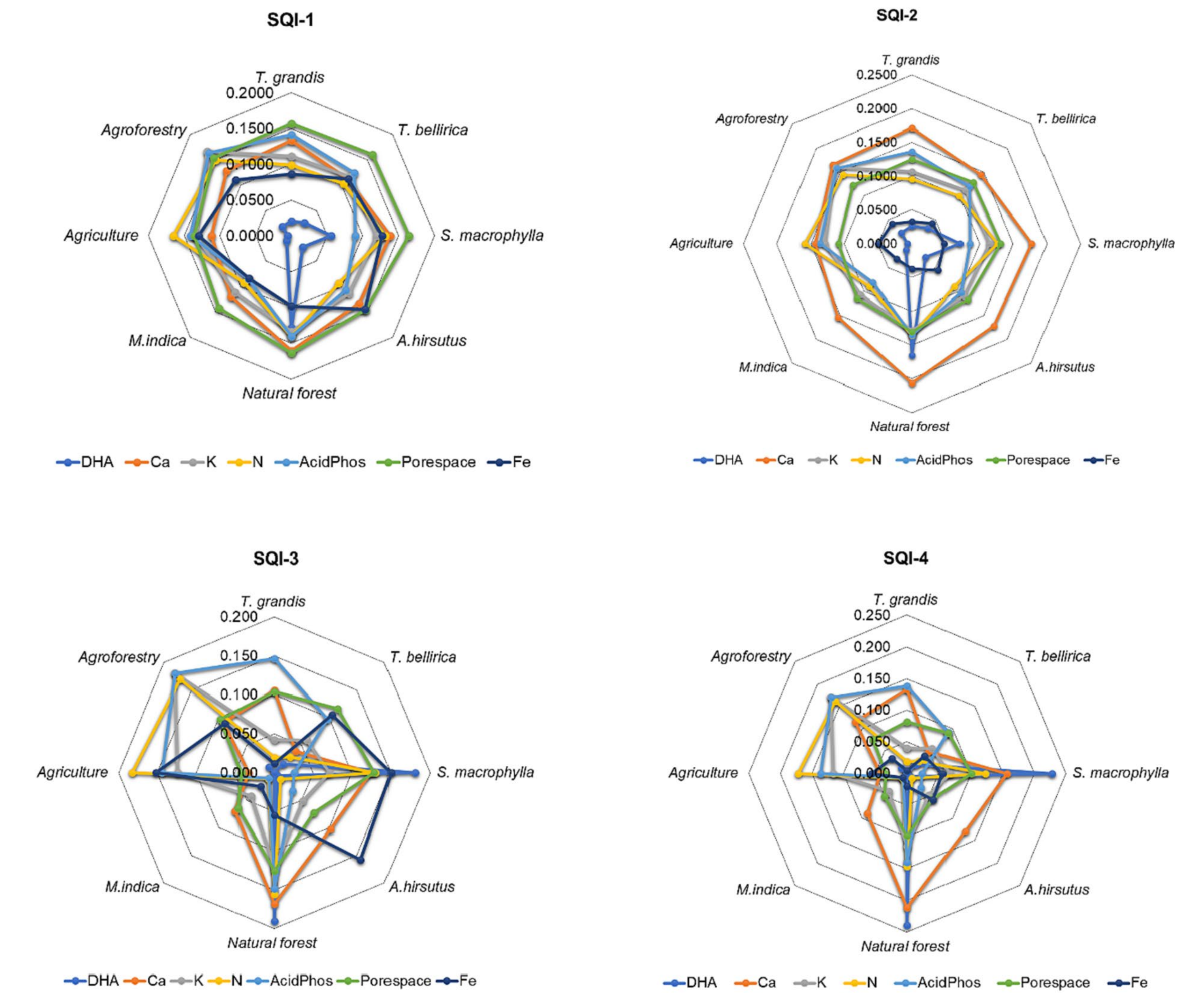

FIGURE 5
Radar diagrams of the contribution of selected indicators of the minimum dataset to soil quality indices developed using different indexing method under different land uses.

existing arable land and forest for 5Fs (food, fodder, fuelwood, fibre, fertilizer). Thus, sustainable utilization of natural forests and its conversion into different appropriate LUSs demands scientific approaches to quantify the effects on natural resources, particularly soils. The present study identified a minimum number of soil indicators as MDS and a non-linear weighted SQ indexing approach (SQI-4) as a robust method to detect the changes in the SQ. The method reduces the cost and time of sampling, analysis and enables rapid estimation of SQ. Further, the output of this study could be of immense significance to designing appropriate land management practices for sustainable utilization of converted land uses.

4 Conclusion

The research findings indicate that the LUS has a substantial long-term impact on the physical, chemical, and biological characteristics of the soil in semi-arid climatic conditions.An SQI comprising of soil indicators *viz.*, DHA, AcidPhos, N, K, Ca, porosity, and Fe was developed to assess SQ changes under different LUSs. Of the four SQI approaches, the non-linear weighted approach was the best to assess SQ. In each of the four SQIs, the natural forest emerged as the best land use system, signifying that it is the most SQ-compliant LUS. The conversion of natural forests into other alternative LUSs decreased the SQ, indicating soil deterioration at varying scales. Further, intensive cultivation and unmanaged tree plantations may reduce SQ. SQ assessment using MDS indicators could also reduce the time and cost under similar agro-climatic situations. Therefore, the approach of the SQI using MDS in the current study could be helpful for proper scientific planning and sustainable utilization of natural resources.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AU: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. AD: Conceptualization, Methodology, Supervision, Writing – original draft. BD: Methodology, Software, Writing – review & editing. GM: Writing – review & editing. SC: Software, Writing – review & editing. DJ: Methodology, Writing – review & editing. PJ: Writing – review & editing. PK: Writing – review & editing. AK: Formal analysis, Investigation, Methodology, Writing – review & editing. RK: Methodology, Supervision, Writing – review & editing. NM: Formal analysis, Investigation, Writing – review & editing. CD: Formal analysis, Investigation, Writing – review & editing. IfA: Visualization, Writing – review & editing. SE: Funding acquisition, Writing – review & editing. IbA: Funding acquisition, Writing – review & editing. ME: Funding acquisition, Writing – review & editing. SF: Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Diversity, preference, and conservation priority of woody plant species in coffee agroforestry system in southwest Ethiopia

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The natural forest in southwest Ethiopia is progressively modified to coffee agroforest. To this effect forest composition and diversity is simplified to local preferred coffee shade trees. Woody plant species that are less managed require the conservation priority in coffee agroforest. The study aims at assessing diversity of plant species, investigating local people preference and finally identify woody plants for conservation priority in coffee agroforest in southwest Ethiopia. Data were collected on ecological and ethnoecological information through field assessment and individual interview. Vegetation data were collected from 63 plots distributed across five sites. Ethnoecological data were collected from 96 individuals across five villages living adjacent to the forest through semi-structured interview. The result showed that 48 different woody plant species belonging to 27 families were recorded. Most of the families were represented by single species. The regeneration status of these woody plant species are unsatisfactory or poor. Three species; *Cordia africana*, *Croton macrostachyus*, and *Milletia ferruginea* were accounting for 41 percent of the total number of woody plant species in coffee agroforest. The aggregate relative preference score showed 15 most preferred woody plant species in coffee agroforest. The use value of these species were cited mainly for timber, hanging beehive and beehive making than coffee shade. The findings suggest that 12 woody plants need high conservation priority, 19 species need moderate conservation priority and 17 woody plants need low priority for conservation. The Spearman correlation showed negative correlation between woody plant abundance and conservation priority [r_s (46) = −0.681, p = 000]. The study findings suggest that woody plant conservation priority in coffee agroforest should take into consideration local preference of woody plant species.

KEYWORDS
diversity, ecological, ethnoecology, use value, local preference, coffee shade

1 Introduction

Coffee agroforest is human modified natural forest where the local people progressively manage wild coffee inside the natural forest leading to the development of coffee agroforest (Senbeta and Denich, 2006; Schmitt et al., 2010; Aerts et al., 2011; Hundera et al., 2015; Mertens et al., 2018). The experience is more practiced over the last two to three decades in southwest Ethiopia (Cheng et al., 1998; Schmitt et al., 2010; Mertens et al., 2018; Kefalew et al., 2021). Rapid forest cover change assessment has shown 26.1% of the Belete Gera forest is modified to coffee agroforest (Cheng et al., 1998). As forest modification to coffee production continue, coffee agroforest plays an important role in conservation of woody plant species in southwest Ethiopia (Senbeta and Denich, 2006; Hernandez et al., 2013; Hundera et al., 2013; Tadesse et al., 2014; Valencia et al., 2016).

Coffee management intensification simplify forest composition and structure through selective removal of woody plant species (Senbeta and Denich, 2006; Schmitt et al., 2010; Aerts et al., 2011; Hundera et al., 2013; Hwang et al., 2020). A study from Bonga region southwest Ethiopia has shown that coffee management activities roughly remove 30% of the canopy tree species in coffee agroforest (Schmitt et al., 2010). Under large canopy size, light demanding woody plant species take an advantage over shade tolerant species. Likewise continuous coffee management such as weeding and slashing undergrowth plants hamper the regeneration of late successional woody plant species in coffee agroforest (Aerts et al., 2011; Hundera et al., 2013, 2015; Valencia et al., 2016). Moreover, the response of pioneer and late successional woody plants to coffee management intensity resulted in a change of woody plant species composition and structure (Hundera et al., 2015; Valencia et al., 2015; Shumi et al., 2019).

Regeneration status of woody plants indicate the population structure of an individual and woody plant composition of coffee agroforest (Tadese et al., 2021). Seedlings and saplings are the indicators of woody plant regeneration status (Siraji and Balemaly, 2021; Tadese et al., 2021). Woody plant species with poor regeneration or absence of seedling and sapling require effective conservation priority (Teketay et al., 2018; Tadese et al., 2021).

Ecological and sociocultural value determine the local people preference of woody plants (Tabuti et al., 2009; Kalanzi and Nansereko, 2014; Valencia et al., 2015; Tumuhe and Nyamaizi, 2020). A study has shown that locally preferred woody plants are dominant in coffee agroforest (Valencia et al., 2015). The shade value of woody plants are the primary criteria for woody plant management in coffee agroforest in southwest Ethiopia (Albertin and Nair, 2004; Kalanzi and Nansereko, 2014; Ordoñez-Jurado et al., 2021). Despite diversity of woody plant species in coffee agroforest, only a few species are preferred to coffee shade (Soto-Pinto et al., 2007; Muleta et al., 2011; Hundera et al., 2015; Hundera, 2016). Woody plants such as *Millettia ferruginea*, *Albizia* spp., and *Acacia* spp. are the most preferred coffee shade trees in southwest Ethiopia (Muleta et al., 2011).

Some woody plant species in coffee agroforest provide products such as construction materials, fuelwood, medicinal and timber, and heavily utilized (Albertin and Nair, 2004). Although these uses are known, the general picture of how people use these trees is unknown.

Overexploitation of woody plant species obviously lead to the concern of conservation priority for sustainable utilization (Lokonon et al., 2019). Woody plant composition and diversity is manipulated in coffee agroforest due to local people preference for specific uses (Senbeta and Denich, 2006; Valencia et al., 2015, 2016). Effective conservation in coffee agroforest among others requires identifying managed woody plant species and their local uses (Senbeta and Denich, 2006; Tabuti et al., 2009; Valencia et al., 2014).

Coffee management activities and local uses raises the concern for conservation of woody plant species in coffee agroforest in southwest Ethiopia. It is obvious that coffee management activities and local uses hamper woody plant species conservation effort in coffee agroforest (Hundera et al., 2015). Woody plant species conservation should follow the priority for conservation. Nevertheless, there is limited information on woody plants that require priority for conservation in coffee agroforest in southwest Ethiopia. Less known is the local people priority and the status of woody plant species in coffee agroforest. To contribute to this knowledge gap, the study was undertaken with the following objectives; (1) to assess the diversity of woody plant species maintained; (2) to investigate the local preference of woody plant species; (2) identify priority woody plant species for conservation in coffee agroforest in southwest Ethiopia.

2 Materials and methods

2.1 Study area

The study was conducted at Belete forest southwest Ethiopia. Geographically, it is found between 36° 15′ E and 36° 45′E and 7°30′ N and 7°45′N (Figure 1). Belete forest belongs to the moist evergreen Afromontane forest of southwest Ethiopia. The forest is one of a few remnant Afromontane moist evergreen forests in southwest Ethiopia. Belete forest, together with Gera forest, was designated as one of 58 national forest priority areas in Ethiopia in 1989 (Cheng et al., 1998). The study area is characterized by a mosaic of forest, cultivated land and settlements. The most accessible area is managed for coffee production involving planting of wild coffee taken from coffee forest and intensive (under growth removal and canopy reduction) management for coffee agroforest. The forest has been under participatory forest management for the last two decades. The forest is divided into blocks of forest among the forest user groups. Forest is a source of livelihoods for people living in and adjacent to the forest. The present study worked with five forest user groups namely: *Dabbiyee*, *Gurrattii*, Q*artammee*, *Mexxii-Caffee*, and *Sokii* forest user groups. The total number of households within a village are in the hundreds. The dominant ethnic group are the Oromo, most of whom are Muslim with a few Christians. The local people organized into forest user groups and signed an agreement with Oromia Forest and Wildlife Enterprises to be entitled in accessing and using forest resources. Forest resource use pattern of the local people changes with time. Currently, the tradition of forest resources use is dominated by coffee production.

2.2 Data collection and analysis

Both ecological and ethnoecological data were collected (Lucena et al., 2013; Lokonon et al., 2019; Ribeiro et al., 2019; Korach et al., 2020). The data were collected in two steps. First coffee agroforest inventory was carried out to collect ecological data in five sites (*Dabbiyee*, *Gurrattii*, Q*artammee*, *Mexxii-Caffee*, and *Sokii*) and then coffee agroforest owners were interviewed on the use and preference of woody plant species in coffee agroforest. A total of 63 plots (400 m^2) (*Dabbiyee* = *15*, *Gurrattii* = *12*, Q*artammee* = *11*, *Mexxii-Caffee* = *12, Sokii* = *13*) were selected for woody plant species inventory. It covered a total area of 2.52 ha. The plots were laid systematically along the transect in coffee agroforest in each site. Within 20 m × 20 m, all

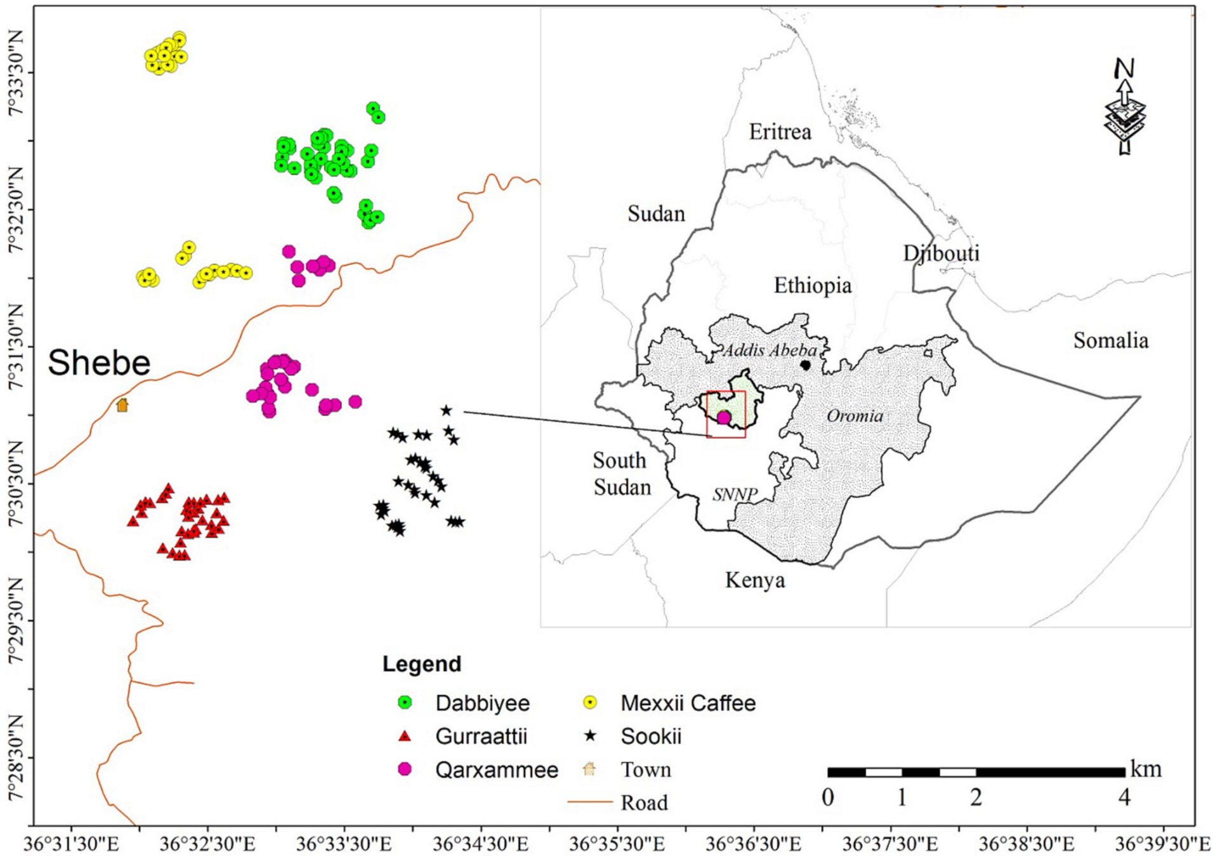

FIGURE 1
Map of Ethiopia with Oromia region, Jimma zone, location of study villages.

woody plant species with diameter at breast height ≥ 10 cm were identified and recorded. The researcher identified woody plant species in the field by their local names with the help of local people and cross-checked using available literature (Bekele-Tesemma, 2007; Eyasu et al., 2020). The specimen of woody plants difficult to identify in the field were collected and taken to lab for further identification with the help of botanist. Plant specimens were deposited at Jimma University Department of Biology. For regeneration assessment, seedlings and saplings were identified, counted and recorded within a sub-plot of 10 m × 10 m and 5 m × 5 m, respectively. All methods were performed in accordance with the relevant guidelines and regulations. Plant identification was done following the flora of Ethiopia and Eritrea.

Ethnoecological data were collected through semi-structured interview. A checklist for an interview was prepared focusing on the use and preference of woody plant species in coffee agroforest. All woody plant species recorded in the field were included in the semi-structured questionnaire. Free listing technique was used to record the use of each woody plants. Coffee owners list as much as they can remember the use of the plant (Martin, 1995). The use of woody plant mentioned by interviewees were grouped into different use categories. Moreover, coffee owners were asked to mention the most preferred coffee shade trees and their management practices. The ethnoecological data were collected from 96 individuals (11 females) (*Dabbiyee = 20*, *Gurrattii = 18*, Q*artammee* = 17, *Mexxii-Caffee = 21*, *Sokii = 20*). The age of interviewees ranges from 20 to 80. Permissions were obtained from Oromia Forest and Wildlife Enterprises, Shabe Sombo district office and the lowest administrative Office (kebele) to undertake the study. All methods were performed in accordance with the relevant guidelines and regulations. The interviewees gave their consent on verbal than written form for an interview. To minimize the bias due to peer interference, an interview was carried out on an individual based on the convenient time and place to interviewee.

Alpha diversity and other indices were computed for diversity assessment using PAST version 4.03 software. Alpha diversity is expressed as the total number species (species richness) in coffee agroforest (Manaye et al., 2021; Marzialetti et al., 2021).

Species richness was computed using the formula:

$$S = \sum ni$$

where ni is the number of species in a coffee agroforest.

Woody plant species preference in coffee agroforest was analyzed using the number of citation given to each woody plant species for the respective use categories. Citation refers the number of use of wood plants the interviewee mentioned (Lucena et al., 2013; Lokonon et al., 2019). Literature has stated that more preferred woody plant species are more cited (Lokonon et al., 2019). Woody plant preference in coffee agroforest was estimated using the equation adopted from Duguma and Hager (2010) as follow:

$$MSc\ spp(x),use(y) = \frac{\sum score\ spp(x),\ use(y)}{n}$$

$$ARPS\ spp(x),use(y) = \frac{MSc\ spp(x),use(y)}{\sum Msc\ spp(all),use(y)} \times 100$$

$$AGRPS\ spp(x),use(y) = \frac{\sum ARPS\ spp(x)}{\sum APRS\ spp(all),use(all)} \times 100$$

Where $MSc\ spp(x),use(y)$ stands for mean citation score of species x for use type y, n stands for the total number of interviewees ($n=96$); $ARPS\ spp(x),use(y)$ stands for the adjusted relative preference score of species x for use type y in % and $AGRPS\ spp(x),use(y)$ stands for the aggregate relative preference score of a species across all types in percentage. Aggregate relative preference score was computed for multiple use and shade value of recorded woody plant species in coffee agroforest.

The woody plant conservation priority (CP) analysis adopted with some modification the technique that was employed by scholars (Dzerefos and Witkowski, 2001; Oliveira et al., 2007; de Albuquerque et al., 2011; Lokonon et al., 2017; Kafoutchoni et al., 2018; Ribeiro et al., 2019; Oliveira et al., 2021). Table 1 portrays the criteria and score employed in the analysis. Woody plant species is calculated using the formula:

$$CP = 0.5(BS) + 0.5(UR)$$

Where CP corresponding to Conservation Priority, BS corresponding to biological score estimated based on relative density (D) as BS = D × 10. The usage risk (UR) is estimated based on management risk and use value (U) as UR = [0.5(H) + 0.5(U)] × 10. Use value is estimated as the average of the sum of the local importance (L) and the diversity of use (V) (Ribeiro et al., 2019). For woody plants that have timber and construction value additional value of 10 points were added as additional usage pressure (Ribeiro et al., 2019). Finally woody plants divided into three categories, category 1 with high priority species for conservation (CP ≥ 85), category 2 with moderate priority species for conservation (60 ≤ CP < 85) and category 3 with low priority for conservation (CP < 60). Spearman correlation was computed to test the relationship between woody plant species preference and conservation priority.

TABLE 1 Criteria and scores used to determine woody plant species conservation priority in coffee agroforest.

Criteria	Score
A. Relative density (D)	
Not recorded- very low (0–1)	10
Low (1 < 3.5)	7
Medium (3.5 < 7)	4
High (≥7)	1
B. Management risk	
Total removal of tree species (i.e., non-coffee shade tree)	10
Thinning or stem reduction of tree species (i.e., retained non-coffee shade trees)	7
Slashing and under growth removal of tree species (i.e., shade secondary use)	4
Branch removal or canopy reduction of tree species (i.e., Shade primary use)	1
C. Local use (L)	
High (quoted by >75% of local informants)	10
Moderately high (cited by 50 ≤ 75% of local informants)	7
Moderately low (cited 25 < 50% of local informants)	4
Very low (quoted <25 < 10% of local informants)	1
D. Diversity of use	
One point is added for each use, maximum 10 points	1–10

3 Results and discussion

3.1 Diversity of woody plant species

Findings on ecological data showed that many woody plant species associated with coffee agroforest in southwest Ethiopia. The result showed that 48 different woody plant species belonging to 27 families were recorded in 63 plots (Table 2). Most of the families were represented by a single species. Only a few family consists of a maximum of four species. Among the recorded woody plants three woody plant species, *Cordia africana, Croton macrostachyus, Milletia ferruginea* were more abundant compared to the other species accounting for 41 percent of the number of woody plants. Forty five woody plants had contributed each less than 5 percent of the total abundance. The lower abundance of many woody plants were the outcome of coffee management that resulted in stem reduction. Muleta et al. (2011) have reported the family Fabaceae dominate coffee agroforest in southwest Ethiopia. Aerts et al. (2011) reported *Croton macrostachyus* and *Milletia ferruginea* dominate coffee agroforest in southwest Ethiopia. This is attributed to the regeneration characteristics of individuals (Aerts et al., 2011). A Study from Dallo Mena district, southeast Ethiopia has reported 10 different tree species in shade grown coffee (Mengistu and Asfaw, 2016). Another study from Jimma area southwest Ethiopia have reported 38 different tree species in coffee agroforest (Worku et al., 2015).

Higher species diversity with Fisher alpha 12 and Shannon Weiner diversity (H) 3.08 were found in coffee agroforest (Table 3). Previous studies categorized Shannon Weiner diversity as high with a value ≥3, medium with a value between 2 and 3, low with a value between 1 and 2, very low with a value <1 (Atsbha et al., 2019; Fentaw et al., 2022). A Shannon Weiner diversity value of 3.08 of the present study belongs to a high diversity category. The individual based rarefaction curve showed the estimated number of species as more number of individuals recorded (Figure 2). The Choa-1 value of 51.5 showed the maximum species richness estimated with more sampling effort (Table 3). Worku et al. (2015) have reported Fisher alpha diversity of 8.53 in coffee agroforest in Yayu southwest Ethiopia. Kewessa et al. (2019) have found a Shannon diversity of 1.74 in coffee agroforest Bale Eco-Region, southeastern Ethiopia. Senbeta and Denich (2006) have reported a Shannon diversity of

TABLE 2 Woody plant species recorded in coffee agroforest.

No	Scientific name	Family	Abundance	Rel. contribution (%)
1	*Alangium chinense*	Alangiaceae	2	0.38
2	*Albizia gummifera*	Fabaceae	26	4.99
3	*Allophylus abyssinicus*	Sapindaceae	2	0.38
4	*Apodytes dimidiata.*	Icacinaceae	5	0.96
5	*Bersama abyssinica*	Melianthaceae	10	1.92
6	*Cassipourea malosana*	Rhizophoraceae	1	0.19
7	*Celtis africana*	Ulmaceae	20	3.84
8	*Chionanthus mildbraedii*	Oleaceae	4	0.77
9	*Clausena anisata*	Rutaceae	4	0.77
10	*Cordia africana*	Boraginiaceae	66	12.67
11	*Croton macrostachyus*	Euphorbiaceae	41	7.87
12	*Diospyros abyssinica*	Ebenaceae	22	4.22
13	*Dracaena afromontana*	Dracaenaceae	3	0.58
14	*Dracaena steudneri*	Dracaenaceae	5	0.96
15	*Ehretia cymosa*	Boraginiaceae	4	0.77
16	*Ekebergia capensis*	Meliaceae	3	0.58
17	*Euphorbia candelabrum*	Euphorbiaceae	3	0.58
18	*Fagaropsis angolensis*	Rutaceae	12	2.30
19	*Ficus sur*	Moraceae	11	2.11
20	*Flacourtia indica*	Flacourtiaceae	5	0.96
21	*Galiniera saxifrage*	Rubiaceae	2	0.38
22	*Ilex mitis*	Aquifoliaceae	1	0.19
23	*Macaranga capensis*	Euphorbiaceae	4	0.77
24	*Maesa lanceolata*	Myrsinaceae	5	0.96
25	*Maytenus arbutifolia*	Celastraceae	1	0.19
26	*Milletia ferruginea*	Fabaceae	110	21.11
27	*Mimusops kummel*	Sapotaceae	3	0.58
28	*Olea welwitschii*	Oleaceae	21	4.03
29	*Oxyanthus speciosus*	Rubiaceae	3	0.58
30	*Persea americana*	Lauraceae	1	0.19
31	*Phoenix reclinata*	Arecaceae	3	0.58
32	*Pittosporum viridiflorum*	Pittosporaceae	1	0.19
33	*Polyscia fulva*	Araliaceae	9	1.73
34	*Pouteria adolfi-friederici*	Sapotaceae	18	3.45
35	*Prunus africana*	Rosaceae	14	2.69
36	*Rhus natelensis Krauss*	Anacardiaceae	1	0.19
37	*Rothmannia urcelliformis*	Rubiaceae	6	1.15
38	*Rytigynia neglecta*	Rubiaceae	2	0.38
39	*Sapium ellipticum*	Euphorbiaceae	5	0.96
40	*Schrebera alata*	Oleaceae	1	0.19
41	*Schefflera abyssinica*	Araliaceae	5	0.96
42	*Syzygium guineense*	Myrtaceae	26	4.99
43	*Teclea nobilis*	Rutaceae	2	0.38
44	*Trichilia dregeana*	Meliaceae	12	2.30
45	*Trilepisium madagascariense*	Moraceae	*3*	0.58
46	*Vangueria apiculata*	Rubiaceae	*3*	0.58
47	*Vepris dainellii*	Rutaceae	*3*	0.58
48	*Vernonia amygdalina*	Asteraceae	*7*	1.34
Total number		27	521	100

2.82 at Bebeka southwest Ethiopia. Rigal et al. (2018) has reported a Shannon diversity of 3.42 with 30.57 effective number species in coffee agroforest from southwest China.

Coffee agroforest is a source of livelihoods for the local people. It provided ecosystem services that benefit the forest users (Bukomeko et al., 2019). The present study showed that woody plants maintained in coffee agroforest provide diversity of uses. Ten uses such as fuelwood, charcoal, Construction, medicinal, coffee shade, bee forage, beehive, farm tool, hanging beehive and timber that determine the management of woody plants species in coffee agroforest were frequently mentioned. These uses can be destructive (timber, beehive, construction, charcoal, farm tool), partial destruction (fuelwood, medicinal) and non-destructive (coffee shade, bee forage, hanging beehive). Ecological and economic reasons are the driving factors for woody plant management in coffee agroforest. In coffee agroforest the shade value of woody plant species are the priority for tree selection and management. Nevertheless, the present study findings showed that coffee agroforest owners obtain multiple benefits from the managed woody plants. Girma et al. (2019) have stated that local people manage woody plants for construction, fuelwood and honey production. A study from Bangladesh showed that local people manage woody plants for multiple uses and the major uses are fruit, fuelwood, pole, timber, medicinal etc. (Tarit et al., 2015).

TABLE 3 Diversity indices of woody plant species in coffee agroforest.

Indices	Coffee agroforest
Taxa_S	48
Individuals	521
Dominance_D	0.08
Simpson_1-D	0.92
Shannon_H	3.08
Evenness_e^H/S	0.45
Brillouin	2.92
Menhinick	2.10
Margalef	7.51
Equitability_J	0.79
Fisher_alpha	12.89
Berger-Parker	0.21
Chao-1	51.5

3.2 Preferred woody plants in coffee agroforest

The aggregate relative preference score (ARPS) showed 15 most preferred woody plant species in coffee agroforest (Table 4). Each woody plant species provided multiple uses and the relative importance differ between the species. Based on the all uses, *P. adolfi-friederici*, *C. africana*, *P. fulva*, *E. candelabrum* were the most preferred woody plants. The use value of these woody plants were mentioned more for timber, hanging beehive, beehive than coffee shade. *A. gummifera* and *M. ferruginea* were the most preferred coffee shade trees. The abundance of *P. adolfi-friederici*, *C. africana*, *P. fulva*, *E. candelabrum* were lower than *M. ferruginea* a well-known coffee shade tree in southwest Ethiopia. A study from Tanzania has shown local people give priority for the tree species that provide food, fodder and fuelwood (Wagner et al., 2019). Bukomeko et al. (2019) have studied the relationship between tree diversity and farmers need for the benefit of trees and found that farmers need did not match with tree diversity in coffee agroforest in Uganda. Lamond et al. (2016) have investigated underpinning factors for tree preference in coffee agroforest and reported that multiple uses (both ecological and socioeconomic) determine the tree selection in coffee agroforest. Albertin and Nair (2004) a have studied farmers' perspective on the role of shade tree in coffee production systems in Nicoya Peninsula, Costa Rica and have found tree species that are not preferred for coffee shade still maintained in coffee agroforest for the benefits they provided for the local people. The same author highlighted the need

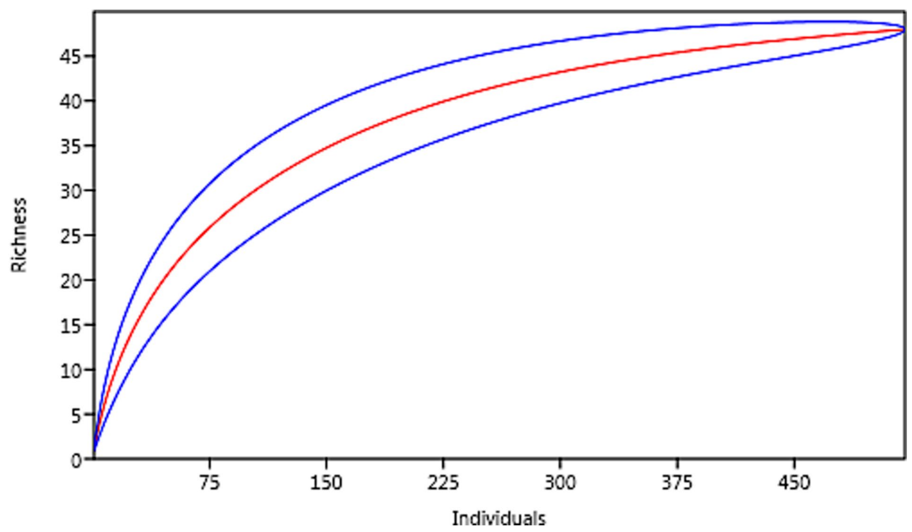

FIGURE 2
Individual based rarefaction curve.

TABLE 4 Uses and relative value of 15 most preferred woody plant species in coffee agroforest.

No	Woody plant species	Adjusted relative preference scores (ARPS) (%)										AGRPS (all use)	AGRPS (Shade use)	Abun
		Fue	Cha	Con	Med	Cof	Bef	Beh	Far	Han	Tim			
1	P. adolfi-friederici	0.00	0.00	0.01	0.00	0.05	0.06	0.00	0.00	0.16	0.29	5.79	5.05	18
2	*C. africana*	0.00	0.00	0.00	0.00	0.08	0.05	0.00	0.00	0.02	0.38	5.31	8.30	66
3	*P. fulva*	0.01	0.02	0.01	0.00	0.02	0.03	0.28	0.00	0.05	0.07	4.77	2.17	9
4	*E. candelabrum*	0.00	0.00	0.02	0.04	0.00	0.00	0.37	0.00	0.00	0.00	4.24	0.00	3
5	*O. welwitschii*	0.01	0.00	0.04	0.00	0.01	0.00	0.26	0.07	0.02	0.00	4.10	1.44	21
6	*P. africana*	0.03	0.10	0.01	0.01	0.04	0.00	0.00	0.08	0.02	0.11	3.95	3.61	14
7	*C. macrostachyus*	0.01	0.01	0.02	0.05	0.02	0.20	0.00	0.00	0.05	0.00	3.63	2.35	41
8	*T. dregeana*	0.00	0.00	0.00	0.31	0.01	0.00	0.00	0.00	0.02	0.00	3.58	1.44	12
9	*S. abyssinica*	0.00	0.00	0.01	0.00	0.07	0.26	0.00	0.00	0.00	0.00	3.54	7.04	5
10	*A. gummifera*	0.01	0.04	0.03	0.00	0.16	0.00	0.00	0.00	0.07	0.00	3.03	16.06	26
11	*M. ferruginea*	0.02	0.05	0.01	0.01	0.16	0.00	0.00	0.00	0.04	0.00	2.98	15.52	110
12	*C. africana*	0.05	0.18	0.00	0.02	0.00	0.01	0.00	0.00	0.03	0.00	2.93	0.18	20
13	*E. capensis*	0.01	0.02	0.00	0.01	0.10	0.01	0.00	0.00	0.08	0.06	2.93	9.93	3
14	*F. sur*	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.00	0.18	0.02	2.80	0.00	11
15	*F. angolensis*	0.00	0.00	0.08	0.17	0.01	0.00	0.00	0.01	0.00	0.00	2.61	0.54	12

Fue, fuelwood; Cha, charcoal; Med, medicine; Cof, coffee shade; Bef, bee forage; Beh, beehive; Farm, farm tool; Han, hanging beehive; Tim, timber; AGRPS, Aggregate relative preference score; Abun, Abundance.

for incorporating more trees and fruit trees in coffee agroforest in the region. A study by Hundera (2016) has shown local people maintain *Schefflera abyssinica* and *Olea welwitschii* in coffee agroforest for honey production in southwest Ethiopia. Valencia et al. (2015) have reported bulk of tree species that have not been valued for coffee shade in coffee in Chiapas, Mexico. Reinforcing reasons that encourage tree management in coffee agroforest are the need for additional benefits such as timber, fuelwood, medicinal and other non-timber forest products (Valencia et al., 2015). A study by Kalanzi and Nansereko (2014) has shown local people in Bukomansimbi district of Uganda prefer tree species that provide multiple products in coffee agroforest.

3.3 Local priority for conservation of woody plant species

The present study findings showed that the conservation priority (CP) varies between woody plants. Three types of categories were identified for local conservation priority that took into account the management practices, utilization and regeneration status of each woody plant (Table 5). Category 1 indicates woody plant species that need high conservation priority and accordingly category 2 and category 3, moderate and low priority, respectively. As indicated in Table 5, 12 species are represented under category 1, 19 species are represented under category 2 and 17 species are represented under category 3. Woody plants that are destructively utilized and removed from coffee agroforest during slashing under growth plants belongs to category 1. These woody plants had a few individuals and insufficient regeneration. Local people do not value these woody plants for coffee shade and totally remove, if possible, from the system. Likewise woody plant species under category 2 are utilized destructively that resulted in low number of individuals leading to loss of the plants in the long run. The Spearman correlation showed negative correlation between abundance and conservation priority [$r_s(46) = -0.681$, $p = 000$]. Most preferred woody plants such as *Cordia africana, Polyscia fulva, Pouteria adolfi-friederic* and *Olea welwitschi* belongs to category 3, *Euphorbia candelabrum, Ekebergia capensis*, and *Fagaropsis angolensis* belongs to category 2 and known coffee shade tree species *Milletia ferruginea* and *Albizia gummifera* belongs to category 3. This work is the first attempt to classify woody plant species in coffee agroforest in southwest Ethiopia. It highlights the status of woody plants under coffee management practices. The study findings complement the notion coffee agroforest is tree diversity conservation hotspot (Valencia et al., 2014). Local farmers knowledge plays a decisive role in conservation of tree species in coffee agroforest (Valencia et al., 2015). Joshi et al. (2019) has stated that woody plant species recognized as useful are under pressure for utilization and need attention for conservation. In the present study *Cordia africa* which is extracted for timber is exceptional due to the nature of plant regeneration characteristics. *Cordia africana* is found in low abundance but withstand timber utilization. Joshi et al. (2019) has reported tree species require high conservation priority compared to shrubs. But, the present study showed that shrubs require more attention than trees as coffee management remove under growth including shrubs through slashing. The study also support Lokonon et al. (2017) that state most used species are not top priority for conservation. For instance, in this study *Cordia africana* is highly utilized for timber but categorized under category 3. *Rytigynia neglecta*, *Maytenus arbutifolia* and *Ilex mitis* are among the species with high diversity of uses but totally discouraged in coffee agroforest in southwest Ethiopia.

TABLE 5 List of woody plant species for local conservation priority in coffee agroforest.

No	Plant name	Major use	Manag	D	L	DU	H	U	CP	Categ	Abun	Sap/ seed
1	*Rytigynia neglecta**	Construction	Removed	10	10	5	10	7.5	103.75	1	1	Present
2	*Maytenus arbutifolia*	Fuelwood	Removed	10	10	5	10	7.5	93.75	1	2	Present
3	*Ilex mitis*	Fuelwood	Removed	10	7	7	10	7	92.5	1	1	Absent
4	*Sapium ellipticum*	Fuelwood	Removed	7	10	6	10	8	91.25	1	2	Absent
5	*Galiniera saxifrage*	Fuelwood	Removed	10	7	5	10	6	90	1	1	Absent
6	*Pittosporum viridiflorum*	Fuelwood	Removed	10	7	5	10	6	90	1	2	Present
7	*Schrebera alata*	Fuelwood	Removed	10	7	5	10	6	90	1	3	Present
8	*Cassipourea malosana*	Farm tool	Removed	10	4	7	10	5.5	88.75	1	2	Present
9	*Teclea nobilis*	Farm tool	Removed	10	7	4	10	5.5	88.75	1	3	Present
10	*Alangium chinense**	Construction	Retained	10	4	3	7	3.5	86.25	1	1	Absent
11	*Rothmannia urcelliformis**	Construction	Removed	7	7	6	10	6.5	86.25	1	1	Present
2	*Syzygium guineense**	Construction	Retained	1	10	5	10	7.5	86.25	1	1	Present
13	*Apodytes dimidiata*	Coffee shade	Retained	7	4	10	1	7	82.5	2	1	Present
14	*Persea americana*	Fuelwood	Retained	10	1	4	10	2.5	81.25	2	1	Present
15	*Mimusops kummel*	Construction	retained	7	7	8	4	7.5	80	2	1	Present
16	*Trilepisium madagascariense**	Construction	Retained	7	7	5	4	6	80	2	1	Present
17	*Flacourtia indica*	Fuelwood	Removed	7	10	5	10	7.5	78.75	2	1	Absent
18	*Fagaropsis angolensis**	Construction	Retained	4	10	5	7	7.5	77.5	2	1	Present
19	*Maesa lanceolata*	Fuelwood	Removed	7	10	6	10	8	77.5	2	1	Present
20	*Vernonia amygdalina*	Bee forage	Removed	7	4	5	10	4.5	77.5	2	1	Present
21	*Euphorbia candelabrum*	Beehive	Removed	7	10	4	10	7	76.25	2	1	Present
22	*Vepris dainellii*	Fuelwood	Removed	7	10	4	10	7	75	2	1	Absent
23	*Clausena anisata*	Fuelwood	Removed	7	4	5	10	4.5	73.75	2	1	Absent
24	*Oxyanthus speciosus*	Fuelwood	Removed	7	7	4	10	5.5	73.75	2	1	Absent
25	*Phoenix reclinata**	Construction	Removed	7	1	2	10	1.5	73.75	2	2	Absent
26	*Rhus natelensis*	Fuelwood	Removed	10	10	3	10	6.5	73.75	2	1	Absent
27	*Dracaena steudneri*	Medicinal	Removed	7	1	1	10	1	71.25	2	2	Absent
28	*Vangueria apiculata*	Fuelwood	Removed	7	7	5	10	6	70	2	1	Present
29	*Chionanthus mildbraedii*	Farm tool	Removed	7	7	4	10	5.5	66.25	2	1	Present
30	*Macaranga capensis*	Fuelwood	Removed	7	10	4	10	7	66.25	2	1	Absent
31	*Ehretia cymosa*	Farm tool	Removed	7	7	6	10	6.5	62.5	2	2	Absent
32	*Bersama abyssinica*	Fuelwood	Removed	4	10	7	10	8.5	55	3	1	Absent
33	*Celtis africana*	Fuelwood	Removed	1	10	7	10	8.5	51.25	3	1	Absent
34	*Polyscia fulva*	Beehive	Retained	4	7	3	7	3.5	48.75	3	1	Absent
35	*Trichilia dregeana*	Medicinal	Retained	1	10	7	7	8.5	47.5	3	2	Present
36	*Diospyros abyssinica**	Construction	Retained	1	7	4	7	5.5	46.25	3	1	Present
37	*Allophylus abyssinicus*	Fuelwood	Removed	7	10	8	10	9	43.75	3	1	Absent
38	*Ekebergia capensis*	Coffee shade	Retained	4	7	8	1	7.5	41.25	3	2	Absent
39	*Croton macrostachyus*	Bee forage	Retained	1	7	7	7	7	40	3	1	Absent
40	*Pouteria adolfi-friederici**	Timber	Retained	1	7	7	10	5.5	40	3	1	Absent
41	*Dracaena afromontana**	Construction	Removed			3	10	1.5	38.75	3	1	Present
42	*Schefflera abyssinica*	Bee forage	Retained	1	10	7	10	7	36.25	3	3	Present
43	*Cordia africana*	Timber	Retained	1	10	6	4	8	35	3	1	Absent

(Continued)

TABLE 5 (Continued)

No	Plant name	Major use	Manag	D	L	DU	H	U	CP	Categ	Abun	Sap/ seed
44	*Prunus africana*	Fuelwood	Retained	1	7	5	10	6	33.75	3	1	Absent
45	*Olea welwitschi*	Beehive	Retained	1	7	7	4	7	32.5	3	1	Absent
46	*Ficus sur*	Hanging beehive	Retained	1	7	5	4	6	30	3	2	Present
47	*Milletia ferruginea*	Coffee Shade	Retained	1	10	6	1	8	27.5	3	1	Present
48	*Albizia gummifera*	Coffee shade	Retained	1	10	5	1	7.5	26.25	3	2	Present

Manag, management practices; D, density; L, local importance; Du, diversity of use; H, Utilization risk; CP, conservation priority; categ, conservation categories; Abun, abundance; Sap/seed, sapling/seedling.
*Associated destructive use.

4 Conclusion and implication to conservation

Coffee management activities and local uses raises the concern for conservation of woody plant species in coffee agroforest in southwest Ethiopia. The study findings highlight the diversity, local preference and conservation priority of woody plant species. We conclude that the most useful woody plants are not the most abundant in coffee agroforest. As most woody plants need high conservation priority, the presence of woody plants in coffee agroforest necessarily does not imply sustainability. Local preference determine woody plant species management and conservation in coffee agroforest. Woody plants are maintained in coffee agroforest for multiple uses than a single shade value. Non-coffee shade trees are the most preferred tree species in coffee agroforest. The study findings suggest that promotion of woody plant species management in coffee agroforest should include the multiple uses and preference of woody plant species.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

ZK: Conceptualization, Formal analysis, Writing – original draft. CO: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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COVID-19, deforestation, and green economy

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Corona has severely impacted many sectors in the past 2. 5 years, and forests are one of the major hits among all sectors affected by the pandemic. This study presents the consolidated data on deforestation patterns across the globe during COVID and also analyzes in depth the region-specific contributing factors. Exacerbated deforestation during COVID alarms biodiversity conservation concerns and pushes back the long-term efforts to combat pollution and climate change mitigation. Deforestation also increases the risk of the emergence of new zoonotic diseases in future, as deforestation and COVID are intricately related to each other. Therefore, there is a need to check deforestation and inculcation of conservation measures in building back better policies adopted post-COVID. This review is novel in specifically providing insight into the implications of COVID-19 on forests in tropical as well as temperate global regions, causal factors, green policies given by different nations, and recommendations that will help in designing nature-based recovery strategies for combating deforestation and augmenting afforestation, thus providing better livelihood, biodiversity conservation, climate change mitigation, and better environmental quality.

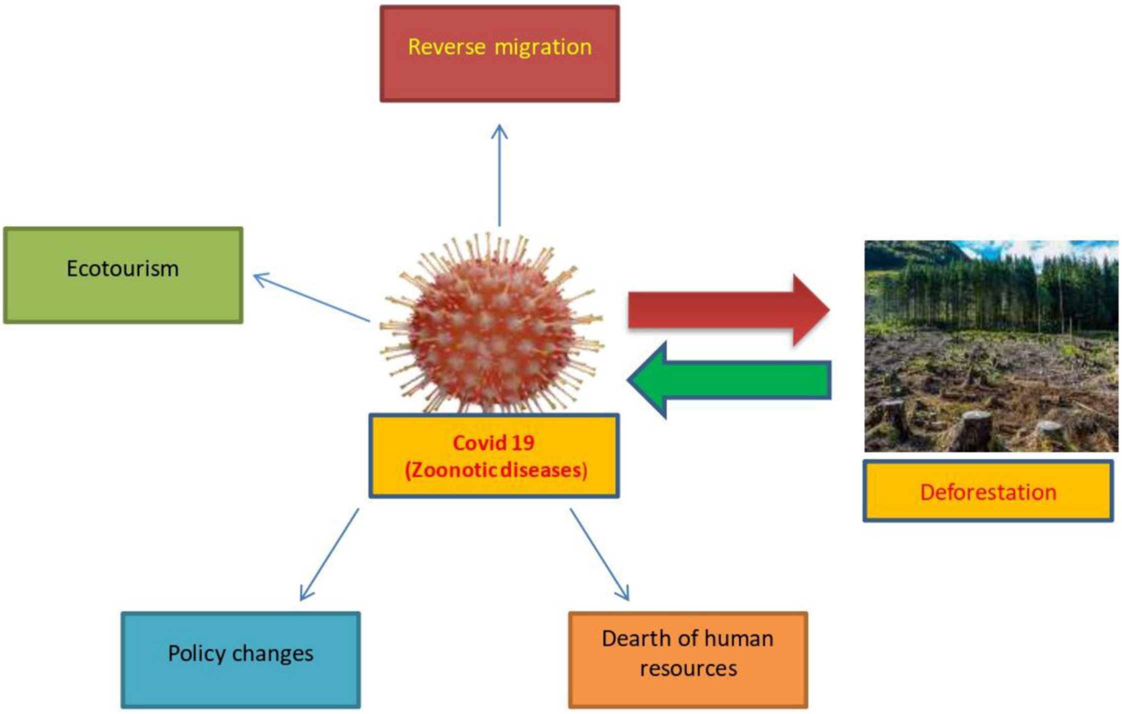
KEYWORDS
COVID 19, deforestation, green economy, reverse migration, ecotourism

Highlights

- Deforestation precipitated in many parts of the world during the pandemic.
- Illegal felling, reverse migration, ecotourism, reduced monitoring due to reduced funds and dearth of staff, and policy changes are the major factors contributing to the increased rate of deforestation.
- There is an urgent need to check deforestation and promote afforestation to prevent pandemics in future, build resilient ecosystems, and reduce the vulnerability of rural and indigenous communities.
- COVID-induced crisis should be utilized as an opportunity to build back better in a green way.

Introduction

The global economy has been shattered due to the turmoil created by the COVID-19 pandemic. Countries across the world have already faced three waves of COVID-19, with millions of people affected and massive loss of life to date. Repeated lockdowns and other restrictions imposed to contain the spread of the virus have adversely affected various



GRAPHICAL ABSTRACT

segments of the modern economy, such as industries, airlines, farming, fisheries, sports, social events, education, and tourism, among others (Blake and Wadhwa, 2020; Galanakis et al., 2022). Although these restrictions proved to be helpful in checking virus spread, they led to an economic depression, also termed as pandemic depression. Even the economy of many powerful countries gets set back due to a sharp rise in the rate of inflation and escalating unemployment due to disrupted chain supplies, lack of productivity, and excessive expenditure on the health sector (OECD, 2020). Extreme poverty is shooting up again due to the pandemic defeating the progress made over a long period. The World Bank predicted that the poverty rate would rise in the near future, pushing 88 to 115 million more people toward extreme poverty, lifting the global poverty rate as high as 9.4% (Miller, 2020). ILO predicted a maximum possible loss of 230 million full-time jobs of 40 h globally, and OECD estimates a fall of around 1.5% in real GDP growth (OECD, 2020). The COVID-19 pandemic caused severe socio-economic, political, and environmental crises in the world. Exacerbated deforestation from different parts of the world in response to pandemic restrictions owing to a number of factors can further raise severe short- and long-term socio-economic and environmental concerns, affecting the lives of a large chunk of the population who directly or indirectly depend on forests for survival (Troëng et al., 2019; FAO, 2020a). Forest sustains the livelihood of ∼20% of the global population, specifically the vulnerable section that depends on forests for food, income, and nutrition (FAO, 2020a; Rahman et al., 2021). In addition, a large segment of people (∼2.4 billion) in rural and urban areas use biomass energy for cooking and heating purposes (Sen, 2020; United Nations, 2020a). Forests are also a source of employment for 86 million people in green jobs. Deforestation can also have adverse effects on ambitious targets of reduced emissions for curbing climate change. Reports from International agencies (UNEP, 2020) showed that we are already lagging behind in accomplishing the targets to combat climate change, thus global warming. Furthermore, the COVID-19-induced economic crisis will increase deforestation rates, which can pose a very serious setback to these international efforts. Apart from these, deforestation can increase the risk of zoonotic diseases as the emergence of a majority of new infectious diseases occurs due to human and wildlife interaction as a result of land use changes such as deforestation and expansion of agriculture (Allen et al., 2017; Rohr et al., 2019). Thus, forest loss disrupts the ecosystem's stability and functioning, consequently a humanitarian crisis as forests provide vital ecosystem services that are crucial to human wellbeing and critical for achieving sustainable development goals. Various research studies showed the impact of COVID-19 on the environment in terms of air, water, and soil, but none have thoroughly discussed the effect of the pandemic on forests, though they form a major life-supporting global ecosystem. Although there are few research studies linking the COVID-19 pandemic and deforestation, these are regional and do not provide a holistic view of deforestation patterns across the globe during the pandemic. This is the first comprehensive review that provides a global deforestation scenario during the pandemic, analyzes the region-specific factors contributing to accelerated deforestation, fiscal packages for a green economy, and the policy recommendation for halting and reversing deforestation that occurred as a consequence of COVID-19. Detailed information and a deep understanding of factors leading to deforestation during the pandemic will help

TABLE 1 Detail of Publications referred for review.

Authors	Title	Journal
Attah (2021, 2022)	Initial assessment of the impact of COVID-19 on sustainable forest management African states	Background paper prepared for the United Nations forum on forests secretariat
Bista et al. (2022)	Impacts of COVID-19 pandemic on the livelihoods of rural households in the community forestry landscape in the Middle Hills of Nepal	Trees, forests, and people
Basnyat et al. (2020)	COVID-19 outbreak, timber production, and livelihoods in Nepal	Tribhuvan University Journal
Bhandari et al. (2021)	Global forestry perspective: COVID-19 impact and assessment.	Natl. Acad. Sci. Lett
Brancalion et al. (2020)	Emerging threats linking tropical deforestation and the COVID-19 pandemic	Perspectives in ecology and conservation
FAO (2020b)	The impacts of COVID-19 on the forest sector: How to respond?	Policy brief
Gregory (2021)	COVID, forests and forest peoples: The implications of the pandemic for forest campaign	Discussion paper
Hardcastle and Zabel (2020)	Initial assessment of the impact of COVID-19 on sustainable forest management western European and other states	Background Paper prepared for the United Nations forum on forests secretariat
Ibn-Mohammed et al. (2021)	DESA brief: Investment in forests critical for successful COVID-19 recovery	Policy brief
ILO (2020)	Impact of COVID-19 on the forest sector	ILO sectoral brief
Laudari et al. (2021)	COVID-19 lockdown and the forestry sector: Insight from Gandaki province of Nepal	Forest Policy and Economics
Maraseni et al. (2022)	Impact of COVID-19 in the forestry sector: a case of lowland region of Nepal	Land use policy
Mohan et al. (2021)	Afforestation, reforestation and new challenges from COVID-19: 33 recommendations to support civil society organizations (CSOs)	Journal of environmental management
Rahman et al. (2021)	The COVID-19 pandemic: a threat to forest and wildlife conservation in Bangladesh	Trees, Forests and People
Wunder et al. (2021)	Coronavirus, macroeconomy, and forests: What likely impacts?	Forest policy and economics

the administrators and policymakers in designing the action plan and recovery packages to restore the ecosystem and economy side-by-side from the aftermath of the COVID-19 pandemic. Therefore, a holistic view of COVID-19-led deforestation and policy recommendations for green recovery is the call of the hour and has its own scientific value.

Methodology

The present study was carried out by collecting the published literature since the beginning of the COVID-19 era, such as research articles, case studies, review articles, policy papers, opinions, and blogs from various government and non-government websites related to the impact of COVID on forestry. Primary pieces of literature were recorded through scientific engines, namely Scopus, Science Direct, and Google Scholar, using key words COVID-19, forestry, illegal felling, ecotourism, reverse migration, deforestation, and green economy. The direct studies linking COVID-19 and forests have been summarized in Table 1. After thoroughly reviewing and analyzing the published pieces of literature on the topic, the present article has been compiled, outlining the status of deforestation during the pandemic period, causal factors, and remedial measures adopted by governments in different parts of the world.

Global deforestation pattern

Like many other sectors, COVID-19 has also affected the forest sector for a myriad of reasons, such as illegal felling, reverse migration, halted ecotourism, and accelerated demand for forest-based products. Global tree cover loss in different countries in 2020 has been presented in Figure 1.

According to an estimate by the University of Maryland, ∼12 million hectares of forests disappeared in 2020 alone in tropical regions (WRI, 2021). WWF observed forest loss to be 1.5 times higher in March 2020 than for the same month in the previous year for 18 countries (WWF, 2020; Wunder et al., 2021). A sum of 9583 km^2 of deforestation alerts was announced throughout the tropical world by GLAD (Global Land Analysis & Discovery) in the initial month of the COVID lockdown period in 2020, declared by regional governments to contain the COVID-19 spread, which was almost twice that observed in the previous year (4732 km^2). There was a notable spike in the deforestation rate (Figure 2) in certain parts of the globe (South America, Africa, and Asia-Pacific) in the first semester of 2020 (Brancalion et al., 2020).

According to an estimate by the same agency (GLAD), a hike of 77% percent has been found in deforestation alerts since the beginning of the coronial period against the average of the past 3 years (2017–2019) (Stanley et al., 2020). However, some workers did not agree with GLAD alert-based studies linking COVID-19 and deforestation (Saavedra, 2020; Wunder et al., 2021). The

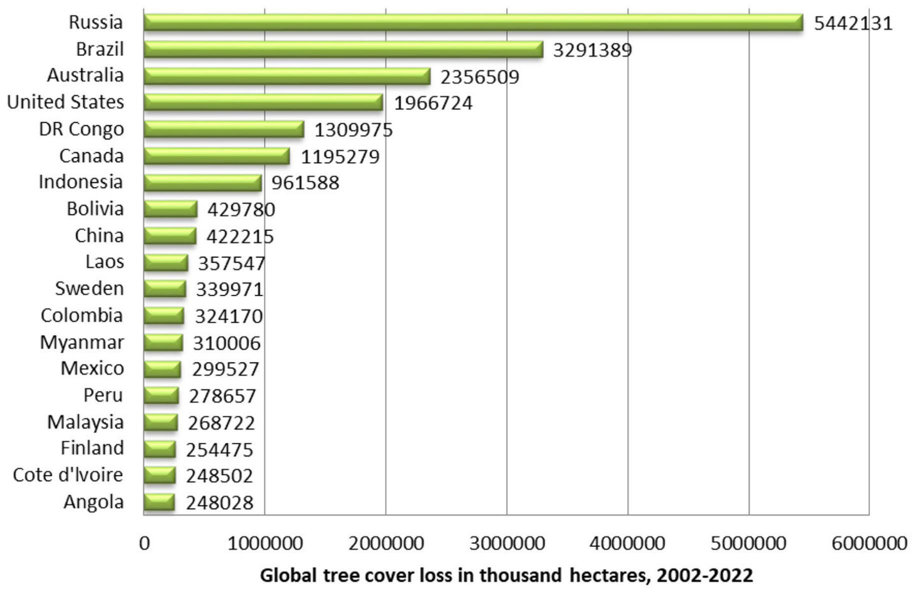


FIGURE 1
Global tree cover loss in 2020 (Source: WRI, 2021).

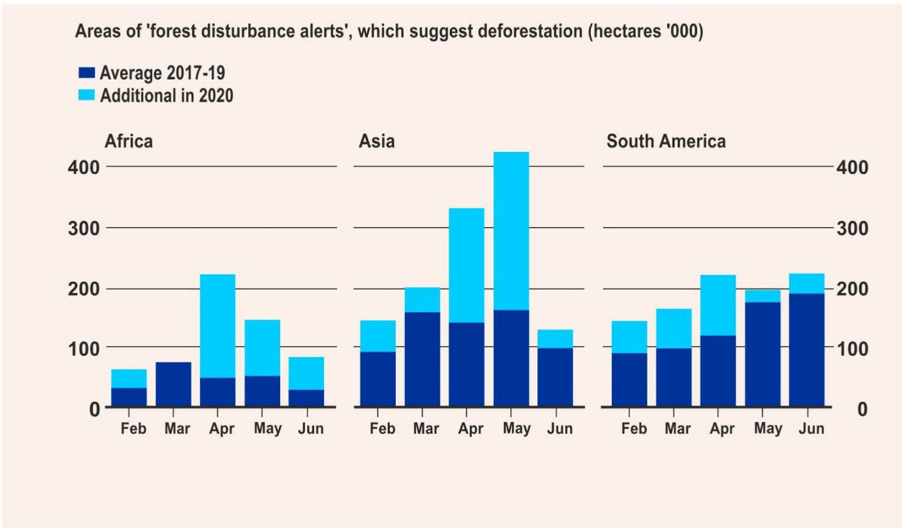


FIGURE 2
Area of forest disturbance alerts (deforestation) in major continents (Source: Brancalion et al., 2020).

Amazon rainforest has lost more than 9000 km^2 (3500 square miles) during the year up to March 2020, constituting an increase of 47% and 9.5% compared to 2018 and 2019, respectively. This is the highest annual recorded loss since 2008 (Qin et al., 2019). Approximately 6.45 lakh ha of rainforest was lost globally in March 2020 only, led by Indonesia, almost thrice of that for the same month in 2019 (Wunder et al., 2021). The other two countries that occupied second and third places were the Democratic Republic of Congo and Brazil, respectively. Indonesia observed the greatest forest loss (1.3 lakh ha) than any other country across the globe during March 2020, which amounted to 130% over the mean of the previous 3 years (2017–2019) for the same calendar month (Wunder et al., 2021). According to an analysis by Greenpeace, the deforestation rate was 50% higher in the first trimester of 2020 in Indonesia than in the previous year in 2019 for the same duration, which also coincided with the fire season (Sloan et al., 2022). The deforestation rate has continued to rise in the Amazon region even during the COVID-19 pandemic period. For instance, as COVID-19 spread across Brazil, which accounts for 60% of Amazon, the rate of forest loss also increased to 55% in the first trimester of 2020 to that of the same period in 2019, which was the highest in the past 12 years (Butler, 2020). Other countries of the Amazon

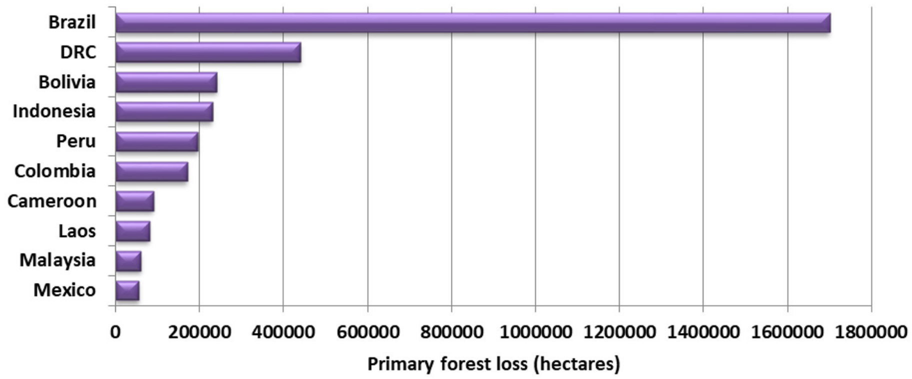


FIGURE 3
Top 10 countries for 2020 primary forest loss (Weisse and Goldman, 2021).

region vis-à-vis Colombia, Cambodia, and Peru also experienced an increased deforestation rate in 2020, particularly in March and April, than the previous year for the same duration as a result of lockdown and quarantine (West et al., 2023). It is a matter of grave concern that 1.2 billion hectares of tropical forests lost in 2020 also included 4.2 million hectares of primary tropical forests. The same pattern of deforestation was observed in 2021, when the tropical regions lost 11.1 million hectares of forests, including the loss of 3.75 million tropical primary rainforests, which are important as the center of biodiversity and carbon sink (Lambin and Furumo, 2023). Brazil lost 1.7 million hectares of primary forest cover in 2020, 25% higher than 2019 and more than thrice than DRC, the second highest country. Bolivia was positioned at number three in terms of primary forest loss in 2020, whereas the South Asian countries, palm-producing Indonesia and Malaysia, occupied fourth and ninth positions, respectively (Figure 3) (Weisse and Goldman, 2021; Céspedes et al., 2023).

The rate of primary forest loss in Brazil has been persistently high for the past several years. Non-fire losses, which in Brazil are most often associated with agricultural expansion, increased 9% from 2020 to 2021. This finding is consistent with Brazil's official monitoring system, PRODES (Silva-Junior et al., 2023), which found that 2021 had the highest rate of clear-cut deforestation in the Amazon since 2006, when measures were put in place to drastically reduce deforestation. DRC lost nearly half a million hectares of primary forest in 2021 due to the expansion of small-scale agriculture and harvesting trees to meet energy demands. Primary forest loss in Bolivia reached its highest level on record in 2021 at 291 thousand hectares, surpassing Indonesia once again to have the third-most primary forest loss among tropical countries. There are reports of increased deforestation in India, where nearly 38.5 thousand hectares (Kha) of tropical forest were lost between 2019 and 2020. The northeastern states of India possessing the largest forest areas (Assam, Mizoram, Nagaland, Manipur, Arunachal Pradesh) observed 29% more forest cover loss in 2020, breaking the declining trend of tree cover loss during the past 2 years (Roy, 2021; Vancutsem et al., 2021). The GLAD deforestation alert services showed that the total deforestation alerts rose by 77% within 10 months in 2020 as compared to the previous year in Bangladesh. Deforestation alerts were more pronounced during the months of lockdown as compared to the period before lockdown. The GLAD service reported that ∼222 ha of additional forest area (8%) in Bangladesh was deforested in the first 10 months of 2020 compared to the preceding year (Rahman et al., 2021). Other countries across the world also registered higher rates of deforestation; similar to Latin America, Mesoamerica surpassed the previous levels of primary tropical forest loss by 27% in 2020 during the COVID pandemic, whereas Nicaragua accounted for a 15% loss of primary tree cover in last 3 years. Belize also stood high with respect to forest loss in 2020, nearly twice the previous year. The primary forest loss rose to 36% in West Africa in 2020. Madagascar also showed an upward trend in deforestation during the pandemic (Eklund et al., 2022). Expansion of agriculture and fuelwood demand due to reverse migration, land grabbing, and relaxation in law enforcement, forest fires and lack of management practices due to a dearth of human resources and budget deficit during the ongoing pandemic may be cited as factors for the spike in deforestation rates in several regions of the world.

Outside the tropics

Temperate regions also bore the brunt of the COVID-19 pandemic. Russia, which is at the top position with respect to overall forest cover, showed a surge of 48% in 2020 during the pandemic over the previous year for forest loss. Russia lost ∼5.44 million ha of forest cover in 2020 owing to forest fires in Siberia and the Russian Far East. In a similar vein, Australia's forest loss also hiked by 42% due to forest fires that took a heavy toll on the forest cover across the eastern parts of the country from the middle of 2019 to the beginning of 2020. Canada and the US, however, unlike other countries, observed a decline in forest loss in 2020. Canada lost 1.2 million ha of tree cover, which was the lowest in the past two decades. Central Europe also registered massive forest cover loss in 2020, the greatest being in Germany and the Czech Republic, which was three times higher than in 2018 (Butler, 2021). The spike was due to a lack of forest management practices due to a dearth of human resources and a curtailed budget during the COVID pandemic, of which fire and bark beetles could not be controlled (Bercak et al., 2023). Outside the tropics, boreal forests experienced the highest rates of tree cover loss in 2021 (Rotbarth et al., 2023). While tree cover loss in boreal forests rarely results in permanent deforestation, the rate of loss reached unprecedented levels in 2021, increasing 29% over 2020. Russia experienced the worst fire season since record-keeping began in 2001, with more than 6.5 million hectares of tree cover loss in 2022 (Johansen, 2023).

Spike in deforestation

Excessive harvesting of timber and non-timber forest products (NTFPs) has been on the increase in response to global mayhem during this pandemic due to restrictions on movement, lockdown, social distancing, staff shortage, weak enforcement, relaxation of government policies, and budget deficit. In addition, reliance on forests has also increased during the colonial period to meet the rising demand for forest-based essential hygiene and sanitary products such as tissue paper, toilet paper, paper towels, and alcohol-based hand rub (FAO, 2020a). The demand for toilet paper, in particular, skyrocketed at the beginning of the outbreak, and some companies reported an increase of up to 700% in their sales (Garbe et al., 2020; Jones, 2020). As per directions of the WHO, crowded places should be avoided to prevent and slow down the transmission of COVID-19. In this scenario, people are dependent on e-commerce for the purchase of goods instead of visiting the markets. The growth of e-commerce is likely to contribute to increased demand for packaging boxes made up of paper and cardboard for home delivery services. Even the manufacturing of paper gowns, surgical masks, and caps used in personal protective equipment (PPE) kits for medical workers also utilizes wood pulp and fiber (United Nations, 2020b). Three of the four largest pulp-exporting countries, Brazil, the US, and Chile, increased their shipments between 12 and 26% in March (month-over-month). The five top importing countries all purchased more pulp in March than in February, with China and South Korea increasing their volumes the most (40 and 29%, respectively). Enterprises have taken innovative measures to expand their production, particularly of products for which demand has been stable or has increased during the crisis, such as surgical masks. In Italy, the decision to classify paper as an essential product due to its importance for food packaging and sanitary and pharmaceutical products ensured the continued operation of paper mills during the state of emergency. In Canada, a paper mill that turned to manufacture medical-grade pulp suitable for masks and gowns doubled its production. Researchers suggested that Ashwangandha (*Withania somnifera*), along with other Ayurvedic rasayanas, such as *Tinospora cordifolia* (Guduchi), *Asparagus racemosus* (Shatavari), and *Phylanthus emblica* (Amalaki), are helpful against COVID-19 due to their immunomodulatory properties and potential as an immunity booster (Patwardhan et al., 2020). The exploitation of wild medicinal plants for their proven scientific use and additional pressure on forests for food, fuelwood, and fiber may precipitate deforestation to a greater extent. Many countries, such as Brazil, Colombia, Cambodia, Indonesia, Nepal, India, Bangladesh, and Madagascar, reported a higher incidence of illegal extraction of forest resources since the initiation of the pandemic (Muche et al., 2022). In Nepal, a compilation of studies of 11 protected areas revealed 227% higher cases of timber theft during the first month of lockdown than last month. Higher numbers of crime cases related to natural resources were recorded during that period compared to collective numbers of the preceding 11 months (Department of National Parks and Wildlife Conservation and WWF Nepal). The movement of restrictions during the lockdown made it difficult to enforce law and order, monitoring, and conservation practices, which potentially exaggerated the large-scale illegal logging activities within the forest sector (Brancalion et al., 2020; Maraseni et al., 2022). Environmental organizations across the globe, viz Brazil, Colombia, Philippines, Kenya, Cambodia, Venezuela, and Madagascar, reported a rise in cases of timber theft, poaching, and illegal mining and warned that it is very difficult to halt or reverse the precipitation of deforestation occurring during the pandemic (Fair, 2020). A similar situation has been reported in Malaysia and Indonesia, which have the highest rates of forest loss in Southeast Asia; illegal timber mining from rainforests of Sulawesi (Indonesian island) rose by 70% in 2020 (Chandra, 2021). In Ecuador, an increase in illegal mining by indigenous people has been witnessed in the Choco and Amazon rainforests (Brown, 2020). Africa is no exception, where illegal logging and poaching in the forest areas hiked during the pandemic. Due to the diverted attention of the government on the medical sector, criminal syndicates became active and increased their illegal activities of felling and poaching in the forests in Africa, which already cost the continent US$17 billion annually (African Union, 2020). There are reports of illegal logging in forest regions across Eastern, Western, Central, and Southern Africa. To quote, in Tanzania, illegal felling activities observed a 20% hike during the pandemic compared to the usual number of such events in the past. Such an incidence of illegal extraction of valuable timber was also reported to be happening in Uganda and Kenya during the pandemic. Survey reports from Central Africa also revealed the role of the pandemic in speeding up the illegal felling instances in the Congo Basin (Mbzibain, 2020). As the governments are financially overburdened while dealing with the pandemic, national forest institutions are facing a fund crisis to deploy the staff to carry out forest protection and conservation activities (African Union, 2020). Illegal activities (timber mining and poaching) have also affected mangrove forests in the coastal belt of the EAC region, where pole-cutting and charcoal production accelerated during COVID-19 (Parris-Piper et al., 2023). Therefore, the pandemic is likely to increase deforestation, leading to biodiversity loss and environmental pollution if the forestry sector is left unattended during the course of the pandemic. Illegal activities in the forests will also distort the supply chain of valuable timber species, adversely impacting marketing and trade. This will cause revenue losses to the government and thus significantly impact the livelihood of people engaged in this sector.

Dearth of human resources

Disruption of human resources during the pandemic is one of the major factors adversely affecting forest protection, conservation, and management activities (Corlett et al., 2020). Absenteeism in the workforce due to a number of factors during the pandemic is also on the rise. For example, many forest reserves in Africa, Latin America, and Asia have recorded a low presence of workers since the outbreak of the pandemic. Poor attendance or absenteeism stressed the entire system, leading to higher incidences of illegal logging and hunting during the lockdown period in 2020 (United Nations, 2020a; Pérez Caldentey et al., 2023). More than 50% of countries in Africa reported that the pandemic hampered regular field monitoring and patrolling in forest reserves during the pandemic in the year 2020 (Waithaka, 2020; Waithaka et al., 2021). As the security forces were engaged in implementing COVID lockdowns and enforcing containment guidelines, there was a dearth of manpower to protect forests and wildlife (Werikhe, 2022). The illness and deaths of forest officials of different levels during the pandemic affected the overall performance of forest departments in guarding the protected areas. Wildfires particularly were also difficult to control during the course of the pandemic. In the past few years, incidences of wildfires have been recorded frequently, and the situation has become very intense during the simultaneous occurrence of multiple fires. Deficit staff due to viral infection, quarantine measures, and social distancing affected the ability of workers to deal with multiple fires in active season. Other forest management operations were also delayed by many countries during the pandemic by COVID-19 taking into consideration the wellbeing of workers and forest communities. In Canada, an aerial spray program for checking jack pine budworm was abandoned by the Ontario Ministry of Natural Resources and Forestry. Some provinces canceled prescribed burning while others worked at low capacity. In the US, management operations such as prescribed burning were held back at the majority of places while other activities, such as trimming trees near electrical lines, were slowed down due to pandemic restrictions (Heller, 2020; Stanturf and Mansuy, 2021). Repeated lockdowns and movement restrictions had a negative impact on sustainable forest management and protection measures in all the sub-regions of Africa. The attack of defoliating insects (*Limantrya dispar*) on cork, a valuable non-timber forest product in the countries of the western Mediterranean, could not be controlled during the pandemic, resulting in the hampering of harvesting operations (Araújo, 2020). A dearth of human resources adversely affected many activities linked to forest protection, conservation, and management, and the pitfalls can be observed in terms of illegal logging activities, poaching, rampant wildfires, pest disasters, forest clearance for agriculture, invasive plant growth, and overgrazing/husbandry needs (Simental and Bynum, 2023).

Policy changes

In response to the pandemic, there will be a major shift in budget reallocations as the health sector and COVID containment will be on the priority list at the expense of other important agendas, such as natural resource management and climate change. As developing countries are less prepared to face such disasters, there are more chances of budget curtailing and reallocation in these countries (Werikhe, 2022). Governments across the globe are changing their policies (relaxation of environmental regulations, diversion of funds, and holding back important forestry events) to deal with the pandemic crisis, which is adversely impacting forest protection, conservation, and management activities to a significant extent (Wang B. et al., 2022; Wang J. et al., 2022). The economic recession during the pandemic is expected to reduce funds for forests. The forests in some parts of Asia, Africa, and Latin America are already facing the wrath of this pandemic in terms of curtailed budgets due to the diversion of public funds to the health sector to save human lives from COVID-19. For instance, Mexico and Ecuador in Latin America have already declared budget cuts in the natural resource management sector, challenging law enforcement for forest protection and management of some serious issues, such as climate change (Bertola et al., 2023). The socio-economic crisis has forced governments across the world to review their policy decisions and reorient these toward developmental activities to meet the ends. Governments are promoting agriculture and the industrial sector by providing subsidies and relaxing legislation, which will have detrimental effects on nature and subsequently human health. Deforestation in Brazil precipitated during the pandemic period due to the weakening of environmentally favorable policies through 57 amendments in the legislation in 2021. Various relief policies by different countries in South Asia are also adversely affecting the forests significantly. As in Indonesia, efforts for employment generation and economic revival under Omnibus Law can put forests at risk by compromising environmental regulations. Indonesian Government also changed its previous policy to restore 165,000 ha of abandoned peat land in the wake of the pandemic by bringing it under agriculture to fulfill the food shortage during the pandemic. These peatlands were earlier planned to be restored to reduce emissions and meet national targets (Worrall et al., 2003). To improve economic growth, Indonesia has abandoned the practice of checking the legal states of timber export, which will definitely acerbate illegal timber extraction and deforestation in Indonesia (Maxton-Lee, 2020). Hence, the present relief policies of Indonesia are jeopardizing environmental security by relaxing environmental regulations and converting carbon-rich peatlands into food estates. Similarly, the Manitoba province government in Canada has already cut environmental funding (Robinson et al., 2023) as part of its plan to cope with the fiscal deficit resulting from the COVID-19 pandemic. Unfortunately, this will be counterproductive in the long run since the health of the planet is intricately linked to public health. The budget cut will surely hamper the ongoing and planned nature conservation and protection activities in different forest areas worldwide. After a thorough examination of recovery packages announced by governments across the different parts of the globe, Friedlingstein et al. (2022) reported the withdrawal of the budget for environmental protection in 64 cases from 22 countries. Governmental policies played a major role in the conservation of protected areas by law enforcement. Several countries have set targets to increase their forest cover and reduce emissions to fight climate change. However, many governments have changed their policies and prioritized other sectors over forestry in response to the present crisis. The ongoing pandemic has diverted the attention of governments and public funds toward the general wellbeing of the people and health sector, putting the forests at very high risk. COVID-19 has put the world on hold for quite some time, resulting in the postponement of many important national and international conferences. These postponements gave a setback to the international efforts to address serious environmental issues such as biodiversity loss, greenhouse gas emissions, and climate change (Korngold, 2023). The after-effects of this pandemic will definitely be long-lasting on national and international environmental goals and emission targets.

Reverse migration

COVID-19 caused massive unemployment due to the contraction in the global economy, disruptions in supply chains, and closure of production units, leading to the mass movement of migrants from urban to rural areas for survival (FAO, 2021). There are 164 million migrant workers worldwide, constituting 4.7% of the global labor pool (ILO, 2020). Enforcement of lockdown regulations to contain the spread sent shockwaves to the welfare and economic security of those migrant workers and their families in villages who were involved in seasonal employment. Loss of source of income, fear of being infected, and uncertainty of the situation triggered the mass backward movement of migrants both at the national and international levels to their home state and countries, mostly to rural areas of origin for survival (Khan et al., 2020; Mustaquim and Islam, 2020). In addition to the mass movement of workers from overseas, many nations such as the United States, Mexico, Venezuela, Peru, China, Bangladesh, Nepal, Indonesia, Vietnam, Cambodia, and South and Eastern Africa encountered internal reverse migration from cities to villages and rural areas was reported (Chirisa et al., 2021; Chirisa and Campbell, 2023). In India, the loss of jobs due to the lockdown led to massive reverse migration; ~6.3 million laborers traveled back from cities to rural native places in May–June 2020 only (Suresh et al., 2020; Bhattacharyya et al., 2023). Reports of a study by the UN say that the crisis will jeopardize poor rural communities, particularly the indigenous population dependent on the forests for their livelihood. The pandemic-induced survival crisis will increase the dependence of vulnerable rural and indigenous communities on forests and other natural resources (Amburgey et al., 2023). Forests act as a safety net for rural and indigenous populations in times of crisis (pandemic or any other disaster) by fulfilling their subsistence needs, thus helping their welfare and prosperity (Sengupta and Jha, 2020). A large chunk of the population, ~1.0 billion people, globally depend on forests to some extent for foods such as wild meat, edible insects, edible plant products, mushrooms, and fish as part of their balanced diet. Some 2.4 billion people, i.e., one-third of the global pool both in urban and rural areas, depend on bioenergy for cooking food, heating water, and warming their homes. Wood fuel (including fuelwood and charcoal) remains one of the cheap and easily available sources of energy for people in times of natural disasters and humanitarian crises (Rafa et al., 2022). Because the region will observe massive reverse migration, rural areas and natural resources that support that population will be under extreme pressure. Reports from different parts of the world revealed that rural and indigenous communities living at the fringes of forests responded to pandemic-induced survival crisis by increasing dependency on the forests, giving rise to exacerbated incidences of illegal felling and poaching, charcoal production, tenure conflicts, land clearing for agriculture expansion, land encroachment, forest crimes, and other many such activities for immediate economic relief which led to deforestation and biodiversity degradation (Tripathi et al., 2021). Global economy contraction, along with backward massive urban-to-rural migration as a consequence of the pandemic, will have significant short- and long-term repercussions on forests and forest-dependent rural and indigenous communities (Saxena et al., 2021).

Ecotourism

The travel and tourism industry contributes the lion's share of 10.3% to the GDP of the world, even greater than agriculture. It has a major role to play in employment generation as one in every four new employments is created by this sector in the year 2019 only. According to Nature4Climate, "wildlife tourism" is a US$ 343.6bn a year global industry −21.8 million or 6.8% of all tourism jobs around the world are linked to wildlife; tourism in "protected areas" is even bigger, generating US$ 600bn in revenues annually, compared with the $10bn cost of maintaining protected sites. Interestingly, coral reefs generate US$ 36bn for the global tourist trade (Reynolds et al., 2021). The job created by wildlife tourism in Africa is as high as 36.3% nature for climate. The ecotourism sector of the tourism industry is growing at an impressive speed, specifically in Africa, where it has acquired the status of the second-largest industry responsible for earning a major part of the foreign exchange. Ecotourism was conceptualized very recently in 1980 with the purpose of generating revenue from nature for the protection, conservation, and development of natural resources (Stronza et al., 2019). According to an estimate by Folinas and Metaxas (2020), almost all the countries across the globe with tourism destinations saw a sharp decline in tourism (20–30%) in 2020 owing to travel restrictions imposed during COVID-19, as it was clear from the reduced number of travelers (290–440 million). The measures to check the dissemination of corona across the countries, such as border closures, travel restrictions, and time and again lockdowns, collapsed the ecotourism industry completely and gave set back to many ambitious conservation programs across Asia, Africa, and South America aimed at protection and conservation of some of the rare wildlife and the natural habitats. In the opinion of experts, this situation will certainly increase the incidences of illegal activities such as tree mining and wildlife hunting as many of the conservation agencies will be forced to rest their activities due to the dearth of funds available from ecotourism besides threatening employment in this sector (Fernández-Bedoya et al., 2021). Most of the protected sites under ecotourism have been shut down due to the imposition of coronavirus-related restrictions to check the spread of the virus. The tourism industries where these are based on nature to a greater extent—as in the countries of Costa Rica and India—have been under long-term crisis since the outbreak of this pandemic, and this can disturb the associated ecosystems due to hampering conservation efforts, difficulties in law enforcement, and increased dependency of local communities on the nature for their survival (Shah et al., 2023). There are such reports of the forest-based tourism industry being affected severely during the COVID-19 pandemic across the globe. Ecotourism in all protected areas of Bangladesh, including the Sundarbans mangrove forest and the hill forest in Sylhet, was prohibited by the Forest Department in response to the pandemic situation, causing financial losses besides rendering thousands of people involved in this sector jobless. According to an estimate by the Bangladesh Tourism Board (BTB), the tourism industry in Bangladesh lost USD 177 million in the first quarter of the pandemic and is also anticipated to bear losses of more than USD 700 million by the end of 2020 (Rahman et al., 2021). Reports from Nepal are also similar in line, where ecotourism and the hospitality industry have been the worst affected sectors due to the pandemic. Findings revealed that tourism contributing 8% of the GDP of Nepal, accounting for a million job opportunities, has brutally collapsed (Laudari et al., 2021). The Dhorpatan Hunting Reserve in Nepal, which is famous for hunting Himalayan tahr and blue sheep, lost an income of 10,000 USD in 2020 due to a lack of tourists during the pandemic (Uprety et al., 2021). As a consequence of pandemic-related guidelines and restrictions, 1.2 million USD was missed from the tourism sector on a daily basis (excluding homestay) in the province (ESCAP and Network, 2021). Even the homestay business suffered the mayhem of the pandemic, losing an income of 1.26 million USD during the lockdown period. Tourism is estimated to have directly contributed 2.7% to GDP and 6.7% to the employment of the country in 2019–20. In India, tourism-based employment fell from 12.7 to 8.0% in 2019–2020 (Singh and Neog, 2020). Malaysia also encountered the same scenario where the pandemic crashed the tourism industry severely. Following the restrictions to contain the pandemic, the number of tourists to Sabah fell by 98% in the initial 2 months of lockdown (April and May 2020), causing 90% revenue loss to tourism agencies. Ecotourism in other parts of the world, such as East and Southern Africa, came to a halt as a consequence of restrictions imposed during COVID, leading to a sharp decline in the number of visitors at forest-based sites. This has resulted in revenue losses from ecotourism for funding conservation programs and related expenditures. The local economic crisis has also affected the rural communities living on the fringes of the forest, which are potential ecotourism (Lindsey et al., 2020; Enns et al., 2023). The Zimbabwe Parks and Wildlife Management Authority estimated a US$3.8 million (50%) deficit from April to June 2020 due to a decline in revenue generated by tourism (Lindsey et al., 2020). The community ecotourism sector under the CAMPFIRE in Zimbabwe is one of the most affected industries by the COVID-19 pandemic (Mudzengi et al., 2022). Similarly, the Uganda Wildlife Authority (UWA), which earns 88% of its income from tourist entrance fees, projected a loss of US$1.4 million for conservation activities in the third quarter of 2020 (Lindsey et al., 2020). Out of ∼1.5 million visitors per year in Kenya, on average, 70–80% come to visit national parks and generate a hefty sum of $1.6 billion as annual revenues. According to the African Wildlife Foundation, the pandemic has left ∼3 million people in Kenya jobless who were previously involved in conservation activities at the end of May 2020. Results of preliminary online studies to observe the effect of the COVID-19 pandemic on ecotourism showed that the pandemic caused a significant adverse impact on the number of visitors at forest-based destinations, the livelihood of local communities, and conservation activities in 38 African countries (Waithaka, 2020; Cumming et al., 2021). The revenue generation by federal land management agencies in the United States has decreased manifold due to the pandemic. Generally, these agencies collect revenues by extractingresources and permitting various activities in the forest land under the guidance of forest personnel, which involves fee collection. As per the Matikiti-Manyevere and Rambe (2022), a sharp decline of almost 70%, amounting to US$1.1 billion, has been lost by the US due to the delayed opening of parks, strict health guidelines, and travel restrictions imposed across the globe as well as within the country. This reduction in the revenue generation is likely to affect the 25000 permanent and contractual employers employed at various capacities under the National Park Service, having ∼500 concessionaires in 100 park units. The decline of international tourism will lose trillions of dollars and millions of jobs. The pandemic-led impact on ecotourism will further reduce the funds for the protection and conservation of natural resources, which are already deficit as economic fallout and humanitarian crisis have diverted the attention and funds to the health sector and for securing livelihood (Cherkaoui et al., 2020).

Green economy

The world has witnessed three waves of pandemic till date with fourth in continuation, resulting in severe public health crisis. Measures to check the transmission of COVID-19 has sent shock waves to global economy, exacerbating poverty and job crisis. The COVID-19 pandemic has caused an economic crisis and poverty alleviation (Figure 4) specifically due to exorbitant spending on health (Figure 5), resulting in the accelerated vulnerability of society, especially rural and indigenous communities, and increased pressure on natural resources. The pandemic and environment are interlinked as the zoonotic diseases originate due to close human—wildlife interaction as a consequence of biodiversity loss and land use changes while pandemic causes biodiversity loss by precipitating deforestation in lieu of increased dependency of people on forest as social safety nets during crisis (Terraube and Fernández-Llamazares, 2020; Akinsorotan et al., 2021; Lawler et al., 2021). Therefore, conservation of biodiversity is important to check the next pandemic. The pandemic-induced socio-economic crisis calls for sustainable recovery which demands investment in nature to prevent the future emergence of zoonotonic diseases while rebuilding global economy (Platto et al., 2021). There are multiple green solutions which can be explored, identified, and integrated in pandemic recovery packages with urgency. The nature-based synergies will help in achieving the immediate goal of economic recovery while taking care of long-term targets of biodiversity conservation and healthy ecosystem to prevent human wildlife interaction in close proximity. Conservation of nature is job intensive and can be harnessed to generate employment in various sectors such as afforestation and reforestation, ecosystem restoration, watershed development, management and protection of forests & wildlife, sustainable food production, and resource conservation and recycling (Morand and Lajaunie, 2021). Investing in nature helps in preventing future pandemics, mitigating climate change, and providing ecosystem goods and services to the people. Nature-based solutions employ cost-effective strategies to make human societies more resilient by helping in achieving many of Sustainable Development Goals. The United Nations called for the immediate need of sustainable recovering strategies guided by 2030

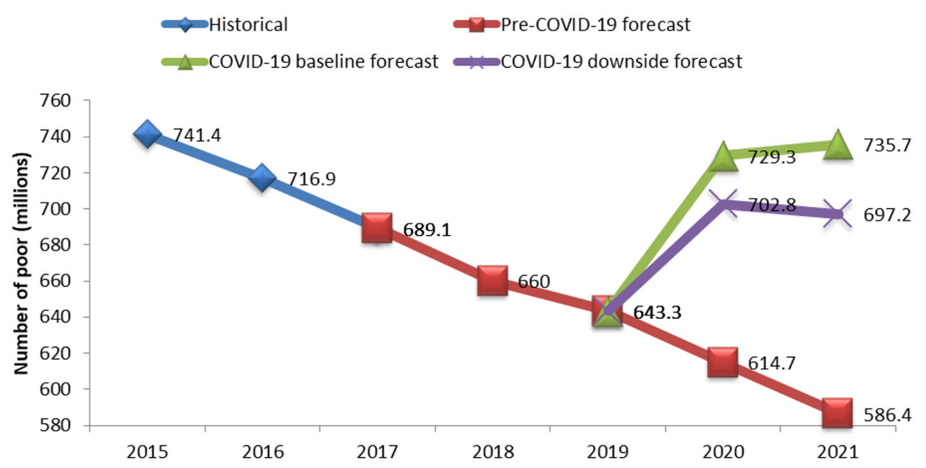


FIGURE 4
Impact of COVID on poverty worldwide (Source: Lakner et al., 2020).

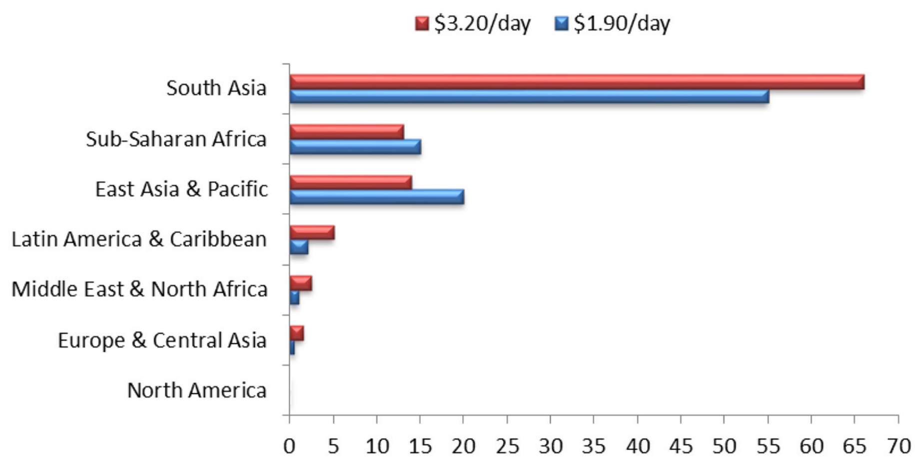


FIGURE 5
Impact of COVID on poverty due to health spending (Source: Blake and Wadhwa, 2020).

agenda to deal with the socio-economic crisis due to COVID-19 at the national level. While issuing guidelines at the country level, the UN announced the Partnership for Action on Green Economy (PAGE) program, which will employ green means for economic reforms based on integrated approaches. PAGE, mobilized by the UN as a joint venture, is an attempt to support nature-based solutions aimed to tackle economic and environmental issues concurrently. Green stimulus packages adopt cost-effective and environment-friendly sustainable integrated measures that work toward economic growth and resilience by creating a healthy ecosystem and mitigating climate change. The COVID-19 situation presents an opportunity for a transition to a green economy, which can help in achieving the sustainable development goals set under the 2030 agenda. The recovery measures guided by SDG and NDC targets will not only reform economic growth but also deal with the issues of climate change, abiding by the fact that the poor and vulnerable are more prone to climate change and ecological instability. Many governments across the globe have announced a range of fiscal stimulus packages for socio-economic reform following the pandemic crisis. Although various countries have announced financial recovery packages of a considerable amount, they allocated a minor share to green recovery (Koasidis et al., 2022). As per Vivid Economics' Green Stimulus Index, a hefty sum of USD 3.5 trillion has been allocated to different sectors (agriculture, energy, industry, transport, and waste) by 17 economies (OECD and G20 countries), which are intimately related to nature (Figure 6).

However, in most of the countries except France, Germany, and the United Kingdom, funds apportioned to sectors having a negative impact on nature outweigh the finances to the nature-friendly sectors (Rechsteiner, 2021). Across the globe, financial recovery packages of ~10 trillion USD have been announced to date to deal with the pandemic crisis. Canada is one of the major leading countries that have shown their political determination to transition to a green economy. In December 2020, Canada established World Bank Clean Energy

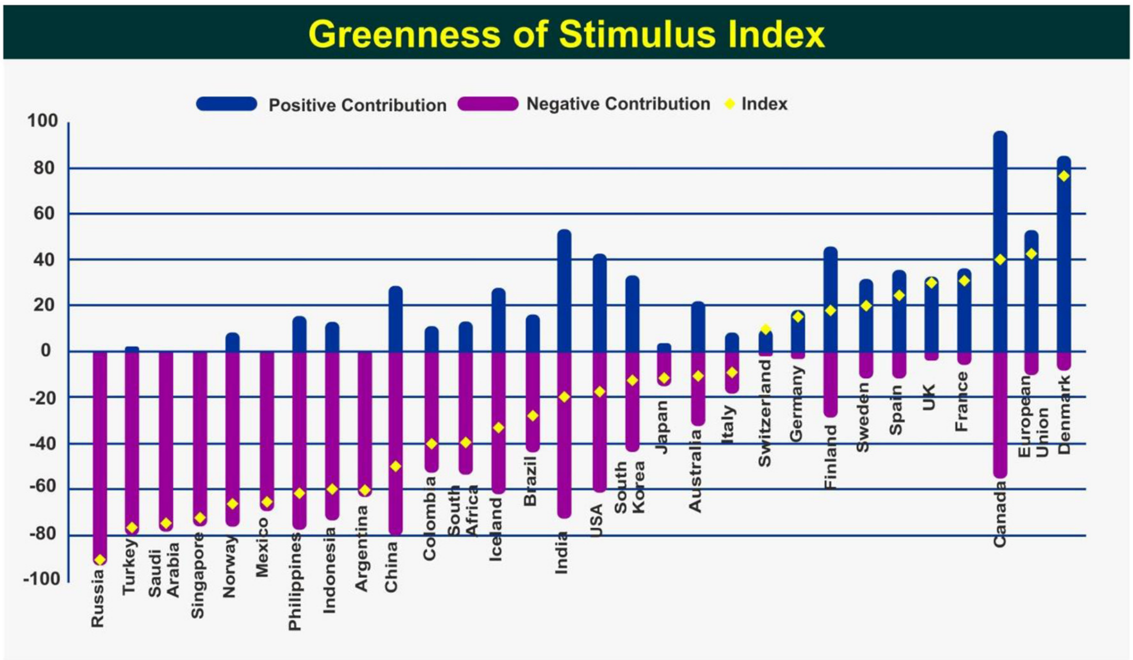


FIGURE 6
Percent allocation of the stimulus package announced by different countries toward nature (Source: Vivid Economics, 2021).

and Forests Climate Facility to support transformational climate actions of World Bank projects, targeted at mitigating climate change by halting deforestation and forest degradation through protection, conservation, and management of forest resources (Rechsteiner, 2021). In the US, there is momentum to steer recovery strategies toward more sustainable environmental and economic development. The USA Government constitutes a Civilian Climate Corps, which will help in employment generation in green areas (Boone et al., 2023). European countries such as Germany decided to invest in the conservation of nature to deal with the pandemic crisis in an environmentally sustainable and socially responsible manner. Netherlands suggested that EU fiscal packages should be guided by a regional "green finance taxonomy" that aims to support investment in green technologies by giving incentives. UK Research and Innovation (UKRI) is sponsoring the projects aimed at exploring the socio-economic and environmental impact of the pandemic outbreak (Ruiu et al., 2022), and France's National Research Agency has called for short-term proposals (RA-COVID-19) for carrying out research on different aspects of COVID-19 related to life and environment (Morand, 2022). Other countries across the globe, such as New Zealand, Australia, India, and Pakistan, are also focusing on nature-based solutions to fight pandemic-generated socio-economic and environmental problems.

Conclusion

COVID-19 has affected many dimensions of human society, forests being one of the major hits. Deforestation took place at an increased rate during COVID period due to exacerbated demand for forest products, a dearth of human resources, diversion of funds, a sharp decline in ecotourism, and reverse migration. Deforestation and zoonotic diseases are interlinked to each other intricately. Deforestation causes increased chances of human and wildlife interaction, thus communication of zoonotic diseases to mankind. Zoonotic diseases precipitate deforestation due to greater dependency on forests during a crisis, deficit manpower, and curtailed budgets due to the priority of the health sector over natural resource management. Therefore, efforts should be aimed at building back better through a green economy. Investing in nature is a sustainable way of recovering from the pandemic, economically by employment generation and environmentally through maintaining and restoring ecosystem health and climate change mitigation. Governments across the globe are announcing huge fiscal packages to deal with COVID-19 induced socio-economic crises. This situation provides an opportunity to steer COVID-19 stimulus packages toward nature-based solutions for transition to a green economy, which will not only help in socio-economic recovery but also in building community resilience to cope with livelihood crisis, particularly for rural communities that depend on nature and land use for their survival. Nonetheless, the recovery spending could provide a unique opportunity to change this: If recovery packages would focus on accelerating the transition toward low-carbon energy and improving energy efficiency, it could be a significant boost toward reaching the Paris Agreement targets and national climate policy goals (Ortiz et al., 2021). The present disruption due to the pandemic, in this way, may facilitate the shift toward sustainability, which is an ambitious goal to achieve as per the 2030 agenda. Policymakers should use this opportunity to propose inclusive policies for using the recovery funds for a green and sustainable future. Recent studies by economists suggested "investment in ecosystem health and resilience" to be one of the major recommendations to achieve economic recovery and climate mitigation goals. The concept of green recovery pushes for building a sustainable and resilient future (Moglia et al., 2021). The efforts to recover from the pandemic-created crisis should be centered on employment generation, mostly in green sectors, judicious use and sustainable management of natural resources, ecosystem resilience, and acknowledging the rights of indigenous communities. COVID-19 has caused a major setback to climate change programs and other efforts to achieve sustainable development goals, the recuperation of which is possible only through green recovery. The COVID-19 crisis divulged the strength of forestry as an effective measure to address social, economic, and environmental issues. Recognizing the importance of forestry in poverty alleviation, employment generation, enhancing ecosystem resilience, and reducing the vulnerability of rural and indigenous communities, it is a wakeup call to introduce forestry-based solutions into pandemic recovery strategies to strengthen the economy and societies to face the global challenges in future.

Government and non-government national and international bodies should take swift initiatives at the policy level to reap the benefits of sustainable forest management by allocating funds to the forestry sector in response to COVID-19. Although the UN Strategic Plan for Forests 2030 already envisaged forestry as a vital component for economic development, social wellbeing, and environmental resilience, integrated efforts at the political level and accelerated decisive actions are urgently needed to achieve a green future. The green recovery from the pandemic is possible only through sustainable and healthy forest ecosystems and resilient communities residing on the fringes of the forest.

Policy recommendations

The following recommendations in the context of forests for COVID-19 green recovery could be acknowledged:

1. Strengthening of forest governance by using modern technologies such as real-time satellite imagery, which rely less on manpower.
2. Ensuring legal and sustainable global timber trading.
3. Employment generation in the green sector.
4. Recognizing the role of indigenous communities in forest protection and conservation and ensuring legal protection of their land tenure rights.
5. Incentives for halting deforestation and reducing emissions.
6. Ruling out the relaxation of environmental laws during the pandemic and effective enforcement of environmental regulations to check illegal felling, wildlife trade, and land-use changes.
7. Design and formulate policies and strategies for a post-COVID-19 green recovery.
8. Exploiting the potential of carbon sequestration in the forest products sector for building back better post-COVID-19.
9. Conceptualization of green cities through expansion of natural ecosystems in urban areas is an effective way of conserving nature while being socio-economically beneficial.
10. Integration of agroforestry in the nature-based solutions for COVID-19 recovery as an immediate means of alleviating poverty and hunger by improving productivity and diversifying the livelihood of particularly small landholders.
11. Industries such as ecotourism, which rely on natural ecosystems, should be supported by COVID-19 fiscal recovery packages.
12. Intensify international cooperation and finance to conserve and restore the ecological integrity of natural ecosystems and address the drivers of ecosystem degradation, fragmentation, and conversion.
13. Environmental responsibility should be fixed for the sectors that are associated with a heavy biodiversity footprint, such as agriculture, energy, and industry.

Author contributions

VS: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. DJ: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. AR: Data curation, Formal analysis, Writing – original draft. RP: Conceptualization, Data curation, Formal analysis, Writing – original draft. IS: Formal analysis, Writing – review & editing. TB: Conceptualization, Data curation, Formal analysis, Writing – original draft. VP: Data curation, Formal analysis, Writing – review & editing. SF: Data curation, Formal analysis, Writing – review & editing. LJ: Funding acquisition. NA: Funding acquisition. MJ: Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Global assessment of production benefits and risk reduction in agroforestry during extreme weather events under climate change scenarios

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Climate change and extreme weather events are threatening agricultural production worldwide. The anticipated increase in atmospheric temperature may reduce the potential yield of cultivated crops. Agroforestry is regarded as a climate-resilient system that is profitable, sustainable, and adaptable, and has strong potential to sequester atmospheric carbon. Agroforestry practices enhance agroecosystems' resilience against adverse weather conditions via moderating extreme temperature fluctuations, provisioning buffers during heavy rainfall events, mitigating drought periods, and safeguarding land resources from cyclones and tsunamis-type events. Therefore, it was essential to comprehensively analyze and discuss the role of agroforestry in providing resilience during extreme weather situations. We hypothesized that integrating trees in to the agro-ecosystems could increase the resilience of crops against extreme weather events. The available literature showed that the over-story tree shade moderates the severe temperature (2–4°C) effects on understory crops, particularly in the wheat and coffee-based agroforestry as well as in the forage and livestock-based silvipasture systems. Studies have shown that intense rainstorms can harm agricultural production (40–70%) and cause waterlogging. The farmlands with agroforestry have been reported to be more resilient to heavy rainfall because of the decrease in runoff (20–50%) and increase in soil water infiltration. Studies have also suggested that drought-induced low rainfall damages many crops, but integrating trees can improve microclimate and maintain crop yield by providing shade, windshield, and prolonged soil moisture retention. The meta-analysis revealed that tree shelterbelts could mitigate the effects of high water and wind speeds associated with cyclones and tsunamis by creating a vegetation bio-shield along the coastlines. In general, existing literature indicates that implementing and designing agroforestry practices increases resilience of agronomic crops to extreme weather conditions increasing crop yield by 5–15%. Moreover, despite its widely recognized advantages in terms of resilience to extreme weather, the systematic documentation of agroforestry advantages is currently insufficient on a global scale. Consequently, we provide a synthesis of the existing data and its analysis to draw reasonable conclusions that can aid in the development of suitable strategies to achieve the worldwide goal of adapting to and mitigating the adverse impacts of climate change.

KEYWORDS

agroforestry, extreme weather, climate change, resilience, adaptation

1 Background

Modern agriculture is greatly affected by a variety of factors, including meteorological conditions, agronomic practices, supply and demand dynamics, price fluctuations, government regulations, and socio-cultural influences (Simelton et al., 2015). The changing climate conditions, including the increasing intensity, frequency, and duration of extreme weather events, pose significant challenges to the both global agricultural production and economies of local communities (FAO, 2015). Recent studies have thoroughly investigated how shifting weather patterns affect the growth and economic output of important crops, offering insightful data analysis (Asseng et al., 2015; Challinor et al., 2016). These studies have shown that despite the general decrease in crop yield and livestock productivity due to changing climate conditions, there can be location-specific differences. Researchers have projected a decline in crop yields ranging from 2.5 to 10% with rising temperatures in the 21st century (Hatfield et al., 2011). Various crops can experience varying degrees of impact, even within the same area (Figure 1). For instance, Zhao et al. (2017) predicted a decrease in the yields of wheat, rice, maize, and soybean crops by 3.2, 7.4, 6.0, and 3.1%, respectively, for every degree rise in the earth's mean temperature (Figure 2). Studies from sub-Saharan Africa show that shifting climate patterns have different but negative impacts on intensively cultivated crops. Further, Blanc (2012) modeled data on different crops from 37 countries for the period 1961–2002 and predicted that the yield changes under alternative climate scenarios relative to no climate change in 2100 would be −19 to +6% for maize, −38% to −13% for millets, and − 47% to −7% for sorghum. Similarly, Warsame et al. (2023) examined the impacts of climate change and non-climatic factors on maize production in Somalia between 1980 and 2018 and suggested that the mean temperature and rainfall had negative effects on crop yield in both the short and long term.

Climate models predict a greater temperature rise in regions closer to the poles than in areas near the equator and in the middle latitudes (IPCC, 2021). As a result, the cultivation of cereal and winter crops would shift toward the north due to the formation of a more favorable climate for their growth (Maracchi et al., 2005; Tuck et al., 2006; Olesen et al., 2007). For example, in the Indian Himalayas, the effect of temperature on apple productivity revealed that rising temperatures at higher elevations create more favorable conditions for plant growth, resulting in greater fruit yields than in lower and mid-altitude regions (Rana et al., 2011). Furthermore, it is crucial to prioritize adaptation and risk mitigation strategies in order to minimize the adverse effects of extreme climatic conditions. Agroforestry, multilayer farming, and silvopastoral systems are a few examples of complex agro-ecosystems that exhibit significant potential for coping with and adapting to extreme weather (Altieri et al., 2015). As a result, it is critical to examine climate-resilient agricultural and agroforestry practices that are appropriate for specific regions and commodities in order to adapt to extreme climatic conditions.

The deliberate introduction of trees in agricultural systems in the form of block plantations, tree-crop combinations, and boundary plantations is widespread agroforestry practice across the globe (Nair et al., 2011). Tree plantation in cropping systems, under diverse management regimens and in various kinds of spatial and temporal

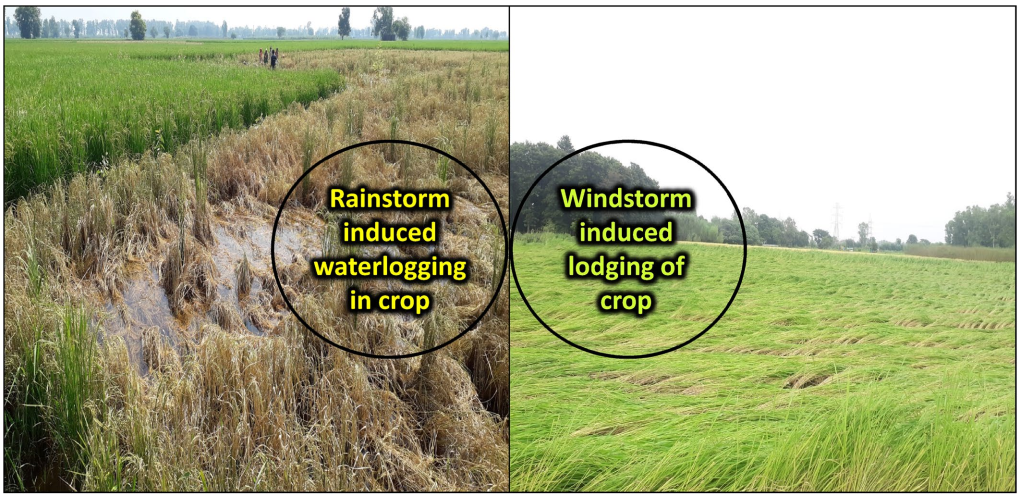

FIGURE 1
Extreme weather induced damage in rice crop (Photo courtesy: Raj Kumar; Sept, 2023, Karnal, India).

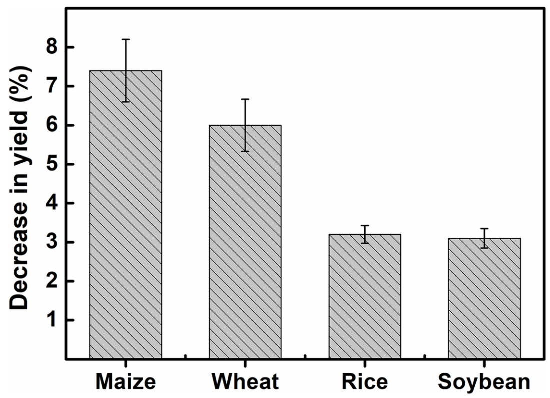

FIGURE 2
Impacts of a 1°C increase in global temperature on crop yields (adapted from Zhao et al., 2017).

arrangements, is essential for reducing vulnerability to uncertain and changing climates (Kumar et al., 2022). Numerous studies have reported the benefits of agroforestry in terms of improving the sustainability, productivity, and profitability of farmlands (Schoeneberger et al., 2012). However, the introduction of trees in croplands also offers a variety of climatic benefits, such as microclimate regulation (Singh et al., 2024), extreme climate tolerance (Noordwijk et al., 2011), and atmospheric carbon sequestration (Kumar et al., 2021). In particular, agroforestry systems have the capacity to enhance the resilience of agronomic crops in the face of a variety of climatic conditions, such as frequent droughts, infrequent floods, and extreme temperature and rainfall events (Altieri et al., 2015). This is accomplished by minimizing the intensity of the adverse effects of changing weather conditions. For instance, tree-crop combinations may be beneficial in regions where the negative effects of climate change are often observed, as crop damage resulting from different weather events can be countered by the output obtained from trees (Kumar et al., 2020a). A large number of farmers have asserted that the diverse tree species play an active role in the adaptation process of the farmers and that this constitutes advance preparation for the anticipated extreme events. For example, Pulhin et al. (2016) found that farmers prefer afforestation and tree protection in anticipation of climate change impacts across all extreme events, including typhoons (19%), drought (21%), and heavy rains (27%), over irrigation and embankment construction. This suggests that agricultural systems that are vulnerable to the adverse impact of climate change, particularly extreme weather events, should consider the implementation of agroforestry practices and tree plantations (Simelton et al., 2015). However, various countries implement a wide range of agroforestry practices, which play a pivotal role in ensuring the long-term sustainability of farming systems (Iizumi and Navin, 2015). Consequently, it was essential to collect factual information regarding the kinds of species and agroforestry systems that have clearly demonstrated a high level of resistance to extreme weather events in the climate change-vulnerable regions of the world (Tables 1, 2). We hypothesized that the integration of trees in agro-ecosystems could enhance crop resilience against extreme weather events under climate change scenarios. This compilation addresses two important issues: (i) What kinds of agroforestry systems are most effective in lessening the effects of extreme weather events? (ii) What types of trees and associated components, as well as their spatial and temporal design, can effectively mitigate the effects of harsh weather in various farming systems? The primary goal of this review was to identify species and propose agroforestry approaches that have demonstrated strong potential for enhancing the resilience of agroecosystems to extreme weather conditions. For the first time, we have made available a special compilation of the potential benefits of agroforestry practices during extreme events. This will enable the drawing of lessons and promote the adoption of climate-resilient practices, which will aid in the development of policies and programs at the regional and global level.

2 Methodology and literature search

The potential of agroforestry to respond and adapt to extreme weather events was analyzed by searching the keywords on the Google and Web of Science. The keywords used are based on ("Agroforestry") and ("Climate change mitigation" or "extreme weather events" or "extreme temperature" or "extreme rainfall moderation" or "drought" or "tsunami mitigation" or "cyclone"). A dataset comprising 1,222 publications were first extracted which was screen out based on exclusion criteria and within scope of the study. The PRISMA framework is shown in Figure 3.

We retrieved 70 research publications from 1991 to 2023 based on these keywords, and collected the data from the databases. The extracted information was categorized into various sections, including the extreme temperature, high rainfall, drought, tsunami, and cyclone. Under each section, the information was organized both agroforestry system-wise and region-wise. Additionally, under each category, all the similar information was organized in a single paragraph and discussed in a chronological pattern based on their relatedness. This subject matter was then followed by other pertinent information on the same aspect. After analyzing the reviewed information, we identified various potential agroforestry models to counter the extreme temperature, high rainfall, drought, and tsunami/cyclone conditions. We conducted a comprehensive analysis after carefully considering the available evidence and information to address the challenges, develop future strategies, and identify the research needs of agroforestry under extreme climate conditions.

3 Agroforestry for mitigating the extreme weather events

3.1 Extreme temperature

The increasing maximum day and night temperatures have a significant impact on crop and animal productivity (Gowda et al., 2018). According to climate models, the earth's average global temperature will increase by an additional 4°C (7.2°F) in the twenty-first century (IPCC, 2021). Similarly, simulations indicate that a 2°C increase in temperature could lead to a 1.7 times higher likelihood of heavy rain events, with a 14% increase in rainfall intensity (IPCC, 2021). Some of the studies have suggested that there could be a rise in temperature and rainfall (5–20%) during the months of December to February and a decrease in rainfall between June and August by the year 2050 in certain regions of the world (Hulme et al., 2005).

TABLE 1 Performance of agroforesty systems and practices during extreme weather events.

Weather hazard	Agroforestry practice	Tree and crop components	Component affected	Country	Source
Drought, flood	Agri-silvi-horticuture	Acacia, Jack fruit, Eucalyptus, Rice	Rice	Vietnam	Nguyen et al., 2013
Multiple hazard	Agri-silvi-horticuture	Acacia, Aquillaria, Rice, Maize, cassava, peanut	Rice, Maize, Cassava, Peanut	Vietnam	Simelton et al., 2015
Flood (Tsunami)	Homegarden	Multi-species	Annual crops	Sri-lanka	Mattsson et al., 2009
Flood	Aqua-horti-forestry	Timber tree, fish, fruit tree	Rice crop	Bangladesh	Shah, 2014
Drought	Agroforestry	Trees species	–	–	Eitzinger et al., 2017
Multiple hazard	Agri-silviculture	Traditional agroforestry systems	Annual crops	–	Altieri et al., 2015
Drought	Agri-Horticulture	Sapota tree, Cowpea and castor	Cowpea, Castor	India	Kumar et al., 2021
High temperature	Silvi-Horticulture	Inga tree, coffee plants	Coffee plants	Mexico	Lin, 2007
Hurricane	Forests	Natural vegetation, coffee plants	Coffee plants	Maxico	Philpott et al., 2008
High temperature and low rainfall	Silvi-pasture	*Leucaena, Prosopis, Cynodon, Panicum, Ceiba pentandra, Syagrus zancona.*	–	Colombia	Murgueitio et al., 2001
High rainfall	Riparian forest buffers	Multiple species	–	United States	Calmon and Feltran-Barbieri, 2019
Drought	Silvipasture	Multiple fodder trees and grasses	–	Zambia	Chibinga et al., 2012
Drought	Agroforestry	Traditional agroforestry systems	Agronomic crops	Peru	Jost and Pretzsch, 2012
Drought	Agroforestry	Cashew, Annual crops	Agronomic crops	Sri-lanka	Bantilan and Mohan, 2014
Multiple hazard	Integrated farming systems	Multiple tree, crops, livestock, Fisheries	–	India	Yadav et al., 2021
Multiple hazard	Agri-silviculture	Multipurpose local tree species	Maize	Kenya	Thorlakson and Neufeldt, 2012
Drought and flood	Agri-silvi-horticuture	Multipurpose tree species, Yams, cassava, maize, banana and rice	Maize, Banana and Rice	Tanzania	Charles et al., 2013
Hurricane	Agroforestry	–	–	Cuba	Rosset et al., 2011
Hot speedy wind	Boundary Plantation	*Azadirachta, Prosopis, Dalbergia and Acacia,* Cotton and Wheat	Cotton and Wheat,	India	Puri and Bangarwa (1992)
Heat wave	Shelterbelt	Eucalyptus, Ber, Tecomella, groundnut, Bajara, guar, Mustard, Wheat and Gram	Groundnut, Bajara, Guar, Mustard, Wheat and Gram	India	Mertia et al. (2006)
High Wind speed	Shelterbelt	Cotton, *Dalbergia sissoo*	Cotton	India	Puri and Bangarwa (1992)
Drought	Tree based systems	*Butea Phoenix, Madhuca Diospyros*	Annual crops	Central India	Chavan et al. (2016)
Extreme rainfall and flood	Agroforestry	*Markhamia lutea, Maesopsis eminii, Casuarina equisetifolia, Albizia lebbeck, Grevillea robusta, Acacia polyacantha*	Annual crops	Indonesia	Van Noordwijk et al. (2017)
Landslides	Tree based systems	*Swietenia, Gmelina, Toona Coffea*, and *Bambusa*	–	West Java, and Sumatra	Hairiah et al. (2020)
Drought and high temperature	Scattered agroforestry	*Prosopis cineraria*, Wheat, Mustard, Gaur, Bajra etc.	Wheat, Mustard, Gaur, Bajra	India	Keerthika et al., 2015
Tsunami	Coastal forest	Mangroves	Reduced the human death toll	India	Kathiresan and Rajendran (2005)
Tsunami	Tree plantations	*Casuarina equisetifolia*	Greater resistance than palm trees	Papua New Guinea	Dengler and Preuss (2003)
Tsunami	Coastal forest	*Rhizophora* spp. and *Avicennia* spp	–	India	Danielsen et al. (2005)
Tsunami	Agroforestry	Combinations of different tree species	–	Indonesia	Bayas et al., 2011
High wind speed	Shelterbelt	*Casuarina* sp.	–	Sri Lanka	De Zoysa (2008)

TABLE 2 Influence of agroforestry on temperature modifications.

Agroforestry system	Region	Findings	Source
Poplar- wheat alley cropping	Temperate region of Germany	1.5°C lower daytime air temperature and 2.5\u00B0C higher night air temperature than open wheat	Kanzler et al. (2019)
Mature agroforestry systems	Mediterranean climate of France	Upto 1.2°C lower daytime air temperature and 0.15°C higher night air temperature than open	Gosme et al. (2016)
Integrated livestock-forestry system	Brazilian Amazon	Improved thermal comfort indices than open pasture	Hawke and Wedderburn, 1994
Pinus palustris- Paspalum notatum based silvopasture	Georgia	Higher air and soil temperature at 5 and 10 cm in silvo-pasture compared to open-pasture	Karki and Goodman (2010)
Wheat in *Faidherbia albida* parkland	Ethiopia	6°C less temperature under trees than in the open fields and higher wheat yield than open	Sida et al. (2018)
Coffee under shade trees	Brazil	2.6°C lower maximum temperature and smaller thermal amplitude than open coffee	Campanha et al. (2004)
Poplar tree based alley	India	Air temperature was inversely proportional to within row spacing of trees	Chauhan and Dhiman (2007)
Integrated livestock-forestry system	Brazil	Lower Black globe temperature-humidity index and radiant thermal load than open pasture	Magalhaes et al., 2020
Silvo-pastoral system	Southern Brazil	3–4°C lower air temperature in summer than open pasture	Deniz et al. (2019)

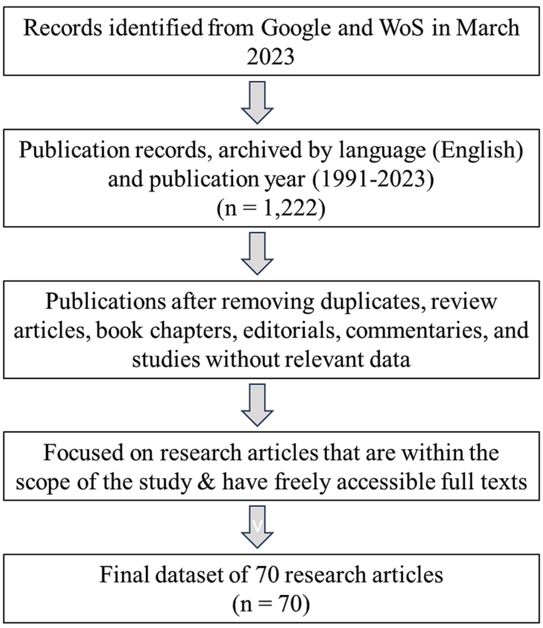

FIGURE 3
Flow diagram of identification, screening, eligibility, and inclusion of the research studies.

The increase in temperatures is projected to have a detrimental impact on most crops, particularly monoculture crops, and the resulting drought could significantly lower crop productivity and create a famine-like situation (Gregory and Ingram, 2000). Smallholder farmers without financial or irrigation resources may use more natural systems to achieve ecological benefits to counteract climate change. Agroforestry systems are natural agro-ecosystems with diverse components that can greatly enhance the resilience of crops to temperature fluctuations (Lin, 2007). The presence of trees on agricultural lands reduces temperature change in a variety of ways (Tables 1, 2). The canopy of trees serves as a buffer against the rapid shift in maximum and minimum temperatures, sheltering the understory from the negative effects of high temperature conditions. The effect of trees on temperature varies not only from one place to another, but also according to the time of year and the day. During the daytime, the tree shade lowers the under-story temperature, protecting the crops from excessive heat during peak summer, whereas at night, the tree canopy maintains higher temperatures, protecting the crops from frost damage, especially during the winter (Gosme et al., 2016). For example, Karki and Goodman (2015) found lower temperatures in agroforestry systems (19.2°C) than in open areas (21.5°C) during the season (Figure 4). This temperature difference between agroforestry and open systems is more marked on clearer days (Gosme et al., 2016). This suggests that the shade of the tree canopy improves the microclimatic conditions for understory crops, increasing their growth and yield (Gregory and Ingram, 2000). The detailed agroforestry system-specific studies are outlined in Table 2.

3.1.1 Wheat based agroforestry systems

Across the globe, agroforestry systems widely cultivate wheat as an annual crop, which is particularly vulnerable to temperature fluctuations. High air temperatures during crucial developmental stages can have a negative impact on grain yield (Porter and Semenov, 2005). Specifically, temperatures above 30°C can lead to pollen sterility and decrease in seed yield (Gregory and Ingram, 2000). Kanzler et al. (2019) found that during hot summer days, the poplar tree-based alley cropping system had a 3.4°C lower temperature than a sole wheat system. Through the practice of agro-forestry, trees play a crucial role in improving water use efficiency and mitigating heat stress in agricultural crops, which ultimately results in the increase in crop yield. For example, Sida et al. (2018) found that agroforestry systems with *Faidherbia albida* trees cut down on the amount of photosynthetically active radiation that reached the wheat canopy. This made the wheat 6°C cooler than in open wheat systems. Additionally, temperature exhibited significant variability in open fields, whereas it showed less fluctuation under the tree canopy. This is due to the ability of trees to buffer heat, providing relief from heat stress during crucial reproductive stages. In India, Kohli and Saini (2003) reported more favorable microclimatic conditions for wheat crop development under *Populus deltoids*, leading to a lower heat load during the post-anthesis period (Figure 5). Such a decrease in heat load under an agroforestry system results in the increase in wheat grain yield by 6.8% (Singh et al., 2024). Similarly, Deswal et al. (2022) showed increase in wheat yield during extreme high temperature conditions with increasing tree density in a *Melia dubia*-based agroforestry system. Research has shown that windbreaks significantly increase wheat yields by 15 to 20% and are highly effective in protecting plants from the damaging effects of winter desiccation (Brandle et al., 1984; Kort, 1988). Thus, the existing research clearly shows the role of tree shade in improving extreme climatic conditions, highlighting the important role of agroforestry in enhancing the ability of the wheat crop to withstand extreme temperatures.

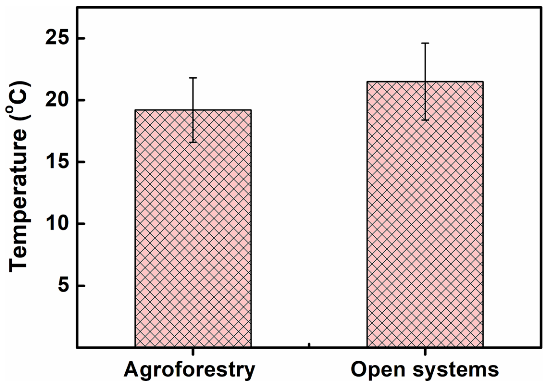

FIGURE 4
Temperature difference between agroforestry and open systems (adapted from Karki and Goodman, 2015).

3.1.2 Coffee based agroforestry systems

Coffee is produced all over the world, with Brazil, Vietnam, Colombia, Indonesia, and Ethiopia being the top coffee-producing nations. Tree species such as Cordia, Albizia, Croton, Persea, Grevillea, and Mangifera are recommended for providing shade to the coffee plants (Wariyo and Negewo, 2023). According to projections, climate change in Brazil might result in a 60% reduction in the area suitable for coffee production (Gomes et al., 2020). However, studies suggest that agroforestry systems have the potential to buffer the negative effects of climate change, and it could preserve 75% of the land suitable for coffee production (Gomes et al., 2020). In Mozambique, the most critical variables that determine the suitability of coffee regions are annual precipitation and altitude. Full sun will be unsuitable for coffee production in Mozambique from 2040 onwards (Cassamo et al., 2023). Shade trees have been found to provide protection for coffee plants against extreme heat and intense sunlight, resulting in a significant decrease in evapo-transpiration loss by 41% during the hot and dry seasons (Lin, 2006). It has been observed that the leaf temperature of coffee plants grown in full sun exceeded the air temperature consistently, while the leaf temperature of shaded coffee plants was lower by 5°C. This difference in temperature could have a positive impact on the physiological processes of the plants (Siles et al., 2010). Further, reports also suggested a decline in the intensity and level of day-night temperature variation in coffee-based agroforestry compared to monoculture. Specifically, Campanha et al. (2004) recorded a 2.6°C decrease in the extreme high temperature in the agroforestry system. Furthermore, literature suggested that trees act as a natural barrier to shield coffee plants from both scorching heat

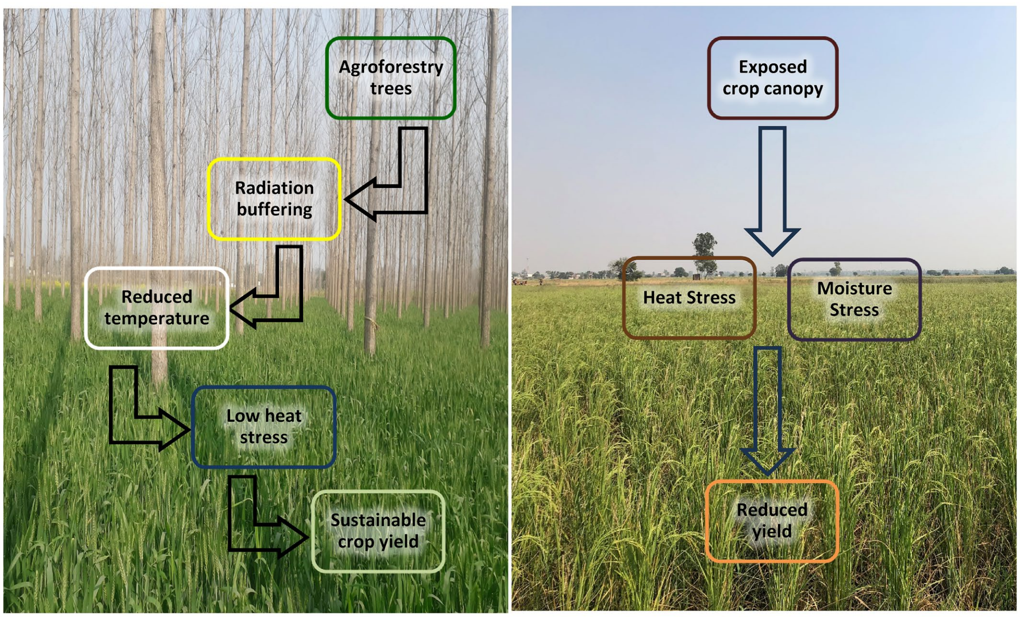

FIGURE 5
Popular (*Populus deltiodes*) based agri-silviculture systems enhances resilience of wheat crop against heat load during during extreme temperature events. (Photo courtesy: Raj Kumar; April, 2022, Yamunanager, India).

and chilling winds, and they play a vital role in conserving water by reducing evapotranspiration. By mitigating sudden temperature changes between day and night, trees help to prevent thermal shocks that can harm the coffee plants. Thus, the presence of trees enhances the microclimatic conditions, creating a more favorable environment for the growth of coffee plants.

3.1.3 Agri-silviculture systems in tropical Hot-arid conditions

Agri-silviculture systems, which combine trees and crops, are the most common agroforestry practices in tropical hot arid climates. The increase in global temperatures negatively affect growth of agronomic crops, especially in the tropical arid and semi-arid regions of the world (Hatfield et al., 2011). In these areas, temperatures under tree canopies are usually 2–4°C lower compared to places exposed to direct sunlight (Cordeiro et al., 2015). The shade of the tree canopy maintains soil and air temperatures, and the row spacing of the trees has been observed to be inversely related to the atmospheric temperature (Chauhan and Dhiman, 2007). Tree species such as *Prosopis* and *Faidherbia* are commonly used in agroforestry systems in the tropical hot-arid regions. In India, *Prosopis* tree-based agroforestry showed a positive impact on the growth of various crops such as cow pea, cluster bean, Pearl millet, Mustard, Taramira, Wheat, and Mungbean in the hot arid conditions of India (Figure 6). They observed a 10–15% higher crop yield under the tree canopy than outside the canopy (Keerthika et al., 2015). This improvement can be attributed to the positive change in the microclimate, particularly the reduction in soil and air temperature. In Africa, studies have found that the *Faidherbia albida* systems increase crop yield by two to seven times compared to open systems (Table 3). Under such conditions, tree windbreaks can lead to a 15–30% decrease in crop water consumption because tree rows help shield the crops from intense and direct sunlight (Thevs et al., 2019). Furthermore, tree-based systems could shield understory crops from heat stress in the face of climate change, as the increase in atmospheric heat and soil moisture stress is expected in the near future. This would be accomplished primarily through microclimate modification, which is influenced by the particular species of trees used and their design (Pezzopane et al., 2015). As a result, tree-based systems and their ability to modify microclimates could play a critical role in addressing climate change in hot and arid environments.

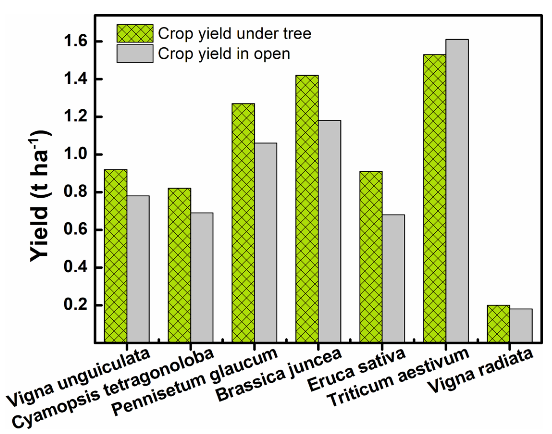

FIGURE 6
Crop yields under *Prospis cineraria* agroforestry in Rajasthan (modified from Keerthika et al., 2015).

TABLE 3 Impact of *Faidherbia albida* agroforestry systems on crop yield under extreme temperatures in the African conditions.

Region	System	Crop	Yield increase	Source
Southern Ethiopia	Parkland trees in farmland	Wheat	11–12%	Haile et al. (2021)
Northern Ethiopia	Parkland trees in farmland	Sorghum	24%	Birhane et al. (2018)
Eastern Oromia, Ethiopia	Parkland trees in farmland	Sorghum	43%	Abdella et al. (2020)
Zambia	Fertilizer tree-based agroforestry	Maize	7–12 times	Yengwe et al. (2018)
Morogoro, Tanzania	Alley cropping	Maize	Remained same	Chamshama et al. (1998)

3.1.4 Silvipasture systems

Silvopastoral systems (SPS), which are practiced across the globe, are a form of agroforestry system that combines trees and pastures to fulfill the fodder requirements of domestic animals. During the daytime, extreme high temperature can have a significant impact on the physiology of the livestock, leading to the decrease in their reproductive and milk production capabilities (Karki and Goodman, 2010). Under such circumstances, agroforestry systems like silvopasture and windbreaks can mitigate the heat stress of the animals as well as maintain the productivity and yield of the forage crops (Dosskey et al., 2017). For example, Mitlöhner et al. (2001) revealed that trees with shade increase cattle weight in less time (20 days early) than those without shade because of the lower air temperature under the silvo-pastoral system than in open pastures (Deniz et al., 2019). Silvipasture systems have the potential to help livestock adapt to the impacts of global warming by creating a more favorable thermal environment that is less restrictive to animal performance (Magalhaes et al., 2020). During spring and summer, the silvo-pastoral system offers a comfortable environment for the livestock (Pezzopane et al., 2019). However, livestock are able to thrive in the treeless pastures in the autumn and winter seasons. They further reported that pasture without trees experiences the unfavorable microclimate and can have a higher thermal comfort index (ranging from 79 to 85) during the early hours of the summer season, making it unsuitable for raising domestic animals (Magalhaes et al., 2020). During the winter season, windbreaks can reduce wind speed, which improves feeding efficiency, lessens animal stress, and increases lamb survival (Dosskey et al., 2017). The triple-row groves under agroforestry systems showed the most significant reductions in heat stress conditions, specifically the Black Globe temperature-humidity index and radiant thermal load for grazing animals compared to open pasture. Moreover, the impact of trees on temperature modification is specific to region, climate, season, and tree density. In Florida, United States, sylvopasture practices lower the wind movement, which leads to lower diurnal dew point and higher temperatures (air and soil) in March, June, and September (Karki and Goodman, 2010). In New Zealand, increasing tree stocking from 0 to 400 stems ha^{-1} in *Pinus radiata*-based sylvopasture system resulted in increase in the minimum temperature of the grass and decrease in the temperature of the soil (Hawke and Wedderburn, 1994). In temperate regions, tree stocking protects animals from sudden increases in the above-ground temperature (Hawke and Wedderburn, 1994). Therefore, silvopastoral systems can be used to lessen the negative effects of climate change because trees can shield pasture land and animals from strong winds, intense sun radiation, and extremely high or low temperatures. This keeps pasture biomass stable and lowers animal stress, which in turn increases the productivity of the livestock and forage resources (Bosi et al., 2020).

3.1.5 Riparian forestry buffers

A riparian forest buffer consists of a wide variety of trees and other perennial plants that are strategically planted alongside a stream, lake, or wetland. These buffers are intended to provide valuable conservation benefits. The increasing air temperature has a direct impact on the temperature of water resources, which in turn affects the habitats of aquatic fish and animal species (Bowler et al., 2012). According to Mugwanya et al. (2022), the rising temperatures of stream water may have a negative impact on the habitat of cold-water aquatic species. However, the shade provided by riparian forest buffers can help keep the water temperatures cooler (Bentrup and Dosskey, 2017). For instance, Cross et al. (2013) showed that increasing stream shade from 0 to 75 percent can lead to a 4.8°C decrease in maximum temperature. This highlights the crucial role that trees play in regulating and preventing fluctuations in stream temperature. A meta-analysis of 10 research studies reported that riparian forest buffers can reduce maximum and mean summer stream temperatures by 3.3 and 0.60°C, respectively, compared to streams without buffers (Bowler et al., 2012). In snow-covered areas, field windbreaks can impede snow and retain moisture by reducing wind speed and dispersing snow throughout the field. This demonstrates the immense potential of tree-based farming systems to regulate the maximum and minimum temperatures of water resources.

4 High rainfall

Rainfall is important to fulfill the water requirements of both cultivated annuals and perennials. However, high rainfall negatively affects agronomic production, and integrated crop-tree production can mitigate the damage from such rainfall events (Kumar et al., 2020b). For instance, Schoeneberger et al. (2012) found that trees and agroforestry-based farming systems are the most preferred farming practices to mitigate the adverse impact of high rainfall on agronomic production. Specifically, compared to agronomic practices such as no till, cover crops, cropping systems, and crop rotation, adding perennial trees to cropland increases rainfall water infiltration by 59% into the soil (Basche and DeLonge, 2019). In agroforestry, trees prevent the direct impact of raindrops, reduce runoff, and increase soil water infiltration, thereby enhancing crops resilience to extreme rainfall events. Furthermore, expanding tree plantations in agroforestry promotes greater rainwater interception and infiltration, which reduces the quantity, speed, and peak flows of runoff, thereby helping landowners adapt to the adverse impacts of extremely high precipitation events (Dosskey et al., 2017; Hernández-Morcillo et al., 2018). Several farmers in the United States reported increased flooding and landslides because of deforestation, which encouraged them to initiate tree plantations and avoid cutting of the existing trees (Philpott et al., 2008). The multi-story combinations of various perennial and annual crop-based agroforestry systems known as homegardens (Figure 7) are considered one of the most preferred and sustainable land use systems for extreme rainfall events in tropical humid conditions (Torquebiau, 1992; Nguyen et al., 2013). Moreover, crop diversification and tree plantations/agroforestry have been suggested as adaptation strategies for reducing the vulnerability of agronomic crops to high rainfall conditions (Altieri et al., 2015).

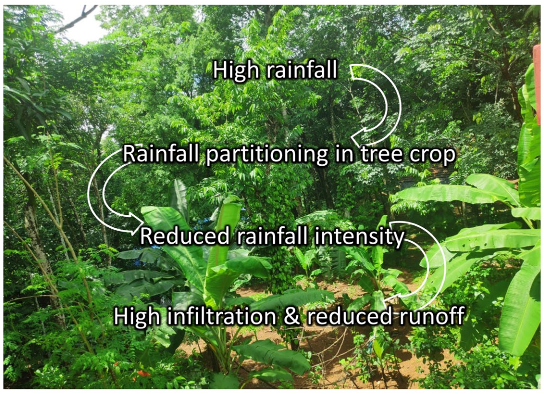

FIGURE 7
Tropical homegardens consists of multiple crops and trees are considered sustainable land use for extreme rainfall events in conditions. (Photo courtesy: A. R. Uttapha; August, 2022, Goa, India).

In the Indian subcontinent, high rainfall often creates water-logging conditions and salinity hazards, leading to an adverse impact on agronomic production. The cultivation of trees along with crops could transpire excess water into the atmosphere, reducing the adverse impact of waterlogging. For example, under waterlogging conditions in Punjab, India, the study findings showed higher evapo-transpiration rates in the agroforestry systems than sole crops, indicating greater removal of excess water from soils and the creation of a better soil environment for plant growth in the tree-dominated systems (Dhillon et al., 2010). In Sri Lanka, the high rainfall-induced rise in water tables increased the soil salinity of low-lying coastal areas, severely affecting the productivity of agricultural land. By designing and practicing agroforestry along the coastal areas, the high water table and salinity level can be reduced to a great extent (Gopalakrishnan et al., 2019). Bangladesh is also highly vulnerable to heavy rainfall events that occur frequently. The anticipated adverse effect includes increased seawater intrusion, which will inundate coastal agriculture lands and human settlements. One of the innovative interventions suggested by the policy planners is the fish, fruit, and forest model (FFF), an agroforestry practice that generates substantial economic return over short, medium, and long terms and, as well as offering diversified livelihood options, reduces salinity, increases protection, and provides resilience against climate change (Shah, 2014). In Vietnam, heavy rainfall-induced extreme flood conditions caused 40% yield loss of the regionally cultivated crops, while farms with trees were less affected (Nguyen et al., 2013). The various tree species performed satisfactorily during extreme weather conditions to provide multiple benefits, including income, food, feed, and other environmental benefits, to the local population. Likewise, in Uttarakhand state of India, an extremely heavy rainfall (338 mm in 1 day) occurred during 2013 that caused widespread flooding and the occurrence of landslides, leading to huge losses to agricultural crops, human property, and animal life. The crop production was severely affected, resulting in a huge loss to the farmers' livelihoods and the state's economy. In contrast, farms with tree-based land use systems were least affected, neutralizing the negative effects of heavy rainfall on agriculture production (Dobhal et al., 2020).

In the United States, high rainfall creates erosion and flooding situations, leading to the occurrence of landslides and the reduction in agricultural productivity. Trees and other permanent vegetation in agriculture systems in the form of agroforestry reduce the adverse impacts of extreme rainfall events, which lead to greater agricultural production (USDA, 2016). Specifically, riparian forest buffers, windbreaks, and alley cropping systems control flooding and soil erosion as well as contribute to sustaining crop production throughout the watershed. Silvopasture and forest farming provide climate-related benefits associated with the extent of forest cover, as well as contributing to diversifying and increasing economic productivity (USDA, 2016). Likewise, in Brazil, analysis showed that integrated systems comprising crops, trees, and animals increase the resilience of farms against extreme rainfall events, as well as control soil erosion, enhance productivity, and generate a large number of socio-economic benefits by increasing the number of products and services available to the farmers (Calmon and Feltran-Barbieri, 2019).

Agroforestry techniques have great potential to reduce farmers' vulnerability to various climate-related challenges in African conditions. In Kenya, researchers identified that farmers are shifting from sole cropping to diverse agroforestry practices in order to protect their farms from future floods (Quandt et al., 2017). In Mesoamerica, coffee-based agroforestry can regulate various ecological services, such as mitigating drought conditions, improving soil health, and preventing flood occurrences that help reduce the adverse impact of extreme rainfall events (Eychène et al., 2014). Such agroforestry systems help reduce farm vulnerability to climate-related hazards by providing multiple ecosystem services (Thorlakson, 2011). Therefore, during high rainfall events, the tree canopy partitions the rainfall and reduces the rainfall intensity, resulting in decreased runoff, increased infiltration, and reduced waterlogging.

5 Intense drought

Drought is a prolonged dry period in the natural climate cycle, which can have a serious impact on society in general and agriculture in particular. The rise in surface temperature is also predicted to increase the frequency of heat waves and droughts, which can severely affect crop production (IPCC, 2021). In particular, arid and semi-arid regions experience prolonged drought conditions caused by low rainfall, resulting in severe damage to agricultural crops. Under drought conditions, the integration of trees into cropping systems provides numerous benefits, such as shade and protection from high winds that help retain soil moisture. This moderation of the harsh microclimate increases crop resilience against drought-induced risks. Specifically, agroforestry can reduce crop water requirements during hot and dry periods of the cropping cycle (Figure 8). One such example is windbreaks, which conserve soil moisture by reducing wind speed, a major factor controlling soil evaporation and plant transpiration (Brandle et al., 2009), and could be highly valuable

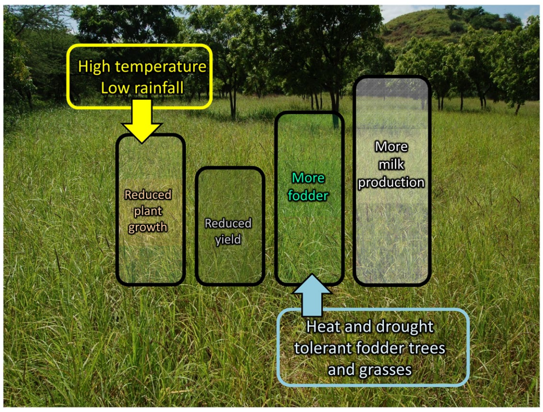

FIGURE 8
Silvipasture systems for extreme drought conditions in hot and arid climatic conditions (Photo courtesy: Arvind Kumar; September, 2022, Bhuj, India).

under water-stressed conditions (Rivest et al., 2013). Such climatic and environmental co-benefits in a tree-based farming system have been proven highly effective in reducing the frequent drought-related risks in arid environments (Eitzinger et al., 2017). The longer and hotter drought periods reduce the vegetation biomass cover and increase the vulnerability of the soil to accelerated erosion (Smukler et al., 2010). Agroforestry practices involving drought-hardy trees can maintain soil by complementing cover crops, which may face establishment challenges in times of drought (Al-Kaisi et al., 2013; Dosskey et al., 2017). The tree canopy also creates a congenial environment for soil biological activities in water-stressed environments (Martius et al., 2004). Further, evidence has shown that low rainfall-induced drought adversely affects annual crops compared to perennial trees, especially in arid and semi-arid rain-fed conditions (Al-Kaisi et al., 2013; Eitzinger et al., 2017; Kumar et al., 2020a). Under normal rainfall conditions, tree shade could decrease the yield of understory crops, while during the drought, the yield could be higher than in an open system, even in intense shade. For example, Kumar et al. (2020a) reported that trees are more resilient to drought conditions than crops, implying that trees have better water and nutrient efficiency during drought conditions. They examined the performance of Sapota trees (*Achras zapota*) and regional crops (Cowpea and Castor) in agroforestry systems, demonstrating that the fruit (Sapota) could offset crop failure during drought conditions, indicating the increased resilience of tree-based farming systems in semi-arid climatic conditions. Furthermore, during the simultaneous production of trees and crops, the trees get water and nutrients from deeper layers, thereby helping to mitigate drought conditions. Blanchet et al. (2021) also reported higher pea yield under trees in drought conditions than normal rainfall. In India, some farmers adopt and promote tree planting to counter the impacts of extreme drought (9% farmers) and intense rains (17% farmers) on their agronomic crops (Udmale et al., 2014).

A silvipasture system (SPS) at the El Hatico farm in Colombia, composed of large trees, medium-sized trees, *Leucaena* shrubs, and a five-story layer of grasses, provided fodder throughout the year for sustainable milk production. In 2009, precipitation declined by 44% that resulted in a 25% decline in pasture biomass production, while the biomass of trees and shrubs was least affected, neutralizing the adverse impact of drought on overall fodder production. Other farmers also reported severe weight loss and reduced milk production in the animals because of starvation and thirst (Murgueitio et al., 2001). Similarly, the agro-pastoralists in Southern Zambia face a significant challenge in securing sufficient fodder for their livestock during droughts. This causes a disruption in their primary source of income because the majority of them does not engage in pasture or fodder management. Trees were the most important source of animal food and milk production during drought (Chibinga et al., 2012), demonstrating the tremendous potential of SPS as a sustainable intensification strategy for climate change adaptation.

In Southeast Asia, farmers who engaged in traditional tree-based agroforestry experienced a speedier recovery from natural disasters, which suggests that they have a greater ability to adapt to climate-related hazards (Burgess et al., 2022). In Peru, multiple weather hazards, *viz.*, frost, floods, drought, and hailstorms, severely affect agriculture and farm animals. The households practicing agroforestry are able to counter the risks and cope with the damages from multiple hazards (Jost and Pretzsch, 2012). In Sri Lanka, farms that are rain-fed and devoid of irrigation are being replaced by drought-tolerant cashew tree plantations to reduce the risk of agricultural failure from severe drought conditions (Bantilan and Mohan, 2014). Recently in India, integrated farming systems, comprising a combination of diverse agricultural, horticultural, forestry, animal husbandry, and fishery practices on a piece of land, have been found quite promising, and these types of farming are also at the top agenda of the Indian government for enhancing climate resilience, in addition to increasing farm income and labor employment (Yadav et al., 2021).

African content is one of the most severely affected regions by frequent droughts, which have a significant impact on the agriculture and livelihoods of millions of individuals. In 2005, Niger experienced one of the worst droughts in its history, resulting in widespread food scarcity, and farmers exchanged timber trees in exchange for cereals. To lessen the effects of drought, some farmers were growing tree species for fruit, fuel wood, timber, and fodder in place of annual crops (Miyan, 2015). These studies demonstrate that establishing drought-tolerant trees and crops can help alleviate high-temperature and low-rainfall-induced drought conditions.

6 Tsunami

Tsunamis are waves that occur near or under the ocean. The rising sea levels induced flooding due to storms and/or tsunamis severely affect coastal communities. Climate-associated geological changes triggered the frequency of earthquakes as well as volcanic eruptions, which, in turn, intensify the threat of tsunamis (Latief et al., 2007). The intensity of damage by a tsunami strike in a coastal area is determined by its strength, coastal geomorphology, area topography, and land use-land cover (Chadha et al., 2005; Kurian et al., 2006). Using coastal vegetation for averting disaster incidences was discussed more than 100 years ago in Japan (Honda, 1898). The coastal vegetation can disperse the energy of the waves, check ingress and flooding debris to a significant level, and reduce the chances of severe consequences (ProAct, 2008). Furthermore, the shelterbelts can be designed to achieve a number of additional benefits, including economic (for provisioning food, fuel wood, timber, and household requirements) and environmental (moderating winds, checking sand dune expansion, improving esthetics, and checking erosion) (De Zoysa, 2008). In contrast, coastlines devoid of any vegetation are always susceptible to storms and tsunami disasters (Danielsen et al., 2005). In some countries, reports have outlined that the coastal communities situated at the back of tree cover are less affected compared to those coastal communities that are directly exposed to the sea (Danielsen et al., 2005; Stein and Okal, 2005; Latief et al., 2007).

The establishment and strengthening of greenbelts or coastal forests (including mangroves) can play an important role in minimizing the consequences of future extreme disaster events (Danielsen et al., 2005). To effectively check tsunami damage, the ProAct (2008) recommends a protective mangrove greenbelt width of 100 to 200 m. Parameters like bioshield width, tree height, and stem diameter have been noted to be the key characteristics influencing impact mitigation (Latief et al., 2007). In addition, multitier agroforestry systems, such as home gardens, have also been found effective in resisting the impacts of climate change. The people living along the coast have acknowledged the importance of these home gardens as protective instruments. Particularly, in Sri Lanka, home gardens have been recognized as future protection measures. In Tamil Nadu, India, areas with mangrove forests aid in protecting human life from tsunami like disasters (Kathiresan and Rajendran, 2005). Overall, most of the research studies have recommended an 'integrated coastal vegetation management system' (Figure 9) that could augment the vegetation bioshield for many years along the coastal areas (Tanaka, 2009).

The resistance to withstand the tsunami varies with the types of tree species and characteristics of the vegetation (Figure 10). For instance, during the 1998 Papua New Guinea tsunami disaster, *Casuarina* trees provided relatively higher resistance compared to palm trees (Dengler and Preuss, 2003). In contrast, the older belts of *Casuarina equisetifolia* trees were found ineffective to provide good quality protection in Sri Lanka and Thailand during the tsunami (Tanaka et al., 2006a,b, 2007). *Casuarina* shelterbelt also provided social and ecological impacts in a better way than the potential economic benefits (De Zoysa, 2008). The effect of the location of tree cover or vegetation indicated that man-made structures placed directly at the back of the most widespread mangroves were not much damaged (Dahdouh-Guebas et al., 2005), and the intense mangroves of *Rhizophora* spp. and *Avicennia* spp. reduced the damage by 96% in most cases (Danielsen et al., 2005). The directly exposed villages experienced maximum damage; those behind the mangroves had a medium level of damage, though the distance between the shoreline and the settlement is also a major factor determining the fatalities and damage. The vegetation in front of the settlement caused around 8% decline in casualties (Bayas et al., 2011). The thick vegetation at the back of settlements resulted in unfavorable effects, increasing structural damage and casualties. Thus, for future coastal planning, productive agroforestry belts should be developed in front of coastal communities, whereas cropping area must be allocated to the back of the villages. The relationship between the crown height and tsunami height is also important in terms of the drag characteristics of broad-leaved trees because they have large diameters sized branches (Tanaka et al., 2007). Moreover, active forest management is necessary to produce all-aged stands with different sizes as well as branches at all levels to improve the mitigation potential, mainly in smaller tsunami events

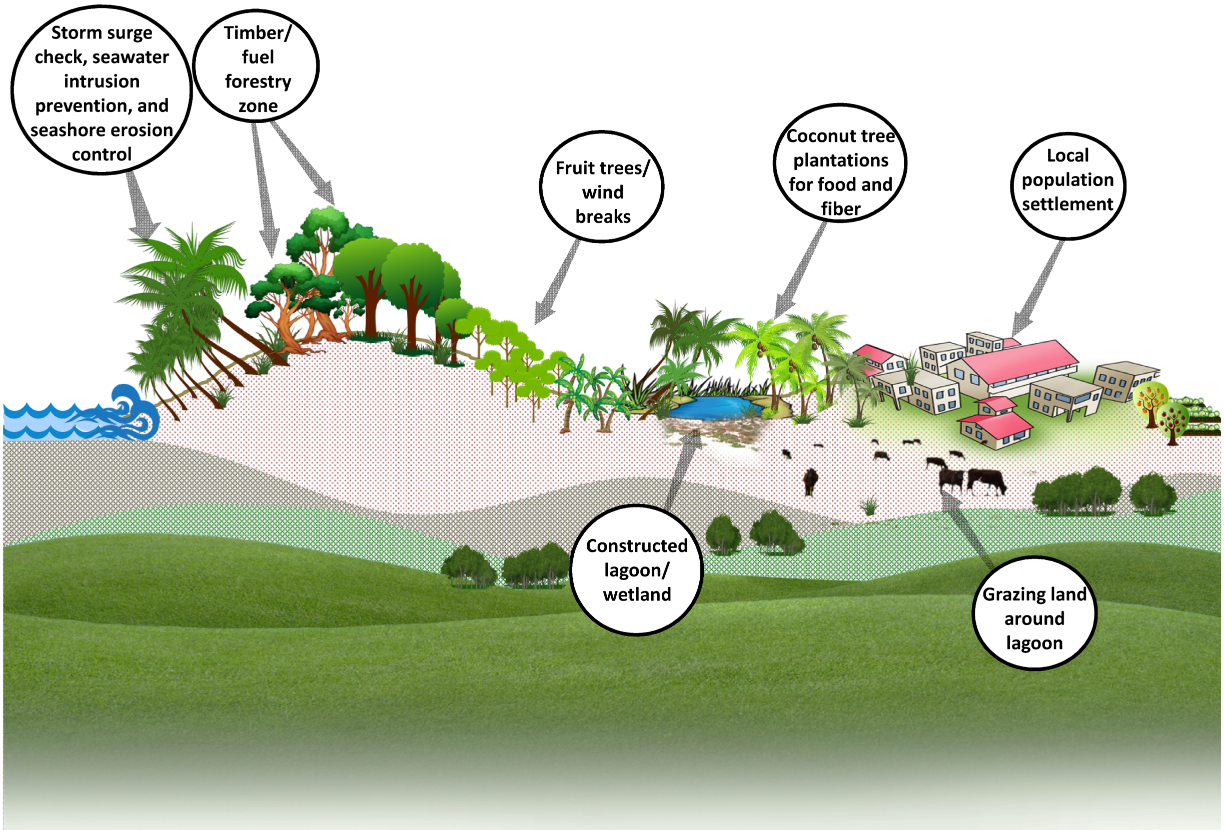

FIGURE 9
Schematic of a vegetation bioshield in the coastal region for storm protection (Adapted from: Tanaka, 2009).

(FAO, 2007). For example, the two layers of vegetation with *P. odoratissimus* and *C. equisetifolia* in a vertical direction demonstrated a strong ability to reduce the damage at the back of the vegetation cover (Tanaka et al., 2007). The coastal grasses (*Spinifex littoreu* and *Ipomoea pes-caprae*) in front of the coastal forest also played an important role in decreasing dune erosion during the low-level tsunami (Sasaki et al., 2007). The integration of diverse tree species has also been advocated along the coastal areas (Tanaka et al., 2007, 2008b). These coastal vegetation captures debris to help humans go up to escape as well as provide a soft landing place during tsunami events (Tanaka et al., 2006b, 2007).

Several studies on the tsunami that ravaged India in 2004 indicated the effectiveness of vegetation along the coastline in saving human lives and infrastructure (Dahdouh-Guebas et al., 2005; Danielsen et al., 2005; Harada and Kawata, 2005; Tanaka et al., 2006a,b, 2007; Nandasena et al., 2007; Sasaki et al., 2007; Tanaka and Sasaki, 2007). In Sri Lanka, the home gardens exhibited greater resilience and protection from the 2004 tsunami, and the houses in their vicinity of home gardens received less damage (Mattsson et al., 2009). The farmers of Central American hillsides have been using diversified practices like intercropping, cover crops, and agroforestry models. They reported less damage in diversified practices compared to their conventional monoculture system during Hurricane Mitch. It was observed that the diversified farms had 20 to 40% more topsoil due to less erosion and better soil moisture and experienced lesser economic losses than the monoculture farms (Holt-Giménez, 2002).

7 Cyclone

A cyclone is a large system of winds that circulates around a center of low atmospheric pressure in a counter clockwise direction. Researchers have predicted that high temperature-induced warming in oceans is expected to intensify storm events, and it is believed that there will be a higher proportion of the most powerful and destructive storms (IPCC, 2021). Tree species play an important role in reducing the severity of storms and other similar events. For instance, during or after typhoons, the top priority could be to use trees for consuming or selling fruits, fuelwood, charcoal, or timber to augment income loss from the damaged crops, besides providing fodder for the livestock (Udmale et al., 2014). Windbreaks can lower cyclone-type high wind speeds across the land surface through a number of physical mechanisms, which in turn reduce the mobilization and movement of dust and dust-related particles (Heisler and Dewalle, 1988; Tibke, 1988). Large agricultural landscapes frequently need multiple barriers to effectively control wind erosion because the zone of reduced wind speed typically extends 10 to 20 times the tree heights downwind of a windbreak (Tibke, 1988). Windbreak also provides additional benefits, such as reduced greenhouse emissions and adaptation to harsh weather (FAO, 2013). For instance, planting a windbreak to reduce the effect of cyclones also sequesters carbon, which in turn maintains the long-term health and productivity of the soil (Schoeneberger et al., 2012). Additionally, compared to monoculture farms, agroecologically

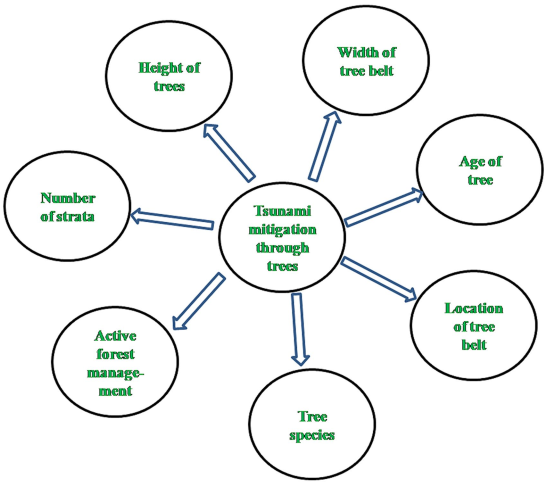

FIGURE 10
Vegetation characteristics that affect the tsunami mitigation potential.

managed farms have the potential for a faster productive recovery (80–90% within 40 days following the hurricane) (Rosset et al., 2011). For example, in Sotonusco, Chiapas, Philpott et al. (2008) reported less damage to more diverse coffee systems during hurricane events compared to less diverse coffee systems. Similarly, in Cuba, diversified farms showed 50% lower losses as opposed to 90–100% extensive losses in monocultures. In order to lessen the perceived risk brought on by the increasing floods and landslide incidents, many farmers grow trees and refrain from cutting them. Farmers may be able to reduce their exposure to major storm events by carefully maintaining their crops. Although unfavorable geographic elements of farms may be beyond farmers' control, the increasing complexity and diversity of the flora within farms could be a successful tactic to lessen some sensitivity to hurricane disturbances (Philpott et al., 2008).

8 Future implications, challenges, and research needs

Across the globe, the increasing frequency and duration of extreme weather events like extreme seasonal temperatures, droughts, and high rainfall events, as well as extreme storms (cyclones and tsunamis), are increasingly posing major threats to agriculture and livestock in general and to humans in particular. The planning and practice of agroforestry have, time and again, demonstrated enormous potential in curtailing extreme weather-related damages to a great extent. Agri-silviculture for crop-tree production and silvi-pasture for pasture production have proven highly effective in countering the effects of extreme temperatures by maintaining crop yield. Under high rainfall conditions, multi-tiered/homestead agroforestry for generating multiple outputs, aqua-forestry for fish-tree production, and alley cropping for erosion control have been found highly effective and may be adopted in regions experiencing extreme rain events. In drought-prone areas, despite the success of large number of tree based farming systems, silvipasture for fodder production showed exceptional performance in terms of maintaining and increasing the livestock milk production. For large-scale catastrophic disturbances such as tsunamis and cyclones, the planning and designing of shelterbelts and windbreak-based bio-shields can largely reduce the damages as anticipated by the predicted climate change. Assessment based on current literature led to the conceptualization of various potential agroforestry systems suitable for obtaining greater economic and ecological benefits under different extreme weather events, as illustrated in Figure 11. However, the extent of climate change mitigation via agroforestry varies with the type of species and the intensification level of each tree component in the agriculture system. Specifically, the findings of the literature available until date explained that the climate resilience is low in a cropland, moderate in a boundary plantation, high in a strip plantation, and very high in a mixed species block plantation (Figure 12). Until now, little to moderate data on field-based evidence is available for countering extreme weather events through agroforestry, therefore, emphasis needs to be given to document precise information for designing the best possible practices to sustain agriculture and animal productivity in the climate change era.

Despite the good adaptation response of agroforestry to extreme weather events, several constraints and challenges at the national and global level have plagued the expansion of agroforestry in new areas. Some of the challenges that were sought were: lack of quality plating material, poor knowledge of local people on agroforestry benefits, poor extension strategies, existence of multiple abiotic stresses, lack of policy and program on promotion of agroforestry, limited best agroforestry practices and models, lack of high-value agroforestry models, and non-availability of data on the relative comparison of resilient agroforestry systems. In order to shift from a crop-based production system to an agroforestry-based farming system, several research, technological, extension, and policy interventions are needed to be addressed immediately and on priority. The most common agroforestry practices in world, include, improved fallow, multifunctional trees on farms and rangelands, alley cropping, home gardens, silvopastoral systems, windbreaks, shelterbelts, taungya farming, and shaded perennial-crop systems. However, the most successful agroforestry practice is the combination of poplar (*Populus deltiodes*) and wheat, which have successfully spread over a thousand hectares in different states in Northern India. Moreover, for successful promotion and upscaling of these types of agroforestry across different region of the globe, various interventions, such as the development of farmer-friendly agroforestry practices, the multiplication and upscaling of superior germplasm, the dissemination of knowledge on ecosystem services, the establishment of wood-based industries, the easy access to wood-based markets, the development of agroforestry based business models, the creation of insurance, credit and subsidy scheme for tree planting, and imparting training and capacity-building to the stakeholders, etc. could be very helpful in transforming crop based production systems to agroforestry based production systems.

Climate change, especially extreme weather events, is causing huge damage to agricultural crops and allied sectors across the

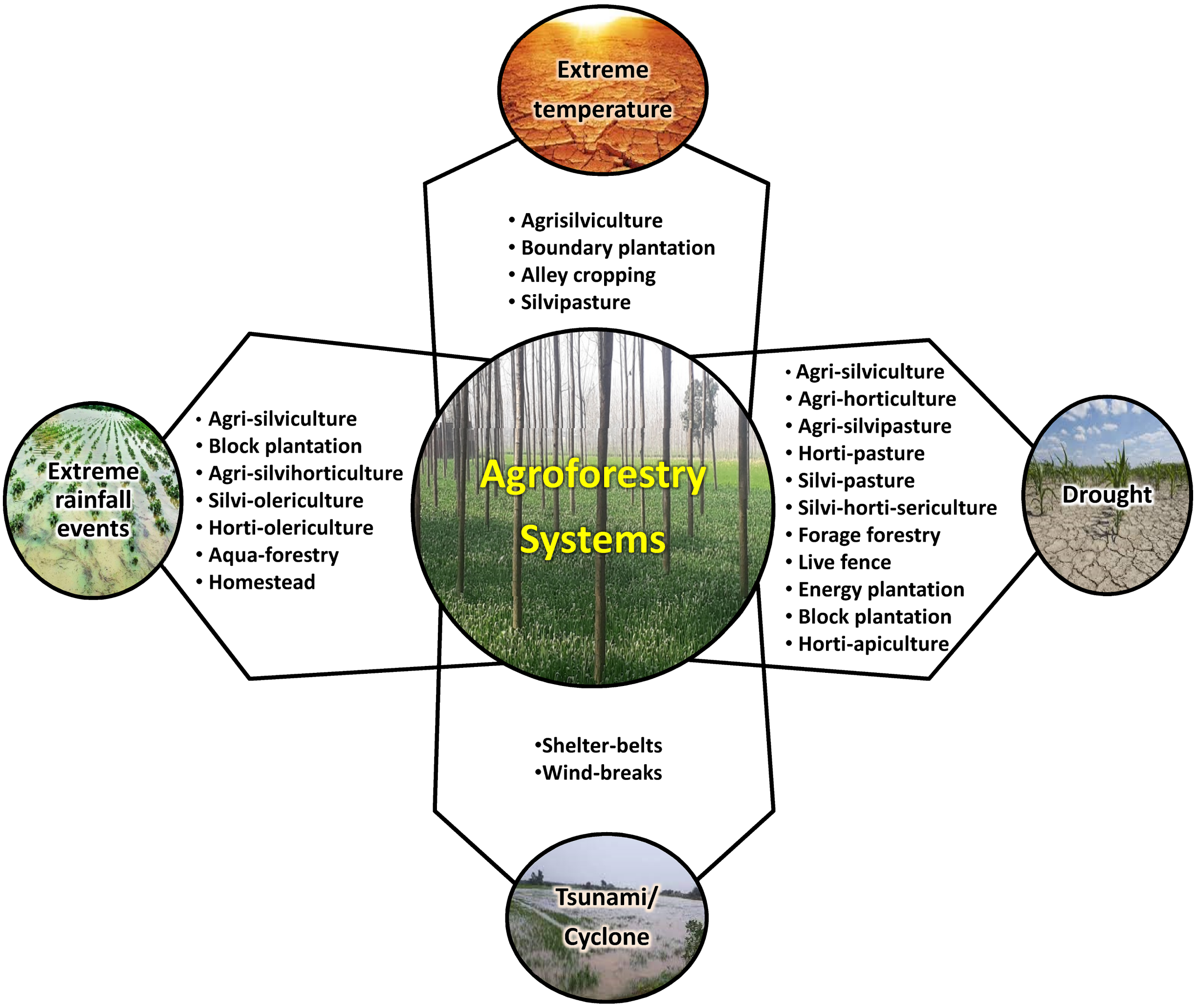

FIGURE 11
Conceptual diagram depicting suitability of various agroforestry systems for different extreme weather events.

globe. The high temperature, abnormal rainfall, and prolonged drought conditions are creating adverse effects on the crops, and in most cases, the failure of agricultural crops has been reported. The devising relationships between extreme weather, crop yield reduction, and agroforestry benefits could provide precise information about crop selection and the design of a mitigation strategy under such conditions. The prolonged exposure of some sensitive tree species to extreme temperatures, rainfall, and drought could adversely affect their growth and biomass production; hence, tree species should be identified those can withstand such harsh conditions. Arid and semi-arid regions are worst affected by extreme weather events, and soil water limitations are the main hindrance to the adoption of commercial agroforestry. Under such conditions, metabolite yielding tree species should be identified, as extreme environments might instigate higher metabolite production in the trees. Further, the complexity of the existence of multiple traits (timber, fuelwood, fodder, and fruit) in tree species makes it difficult to decide which type of trait will be more suitable under a particular type of extreme climate. The information on the level of spatial and temporal intensification of trees in agricultural lands also needs to be redesigned to combat and reduce the adverse effects of extreme weather. To consolidate the claims in the current knowledge further focus need to be exerted on issues that would strengthen adoption of agroforestry as a climate adoption practice.

- Although extreme weather events occur in every part of the world but their documentation is very poor with reference to the analyzing agroforestry response.
- Better analysis of the interaction between the various climate change and mitigation aspects like extreme weather, carbon sequestration, greenhouse gas emission and microclimate moderation, and regional climate amelioration with agroforestry.
- Developing programs for increasing understanding of climate issues and learning from the field experience of farmers on agroforestry designs and their potential in fulfilling adaptation and mitigation objectives, etc., should be prioritized.

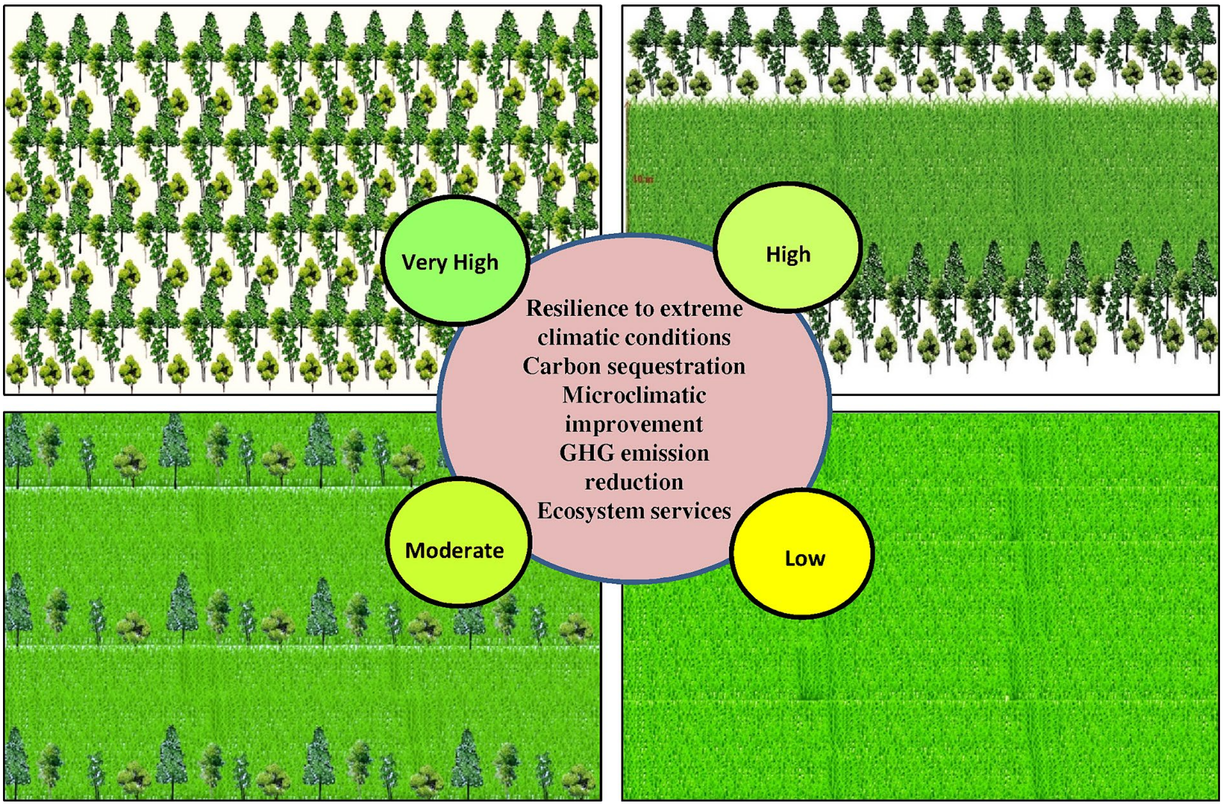

FIGURE 12
Conceptual framework depicting process of enhancing climate resilience of the agro-ecosystem.

- Agroforestry-based climate resilience should also meet productivity, profitability, and sustainability objectives at the farm level.
- Identification of agroforestry tree species for different agroecological and farming systems that meet both production and ecological objectives in general and for the domestication and promotion of tree species suitable for agroforestry in climate-vulnerable regions should be focused on.
- Extreme weather events can also have adverse effects on tree components; therefore, identifying climate-resilient species and their germplasm is important for climate change adaptation.
- The formulation and promotion of appropriate policies, programs, action plans, and institutional infrastructure for greater adoption of agroforestry are urgent needs.

9 Conclusion

The current literature suggests that maintenance and promotion of diverse agroforestry practices at the farm level, with high resilience and multiple benefits, can considerably contribute to the mitigation and adaptation to climate change. Under present conditions, agri-silviculture, home garden, and silvi-pasture are the best systems to cope with the extreme temperature, rainfall, and drought conditions, respectively. Despite the low evidence, the rest of the agroforestry systems can equally contribute to increase farm resilience to extreme weather events. A more complex 'integrated farming system' practice, which is an extension of tropical home gardens, is invariably receiving considerable attention recently among policymakers throughout the world. Though agroforestry practices are adopted by only a small percentage of farmers worldwide, the substantial economic benefits and mitigation-adaptation provided by trees during extreme weather events should be promoted to gather their interest in shifting from monoculture to an agroforestry-based polyculture farming system. Research needs to be focused on the type of tree species to best fulfill the area-specific needs, and the agroforestry package of practices best suited to attain the multiple objectives—climate mitigation, adaptation, productivity, and farm profitability—should be prioritized. A suitable policy framework for localized as well as regional-level adoption of agroforestry to meet the anticipated impacts under the predicted climate change scenarios needs to be urgently developed and implemented with medium- to long-term goals in sight.

Author contributions

SD: Writing – original draft. RK: Writing – review & editing, Formal analysis, Conceptualization, Writing – original draft. AB: Writing – review & editing, Visualization. SC: Writing – original

draft. AU: Writing – original draft. MK: Writing – review & editing, Methodology. AS: Writing – review & editing, Validation. DJ: Writing – review & editing. PR: Writing – review & editing. AH: Writing – original draft, Conceptualization. NR: Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Implementing a sustainable integrated agroforestry system for the cultivation of *Ilex paraguariensis*

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In this work, we advocate agroforestry as a sustainable agricultural method that leverages biodiversity and ecosystem services, simultaneously tackling the problems of adaptation and mitigation to climate change, and of land restoration for sustainable agriculture across scales. While the rise of industrial agriculture has been instrumental in addressing the food demands of an expanding global population, enhancing food quality, yield, productivity, and efficiency, we must now reckon with the consequences. This advancement, which prioritizes simplification, specialization, and external inputs, has escalated detrimental externalities including deforestation, biodiversity loss, soil degradation, pollution, and an increase in greenhouse gases, contributing significantly to global warming and to exacerbated environmental crises. These demand urgent attention. In response, various agricultural methodologies such as organic, biodynamic, ecological, and biological farming have emerged, attempting to propose alternatives. However, these methods have yet to significantly alter the trajectory of mainstream agriculture. For over two decades, we have devoted our efforts to developing and refining a multispecies integrated agroforestry system for the sustainable cultivation of *Ilex paraguariensis*, "yerba mate," in the subtropical north-east of Argentina. With "integrated" we mean that the trees are planted within the *I. paraguariensis* distribution, not between alleys as in "alley cropping" or "hedgrow intercropping." The experimental work we present here was designed and implemented to enable data comparisons across consociations of multiple species of trees, at a relevant experimental scale. We achieve soil preservation and restoration, productivity comparable to or exceeding monocultures, and a significant increase in resiliency, particularly evidenced during the extreme climate events of spring and summer 2021 and 2022. These results underscore agroforestry's potential for climate change mitigation and adaptation.

KEYWORDS

agroforestry, multispecies, sustainability, restoration, biodiversity, adaptation, mitigation

1 Introduction

The Northeast of Argentina is a region that extends into the subtropical forests it shares with Paraguay to the North, Brazil to the Northeast, and Uruguay to the Southeast (Figure 1, left inset; Google Maps, 2024). The whole region was first colonized by the Jesuits (Roca, 2017) who, starting in 1609, built settlements throughout a vast territory that today is part of Uruguay, Paraguay, Brazil, and Argentina (Roca, 2017). In Argentina, most of the missions are in the province of Misiones (Roca, 2017). The Jesuits were pioneers in cultivating the tree *I. paraguariensis* to produce the infusion popularly known as "mate (UNESCO's World Heritage Centre, 2023; Heck and De Mejia, 2007; Gawron-Gzella et al., 2021; Bracesco et al., 2011)." The plant is popularly known as "yerba mate (UNESCO's World Heritage Centre, 2023; Heck and De Mejia, 2007; Gawron-Gzella et al., 2021; Bracesco et al., 2011)" and its crop became in main economic activity of the Guarani territories in the 17th century (UNESCO's World Heritage Centre, 2023), spreading throughout southern South America. Mate gained further diffusion during the independence wars against the Spanish crown and subsequent conflicts involving Paraguay, Uruguay, Brazil, and Argentina (UNESCO's World Heritage Centre, 2023; Sarreal, 2023).

The region is defined by its humid subtropical climate without dry season and its soils are red oxysols with a very high clay content (Pereyra, 2012). While much of Paraguay and southern Brazil have cleared their jungles for cereals, grains, and cattle ranching, the Argentinian part of this territory has retained a mix of native forests and *planted exotic forests*, intersperse with agriculture dominated by perennial species. This fact is immediately apparent in low resolution satellite maps of the region, in which Argentina appears with a much darker green colour than Brazil and Paraguay, the contrast of forests versus arable land cultivated with grains (Figure 1; Google Maps, 2024).

Although *I. paraguariensis* is a native tree species of the subtropical forests of the region, the industrialized production of mate lead to the adoption of the highly mechanized agricultural practices developed for monocultures, using land made available by deforestation. Other agricultural and forestry activities, including, tea plantations, commercial planted forests, annual crops, and animal husbandry, also led to deforestation. There are inherent limits to the expansion of deforestation, primarely because forests are a finite resource. Yet, although the region is well-suited for sustainable practices such as agroforestry and agrosilvopastoral systems (for animal husbandry), these have not been adopted on a transformative scale.

The advent of more frequent and intense climate events, often dramatic in nature, has started to shift perceptions significantly. Throughout most of 2021, the region experienced a shortfall in

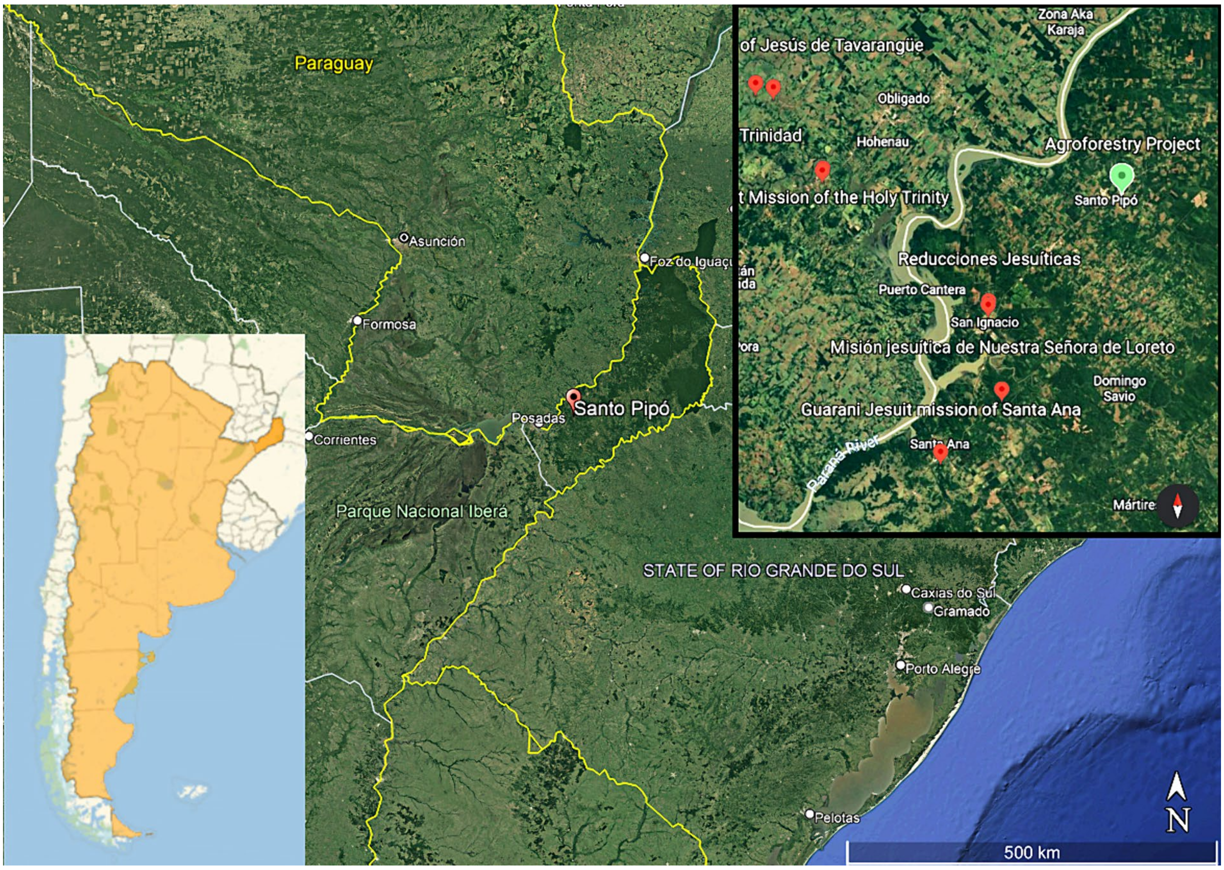

FIGURE 1
Left inset: map of Argentina emphasizing the province of Misiones. Main, map of the north-east of Argentina. The red pin marks the village of Santo Pipo, Misiones, site of this agroforestry project. Political boundaries between Argentina, Paraguay, Uruguay, and Brazil as yellow lines (Google Maps, 2024). Right inset: A blue pin marks the location of the agroforestry project presented here, and the closest red "pin" marks the location of the Jesuit ruin San Ignacio Mini (Roca, 2017). The other red pins mark other Jesuit ruins.

precipitation, with drought periods in May–June and August–September. By early summer, surface temperatures were consistently above historical averages, culminating in record highs of 42.5°C on January 24, 2022. These extreme conditions, persisting through March 2022, resulted in substantial losses in agricultural output, destruction of young, planted perennials, and damage to both ancient forests and newer planted forests. The persistent drought and unprecedented high temperatures led to severe wildfires, further exacerbating the crisis. The combined effect of these events not only devastated local ecosystems but also disrupted both wildlife and human communities, altering public perceptions about climate change and the resilience of traditional agricultural practices in the face of such climate shocks. This crisis has underscores the urgent need for agricultural practices that integrate and leverage the natural complexity of the environment, enhancing resilience against climate variability and promoting sustainability for the future.

Extreme climate events have become more common worldwide, heightening public awareness of global warming (AghaKouchak et al., 2020; Fischer et al., 2021; Zhou et al., 2023; Walker and Van Loon, 2023; Yuan et al., 2023). As global temperatures continue to rise, we can expect more frequent and severe climate hazards (AghaKouchak et al., 2020). The measures we adopt to mitigate global warming will influence the likelihood and severity of these unprecedented extremes (Fischer et al., 2021), as well as their geographical extent (Zhou et al., 2023). With the global population increasing and urban areas expanding, more people are at risk from these climate events. Additionally, the likelihood of simultaneous climate extremes, which significantly affect human welfare and ecosystem sustainability, is expected to increase (Zhou et al., 2023). For instance, concurrent large-scale wildfires, driven by hot and dry conditions, can exceed firefighting capacities, leading to extensive damage and significant ecological consequences (Zhou et al., 2023). Flash droughts, which arise from a sudden deficit in precipitation coupled with increased evapotranspiration, rapidly deplete soil moisture (Walker and Van Loon, 2023; Yuan et al., 2023), making them exceptionally destructive to ecosystems, which cannot adapt swiftly. Projections indicate that under higher emission scenarios, flash droughts could become more frequent and begin more abruptly, posing substantial challenges for climate adaptation strategies (Walker and Van Loon, 2023; Yuan et al., 2023).

How human societies use, manage, and interact with land plays a pivotal role in addressing sustainability challenges and mitigating climate change impacts (Meyfroidt et al., 2022; UN Environment Program, 2023). Addressing the complexities of global climate change requires efforts that extend well beyond reducing atmospheric CO_2 levels (UN Environment Program, 2023). Agroforestry emerges as a viable strategy in this context, notably because it can be initiated and maintained from the bottom up, enabling stakeholders who cannot afford to wait for top-down global solutions to take immediate action. Extreme climate events have starkly highlighted the biophysical effects of deforestation, reforestation, and afforestation, underscoring the local benefits these practices offer, aligned with the self-interest of society.

When we plant a tree, we hope that it will grow tall and straight; that it will have a full, healthy crown with strong, well-spaced branches; that it will cast a broad expanse of sheltering shade; that it will resist damage from wind and ice; and that it will be easy to maintain. Without proper pruning, however, a tree can become unhealthy and expensive to maintain. An unmaintained or poorly maintained tree is more likely to become hazardous, with branches that break during storms, and weak, unsightly shoots. In a multispecies agroforestry system, all the above challenges are present, with the added complexity of managing and calibrating the integration of the trees with the agricultural activity. Our objective is to present the design and implementation of a scalable multispecies integrated agroforestry system capable of sustaining and restoring soil fertility, providing long-term self-sustainable economic results, and contributing to resilience against climate change, insect attacks, and diseases.

2 Materials and methods

2.1 Experimental site

The study was conducted in a 10 has Trial Lot spanning "Lots 1 and 3" (Lote 1 and Lote 3) within "Lote XII" (~98 has), cadastre of the municipality of Santo Pipo, province of Misiones, Argentina, (Google Earth, https://earth.google.com/; 27° 8′30.47″S, 55°23′32.72″W and 27° 8′34.77″S, 55°23′37.18″W respectively). The location is at approximately 175 m above mean sea level. The soils of this region are red oxysols with a very high clay content (Ultisol soil; Pereyra, 2012). The region is defined by its humid subtropical climate without dry season. From year 1967 to year 2020 the average annual rainfall was 1,998 mm, with a minimum of 1,120 (2004) mm and a maximum of 3,034 (2014) mm. Towards the end of 2020 and during 2021 and 2022 the weather phenomenon called "El Niño" brought extremes of heat and drought, while during 2023 "La Niña" brought extremes of rainfall. The total rainfall for 2020, 2021, 2022, and 2023 was 1,310, 1,536, 2,136, and 1,900 mm, respectively. Typically, temperatures range from a minimum just above zero °C to approximately 36°C. The minimum historical temperature was recorded on July 18, 2017, with −8°C at 5 cm above the soil, and the maximum historical temperature on January 24, 2022, was of 42.5°C (Roset, 2022).

2.2 Equipment

During 1993 a Taeda pine or loblolly pine forest was installed for fallow. These trees were fell approximately a year ahead of the plantation of the system in 2010, to allow for the preparation of the land. The remnants of tree crowns were cut down manually with chainsaws, and the field was plowed mechanically. Burning was entirely avoided. Lastly, the fields were marked as described below and a subsoiler was passed tracking the future lines of the plantation. Seedlings were implanted using a shovel, on the track made by the subsoiler, following the distances as planned in the design described below. Field measurements of widths and heights were made using a measuring tape and a telescopic rod, during the month of February of each year (summer). Photosynthetically active radiation (PAR) measurements were performed with a one-meter-long rod ceptometer during the month of September (spring). Soil samples were obtained using a borer or ring sampler of 0.25 m in diameter at 0.2 m of depth, and 1 kg plastic bags for sample transfers. Samples were collected along the rows of each tree species and within the rows of mate (displaced from each tree), for each block of the "trial lot." During

2013 the samples were collected in April and May, with 3 samples at each sampling point (1st, 2nd, and 3rd row of mate away from a tree), that were kept individually separated resulting in 107 soil tests. During 2021 the samples were collected during September, also for each block, but binned at each sampling point, resulting in 36 soil tests. All soil tests análisis were carried out at the Instituto Nacional de Tecnología Agropecuaria (INTA), Estación Experimental Agropecuaria Cerro Azul (EEA Cerro Azul), Ruta Nacional 14. Km. 836, Cerro Azul, Misiones C. P. (3313). The method used for estimations of soil readily oxidizable carbon (ROC %) is based by the chromic acid titration method by Walkley and Black*, standardized in Argentina by the Instituto Argentino de Normalización y Certificación (IRAM) with norm "IRAM-SAGyP 29571-3:2016 Parte 3: Determinación de Carbono orgánico oxidable por mezcla oxidante fuerte- microescala." Oxydazable Organic Matter (OOM) and Total Organic Matter (TOM) are obtained from ROC by multiplicative factors that depend on the context (Walkley and Black, 1934). The values reported were computed from 36 and 107 individual samples for 2013 and 2021, respectively. Soil tests for each individual species have been averaged in aggregate. On-site materials and equipment are described below within Methods as appropriate.

2.3 Methodology

The objective is to establish an experimental multispecies agroforestry system within a 10-ha trial lot. The design of this system will facilitate precise measurements and generate self-consistent data sets. This will allow for meaningful comparisons between different species, ranging from individual plant growth metrics to their contributions to soil health. All *I. paraguariensis* seedlings derived from the seeds created at Estación Experimental Agropecuaria Cerro Azul INTA (EEA Cerro Azul), Ruta Nacional 14. Km. 836, Cerro Azul, Misiones C.P. (3313), Argentina. For the exotic species, seedlings were obtained from local seed orchards, where they undergo selective breeding to enhance specific traits, ensuring a degree of genetic advancement. The seedlings for native species as listed in Table 1 were made in-house from seeds that were meticulously collected from trees within the remnants of native forests in the local region, selected based on their phenotypic characteristics. The nine species were Lapacho negro (*Handroanthus heptaphyllus*), Petiribi o Loro negro (*Cordia trichotoma*), Araucaria (*Araucaria angustifolia*), Cañafístola (*Peltophorum dubium*), Anchico Colorado (*Parapiptadenia rigida*), Guatambú (*Balfourodendron riedelianum*), Toona or Australian cedar (*Toona ciliata*), Grevillea (*Grevillea robusta*), and Kiri (*Paulownia sp*). Figure 2 shows images of the in-house nursery located in "Lote 6A, municipality of Santo Pipo, Misiones, Argentina (https://earth.google.com/; 27° 7′45″S, 55°25′07″W). The seedlings are routinely taken to the field in pots 6 to 8 months after a preselection.

2.4 Experimental design (a scalable model for self-sustainable, integrated agroforestry)

The development of our agroforestry project unfolded gradually, starting in the 1990s. The first step was the soil restoration of a 40-ha swath of highly degraded yerba mate plantations, established in 1934 and managed with conventional methods, by transitioning them into monoculture forest lots of pine (Pinus elliottis and Taeda). This transformation achieved a relevant level of soil restoration through a process of fallowing, in anticipation of a future redevelopment into diversified yerba mate plantations that would integrate various tree species (Comolli et al., 2023). At the heart of this initiative was the creation of a 10-ha agroforestry pilot, or 'trial lot,' carved out from the initially restored 40 has in 2010, as detailed in Chart 1. The pilot project was meticulously designed to enable a comparative analysis of different tree species and to contrast these with control lots that remained treeless. The implementation of the experimental trial lot is the subject of this manuscript. On the basis of this experience and motivated by these results, our agroforestry effort was expanded to 200+ has increasing the number of species as possible, but not keeping this rigorous design for data acquisition and quantitative comparisons. The overall characterization of the 200 + has agroforestry project is explained in a manuscript presented in the open source site agriRxiv (Comolli et al., 2023).

2.5 Planted density of yerba mate and of trees

The planting strategy in our agroforestry lots was meticulously designed for optimal interaction between yerba mate (*I. paraguariensis*) and various tree species. The design of the trial

TABLE 1 Tree Species in the 10 has trial lot planted in 2010, as presented in this work.

Popular name	Scientific name	Planted density	Density in 2015 (at 5 yrs)	Density in 2018 (at 8 yrs)
Cañafístola	*Peltophorum dubium*	741	246	123
Anchico Colorado	*Parapiptadenia rigida*	741	246	123
Lapacho negro	*Handroanthus heptaphyllus*	741	246	123
Petiribi (loro negro)	*Cordia trichotoma*	741	246	123
Araucaria	*Araucaria angustifolia*	741	246	123
Guatambú	*Balfourodendron riedelianum*	741	246	123
Toona (Australian cedar)	*Toona ciliata*	741	246	123
Grevillea	*Grevillea robusta*	741	246	123
Kiri	*Paulownia* sp	741	<20	--

FIGURE 2
View of the seedlings of native spaces and *I. paraguariensis*. In-house production of seedlings to ensure good quality can be achieved with low cost, ordinary means. Benches in **(A)** are seedlings of yerba mate (*I. paraguariensis*) being transferred to pots; **(B)** Lapacho negro (*Handroanthus heptaphyllus*); **(C)** *I. paraguariensis* in pots approximately 7 months later than **(A)** and ready for planting in the field; **(D)** are seedlings of Cañafístola (*Peltophorum dubium*).

lot consists of the randomized installation of nine tree species, providing nine "treatments," spanning 10 has in four repeated blocks. The initial planting density and subsequent adjustments were based on empirical observations and aimed at achieving the best possible synergy between the components of the system. The agroforestry trial lot was created with a high density of yerba mate (*I. paraguariensis*) and trees following the diagram illustrated in Chart 2. The spacing was 1.5 m between plants of yerba mate in 5 adjacent lines or rows separated by 1.5 m, making for paired 5-fold lines. These where then spaced by 3 m "farm roads" for machinery. We call these rows "paired" or "composite" rows. This architecture in groups of 5 adjacent rows separated by a space of 3 m results in 3,700 plants per ha. The trees were planted in one row at the centre of each composite row, with 1.5 m of separation between trees (of a given species for a given group of neighbouring rows). The rows of trees were thus separated by 9 m, resulting in 741 trees per ha (Table 1). Visual examples are shown in Supplementary materials. The whole trial lot, therefore, comprehends approximately 37,000 plants of yerba mate (*I. paraguariensis*) and 7,410 trees of 9 species in equal numbers.

The development of the system was during the first few years, since the seedlings were implanted until the trees had acquired crowns and stems of adult trees, was monitored with great attention to the vitality and adaptability of various species within the integrated setup, and to the lessons we could learn for future work. The most commonly used measures of tree growth (Sterck and Bongers, 1998; Sumida et al., 2013) are stem diameter at breast height (DBH) and tree height (H), which were measured during the fourth and fifth year of the integrated agricultural agroforestry creation, verifying a very satisfactory evolution of the system since its inception, see Charts 3, 4 below. The most significant disparities were observed between Kiri and Araucaria respect to the development of the other species.

Lote 1 Block 1	Lote 1 Block 2	Lote 3 Block 3	Lote 3 Block 4
T9-Kiri	T2-Loro Negro	T2-Loro Negro	T9-Kiri
T0-Control	T7-Toona	T6-Araucaria	T0-Control
T4-Cañafistola	T5-Anchico	T9-Kiri	T4-Cañafistola
T8-Grevilea	T6-Araucaria	T0-Control	T8-Araucaria
T2-Loro Negro	T0-Control	T1-Lapacho	T1-Lapacho
T1-Lapacho	T8-Grevilea	T5-Anchico	T8-Grevilea
T6-Araucaria	T3-Guatambu	T7-Toona	T5-Anchico
T3-Guatambu	T1-Lapacho	T3-Guatambu	T7-Toona
T7-Toona	T9-Kiri	T8-Grevilea	T2-Loro Negro
T5-Anchico	T4-Cañafistola	T4-Cañafistola	T3-Guatambu

CHART 1
Randomized installation of nine tree species for the creation of the multispecies agroforestry system trial lot spanning 10 has in four repeated blocks. Distribution of tree species planted in four repeated blocks, B1, B2, B3, and B4, allotted to "Lote 1 and Lote 3," spanning a total of 10 has. T1, T2, ..., T9 refers to "treatment." A similar chart with this information is also included in an article about general and complementary, but less technical, aspects of the system for divulgation (Comolli et al., 2023).

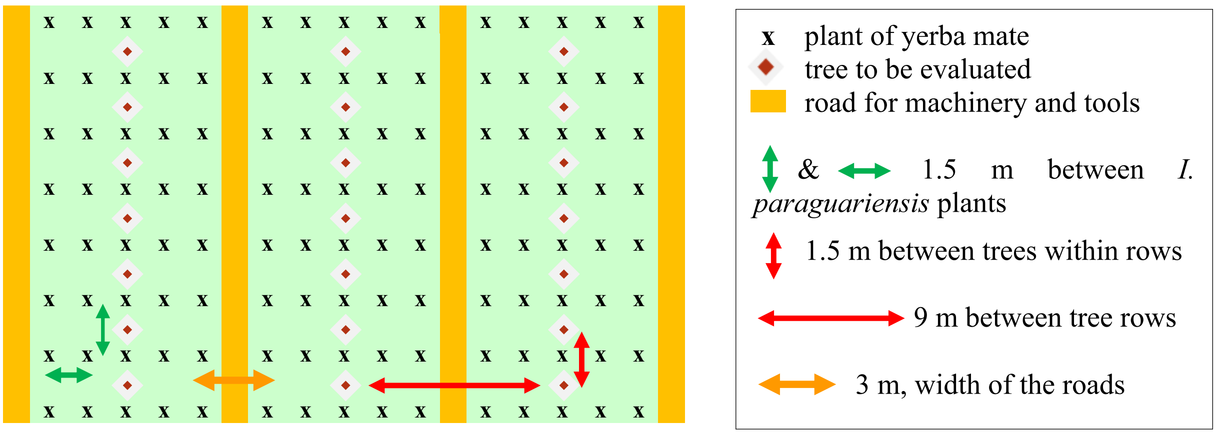

CHART 2
Arrangement of *I. paraguariensis* and trees within the agroforestry system.

2.6 Treatment details

The tree distribution was subsequently thinned at an age of 5 years to a space of 4.5 m between trees within each row as their growth and uniformity exceeded expectations; see Supplementary Figures 1, 2. The remaining trees had the lower branches trimmed to reduce the direct physical competition for space with *I. paraguariensis*, and to provide more space for the cultural manual work during the harvest. This thinning brought the density of trees to approximately 246 trees per ha and provided valuable material to the soil. It also improved growth conditions for *I. paraguariensis* (Table 1). A second intervention of thinning, taking every other tree out was done at an age of 8 years, in parallel with the trimming of the remaining tree crowns. This intervention left a space of 9 m between adult trees, with a density of trees of approximately 123 trees per ha and, and practically no branches at a height lower than 4.5 m (Table 1; Figure 3). The regrowth of the trees is being managed, and any dead tree replanted, so that when the new trees

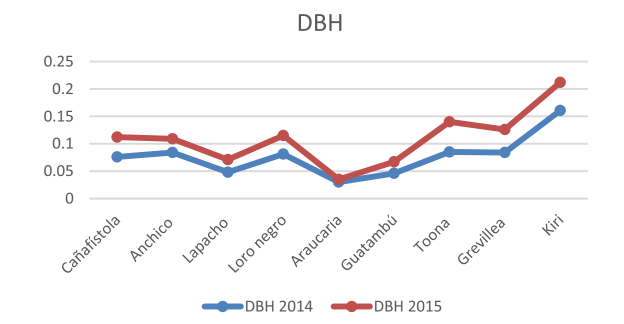

CHART 3
Diameter at breast height, DBH, for 2014 and 2015.

reach a good size, the older trees are cut down, alternating in this fashion to always have young trees and decomposing logs and branches on the ground as shown in Figure 4. In Figures 3A,B, we clearly see the size differences between adult trees and the regrowth from the shoots of the trees that were fell in the interventions.

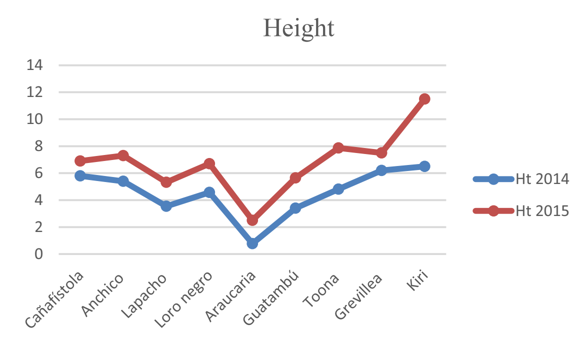

CHART 4
Heights for 2014 and 2015. Diameter at breast height, or DBH (m), and heights, Ht (m), for the tree species in the integrated agroforestry system at the age of 4 and 5 years. These measurements were of key relevance in the creation of criteria for the management of the system. The differences in measured values are statistically significant using a p-value of 0.05, except for the DBH of Araucaria. See also Supplementary Table 1.

3 Results

The first and unexpected result was the vigor and uniformity of growth of all the species of planted trees during the first year, with less than 5% of failures, height variations within less than 10% within species, and the high rate of development of the trees throughout the years (Supplementary Figures 1–3). The species that presented a greater challenge in terms of cultural agricultural maintenance were Kiri and Grevillea, due to their susceptibility to the 'water mold' Phytophthora and to ants, respectively. The seedlings are routinely taken to the field in pots after a preselection (see Methods). Besides, the system is constantly managed with interventions that modify the width of tree crowns and number of trees per planted line, see below, so we cannot derive conclusions about "selective pressures" or "fitness" across the species used in this context. Araucaria trees have a significantly slower growth rate compared to other native species and species commonly used in commercial forestry, whereas Kiri trees grow very quickly. Yerba mate, on the other hand, grows even more slowly than Araucaria. Consequently, all these species develop a canopy that provides shade, beneficial for the Yerba mate plants which are still young and undeveloped. Typically, Yerba mate plants are trimmed for the first time in their third year to shape them. This trimming process is

FIGURE 3
View of the experimental lot in February 2018 **(A)** and May 2019 **(B–D)**. Panel **(A)** Anchico; **(B)** Toona the first two lines or rows, and Loro negro rows further back; **(C)** Toona left of road, and behind there are Lapacho negro and Anchico, **(D)** Toona front plane, Lapacho negro, and Guatambu backwards.

FIGURE 4
Integration of part of the biomass created to the soil. These logs were produced with the thinning that increased the distance between trees from 4.5 to 9 m during spring of 2018, and these images were acquired in May 2019.

repeated in the fourth year, a time when Yerba mate's yield remains low.

The canopy developed by Kiri, and the size and weight of the trunks, rapidly exceeds all other species (Charts 3, 4), and the balance needed for positive synergies with yerba mate. While Kiri has a positive impact on the growth of yerba mate during the first 4 years, beyond 5 years the competition created by the shade is detrimental (Supplementary Figure 2). The trimming and thinning the Kiri trees causes more widespread damage to mate plants than the other species, affecting more plants, as it must be done very early when the trees are at high uniform density. In contrast, all the other species reach a comparable, large size (exceeding the optimal size range for this system) after many more years. By this time the tree density has been reduced by a factor of 6 or more leading to more limited damage from the thinning these trees, and several seasons of positive synergies have been accomplished. Due to these factors, Kiri was quickly discarded as a candidate species for our system, and it largely vanished except for small patches that retained the original density (see Supplementary Figure 2C) for a few more years. All Kiri trees died by 2020. However, it has been subsequently used by other producers of yerba mate attending to its short-term high commercial value which provides a countercyclical activity to their operations.

The evolution of the system into adult trees and mate plants was very favourable, with a steady and consistent development (see Figure 3), and vigorous growth of the tree species. The canopy was managed heuristically by direct human observation through pruning, trimming, and thinning, towards a photosynthetically active radiation (PAR) permeability of at least approximately 50% or above. During the first 6 years interventions were limited to the trimming of lower tree branches, with the dual purpose of enhancing the trees apical growth and diminishing their physical competition for space. Supplementary Figure 2 shows the overall aspect of several tree species at the age of 6 years. After 7 and 9 years the number of trees was reduced as described in the section "Treatment Details." The branches and trunks were systematically cut down in size and distributed along the lines of the plantation to enrich the soil with organic carbon, as shown in Figure 4. In this agroforestry agricultural system, pruning and trimming yerba mate plants accentuates the growth disparity between the canopy of the trees and the mate itself, establishing a lower (mate) and a higher (tree crowns) stratum, and guiding the heuristic management of the trees, as clearly seen in Figure 3.

Table 2 presents a list of stem diameter at breast height (DBH) and tree height (H), which are the most commonly used measures of tree growth (Sterck and Bongers, 1998; Sumida et al., 2013), at the ages of 7 and 12 years. The highest values for DBH and height at year 7 were obtained for Kiri, 37 cm and 11 m respectively, which was phased out of this system. For the rest of the species, the highest values of DBH were measured in Toona, Grevilea, Loro negro, and Cañafístola, with 20, 16, 16, and 15 cm, respectively. The tallest trees were Grevilea, Toona, Loro negro, and Guatambu, with 11, 8.5, 8, and 7.5 m of height, respectively. The smallest values were measured in Lapacho negro, Guatambu, and Anchico, with 11, 10, and 9 cm, respectively. The smallest heights were Guatambu, Lapacho negro, and Anchico with 3.8, 3.5, and 3.5 m, respectively. The allometric relationship, which assesses how these two growth metrics, DBH and H, correlate across different species, appears consistent. This implies that species with higher DBH measurements tend to also be taller, indicating a proportional growth pattern among these species. The smallest DBH measurements at year 7 were observed in Lapacho negro, Guatambu, and Anchico, with correspondingly low heights, marking them as slower-growing species in the early years. By the year 2022, notable increases in both DBH and height are observed for all species, indicating continued growth. Toona showed exceptional growth, reaching a DBH of 37.4 cm and a height of 15 m, marking it as the fastest-growing species in this period. Araucaria shows moderate growth by 2022, confirming the slow growth rate of this species.

TABLE 2 Tree measurements in the multispecies agroforestry system at years 7 and 12.

Popular name	Scientific name	*N*	2018			2022	
			PAR	DBH	Ht	DBH	Ht
Cañafístola	*Peltophorum dubium*	84	71%	15	11	24.4	12
Anchico colorado	*Parapiptadenia rigida*	76	53%	9	5.5	24.1	14
Lapacho negro	*Handroanthus heptaphyllus*	100	63%	11	6	19.4	11
Petiribí / Loro negro	*Cordia trichotoma*	102	60%	16	8	23.5	13
Araucaria / Pino paraná	*Araucaria angustifolia*	94	-	-	-	20.8	9
Guatambú	*Bastardiopsis densiflora*	120	63%	10	7.5	17.9	11
Toona /Australian cedar	*Toona ciliata*	70	67%	20	8.5	37.4	15
Grevillea	*Grevillea robusta*	95	64%	18	10	29.7	14

Diameter at breast height, or DBH (cm), and heights, Ht (m), for the tree species with good survival rates, and good maintenance. *N* is No. of Trees. The photosynthetic active radiation, PAR, was measured with a bar ceptometer. Kiri (*Paulownia* sp.) had a higher failure rate but was also judged to not be viable in this system in the long term due to its exceedingly high rate of growth and large canopy. Kiri trees are often pruned at the end of their first growing season to encourage a healthy, structured growth. In our system we skipped this early pruning that helps establish a strong framework for the tree and can improve its robustness, and the majority slowly died in situ. Araucaria has a significantly slower growth rate that made measurements at young age inconsequential (see Charts 3, 4), so they are not reported for 2018.

TABLE 3 Evolution of total organic matter per tree species.

Year of sampling	2013		2021	
Popular name	TOM %	SD	TOM %	SD
Cañafístola	3.08	0.53	3.30	0.23
Anchico	3.22	0.52	3.65	0.58
Lapacho negro	3.04	0.85	3.36	0.31
Loro negro	3.48	0.46	2.81	0.23
Araucaria	2.96	0.65	2.76	0.55
Guatambú	2.83	0.46	3.97	0.48
Toona	2.97	0.61	3.15	0.81
Grevillea	3.20	0.92	3.46	0.29
Kiri	2.76	0.70	3.50	0.49
Total Average	3.06	0.63	3.33	0.37

These values were obtained from 107 samples for 2013 and 36 for 2021.

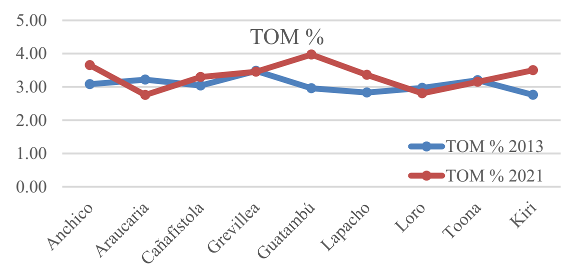

CHART 5
Comparative evolution of the total organic matter per tree species. The values of TOM for Toona and Grevilea are very similar in 2013 and 2021, and their *p*-values are 0.758 and 0.776. All the other differences in values for TOM (%) between 2021 and 2013 are different with a statistical significance better than a p-value of 0.05 for these samples (including the loss of SOM for Loro negro and Araucaria).

Measurements of photosynthetic active radiation (PAR) reaching the lower stratus after 7 years gave similar results in the range between 60 and 71% for Cañafístola, Toona, Grevilea, Guatambu, Lapacho negro, and Loro negro, see Table 2. For Anchico the PAR measurement was 53%, which, for practical purposes, aligns closely with the other species while transmitting slightly less sun light to yerba mate. For the remaining trees of Kiri (e.g., Supplementary Figure 2C) PAR measurements were 31%, validating the elimination of the species from the candidate list for this type of agroforestry system. The differences in recorded PAR values is due to tree canopy structure. On the other hand, due to their slow growth rate, Araucaria trees remained comparatively small and very thin. Even after 12 years, their height was still less than that of Cañafístola and Grevilea at 7 years, as detailed in Table 2. They require several more years to create a canopy stratum at a higher level. Consequently, PAR measurements for Araucaria were considered not relevant at this stage, as they are statistically undistinguishable from open sky measurements.

As illustrated in Table 3 and Chart 5, there is a relevant increase in total organic matter (TOM), from an average value of 3.06% in 2013 to 3.33% in 2021. Nonetheless, to fully account for the contributions to soil organic matter (SOM) by the trees, it is essential to consider the complete decomposition of the thick trunks of the thinned trees. This process is still ongoing at the

FIGURE 5
View of the experimental lot in 2022. A comparison between yerba mate plants consociated with trees, and plants without intercalated trees within the same lot. These are views within the agroforestry experimental pilot lot of 10 has planted in 2010, and an adjacent lot planted in 2011, on the same soil with the same history. **(A)** The tree-planted cultivation of yerba mate; **(B)** a close-up view of yerba mate plants in close association with trees. Species in the field of view include Toona, Grevilea, Loro negro, and Cañafístola; **(C)** the control lot without trees, an area immediately adjacent to that shown in **(B)**; **(D)** close-up view of the state of yerba mate plants in **(C)**, within the control area free of trees of the trial lot. There is a mix of species including Toona, Lapacho, and Loro negro more visible from the background. Photos taken in January 2022.

time of writing this report and contributes incrementally to the soil's organic content. This fact stands in stark contrast to the degradation of the soil typical of traditional, monoculture, yerba mate agriculture (Capellari et al., 2017). However, contrasting contributions are observed among the species studied. Loro negro and Araucaria have negatively impacted SOM, decreasing it by 0.16 and 0.46%, respectively. This reduction correlates with their narrow crowns and, in the case of Araucaria, its coniferous nature with less leafy, triangular-shaped needles. These features likely reduce the litter fall compared to species with broader crowns. All other species contributed to an increase in organic matter.

These results are consistent, as all these species feature well-developed, wide-spreading crowns that contribute extensive canopy coverage. Guatambu, an evergreen tree which features a dense roundish crown, continuously sheds, and renews leaves, contributed the highest increase in SOM over the observed period. We sampled the Kiri sublots where the trees that that were let die in place had fell and decomposed, and the result is an increase in total organic matter as expected. The positive effects on soil from various species consociated with yerba mate are well-documented, leading to the enrichment of micronutrients and key elements such as phosphorous, calcium, nitrogen, and magnesium (Fernandez et al., 1997).

The extreme climate event spanning the spring of 2021 and summer of 2022 brought the ecosystem services provided by agroforestry system into stark contrast with the fragility of yerba mate monocultures. A comparison between yerba mate plants closely consociated with various tree species and those planted further away from trees as shown in Figure 5 reveals that plants consociated to trees experience significantly less stress. Trees provided shade, moderated the temperature, and help conserve moisture in the soil. In the months following the end of the extreme weather event, plants within the agroforestry system returned to produce sprouts and to grow, while plants in the monoculture control required a much longer period and human intervention to prune dry branches. While the harvest of yerba mate in the agroforestry system decrease approximately 20% for the year, the monoculture decreased by more than 30%. Before the extreme climate events of droughts and heat the differences between mate production with or without trees were smaller and subtler, as these are perennial species, and the effects accrue throughout years.

4 Discussion

4.1 What our results show

In this study, we have successfully designed and implemented a multispecies agroforestry system specifically tailored for the perennial cultivation of yerba mate (*I. paraguariensis*) in a subtropical region. To assess the viability of agroforestry in the production of yerba mate, we tested the suitability of several species of trees in a systematic way.

All species were tested in small single species lots, randomized, and repeated four times by design. Trees were integrated with the cultivated species, not along boundary alleys, leveraging inter-species interactions. With a size of 10 has, the experimental lot has the adequate size to isolate causes and effects from the wider context. This integrated multispecies system is proposed as a viable and superior self-sustainable alternative to traditional monoculture practices, in full agreement with previous work (Capellari et al., 2017; Fernandez et al., 1997; Day et al., 2011; Montagnini et al., 2011; Montagnini et al., 2006). This system not only supports the growth of yerba mate but also promotes biodiversity (Comolli et al., 2023), enhances soil quality, and improves ecological resilience.

An important result is that well-chosen agroforestry systems can sustain higher yields of yerba mate harvests while also increasing SOM and improving the working environment. Specifically, yerba mate harvest yields were higher beneath the tree canopy compared to the control plot for species such as Loro negro, Lapacho negro, Toona, and Cañafístola. However, yields were slightly lower for Anchico, Grevilea, and Guatambu. Interestingly, despite its slower growth, Araucaria-associated yerba mate yields also surpassed those of the control after 12 years. This variance in yield over time can be attributed to the differing levels of competition posed by each species, highlighting the dynamic nature of their influence on yerba mate productivity. The biodiversity created by the multispecies integrated system also contributed to a significantly lower incidence of detrimental insects relative to yerba mate traditional monocultures. These results are further discussed in another paper (Comolli et al., 2023) that compiles complementary information for a more general readership and divulgation of the value of agroforestry.

The system prevents soil degradation and irreversible loss of fertility and helps to restore already degraded lands. While the management of the trees through trimming and thinning provides organic matter, their roots help keep the permeability of the soil. Rainfall water runoff is considerably decreased, increasing soil water retention at higher depths. For optimal results, it is recommended that several of the tested species—excluding Kiri—be combined in alternating sequences. This approach would allow for more uniform permeability to photosynthetically active radiation (PAR), create a more natural habitat for birds, and support a broader range of biodiversity. Two species, Araucaria and Loro negro, did not prevent the loss of soil organic carbon typical of yerba mate monocultures (Capellari et al., 2017), a result consistent with their small and narrow crowns The intercalation of multiple species will solve this problem by spreading the contributions to the soil across them. Another important result was the performance of the system as climate change mitigation and adaptation strategy. During the extreme weather events of the spring and summer of 2021 and 2022, the system proved to be significantly more resilient. Plants within the system suffered only a delay in their evolution but no significant damages, while monocultures were devastated. The system harbours birds, and detrimental insect counts reveal average populations to be half, or lower, than outside the system in monoculture lots (Comolli et al., 2023). During the climate shock it was more common to find small animals within the slightly more benign environment provided by the agroforestry system (Comolli et al., 2023), which served a bit as a sanctuary.

4.2 Previous work and context

The effects of trees on the soil of yerba mate cultivation are well documented (Fernandez et al., 1997; Day et al., 2011; Montagnini et al., 2011; Montagnini et al., 2006). The consociation of trees across several species has a significant impact increasing micronutrients in the soil. In addition to organic matter, different species have measurable impact on the content of, e.g., phosphorus, nitrogen, calcium, magnesium (Fernandez et al., 1997; Day et al., 2011; Montagnini et al., 2011). In our case, we fertilize the system with standard, commercial triple nitrogen (N), phosphorus (P) and potassium (K; NPK) at the rate of 50 kg per 1,000 kg of harvested yerba mate distributed uniformly across the whole lot. As we cannot accurately deconvolute the contributions from both sources, we do not report them as absolute values here, but we observe variations across species analogous as the reported variations in organic matter. For example, Toona, Anchico, and Araucaria sublots have higher nitrogen content than the rest, Lapacho, Loro negro, and Toona higher phosphorous content, followed closely by Cañafístola and Anchico while Grevilea has a lesser improvement in values and Guatambu a decrease in values (see Supplementary Chart 1).

Although this project is not about planting tree forests, it is aligned and consistent with work showing much greater response ratios for planted forests made of a variety of different species than mono species (Gurevitch, 2022; Hua et al., 2022; Feng et al., 2022). Forest restoration projects based on multispecies achieve considerably higher results than monospecies using, as metrics, biomass production, above ground biomass, water retention, erosion control, species specific abundance, and biodiversity (Gurevitch, 2022; Hua et al., 2022; Feng et al., 2022). Indeed, multispecies restoration projects can approach values typical of native forests for these metrics (Gurevitch, 2022; Hua et al., 2022; Feng et al., 2022).

4.3 Climate change, adaptation, and mitigation

This conceptual framework also addresses the linked crisis of biodiversity loss, and climate change adaptation and mitigation. As the world continues to warm, climate hazards are expected to increase in frequency and intensity. The impacts of extreme events will also be more severe due to the increased exposure (growing population and development) and vulnerability (aging infrastructure) of human settlements (AghaKouchak et al., 2020). We all depend on nature for our food, air, water, energy, and raw materials. Nature and biodiversity make life possible, provide health and social benefits and drive our economy. Healthy ecosystems can also help us cope with the impacts of climate change. However, natural ecosystems and their vital services are under pressure from urban sprawl, intensive agriculture, pollution, invasive species, and climate change (Feng et al., 2022; Our World in Data, 2021; World Resources Institute, 2019; Food and Agriculture Organization of the United Nations (FAO), 2024; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2016). Integrated sustainable agroforestry systems provide a high intrinsic value independently of hypothetical scenarios of biodiversity and ecosystem services, and leverage Nature's

Contributions to People (NCP; Food and Agriculture Organization of the United Nations (FAO), 2024; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2016; Wilson and Lovell, 2016; van Noordwijk et al., 2021; van Noordwijk, 2021). They provide a set of strategies with the flexibility to incorporate a diversity of values, forms of knowledge or "ways of knowing," which top-down solutions cannot provide (Meyfroidt et al., 2022; UN Environment Program, 2023; Wilson and Lovell, 2016; van Noordwijk et al., 2021; van Noordwijk, 2021).

Ecological and Conservation goals are not simply about "combating climate change," adaptation and mitigation. Nor about aesthetic notions of nature and conservation, although there is wisdom as well in such views. Henry D. Thoreau (Cunningham, 2019) had already formulated a modern environmental philosophy suited for the sustainable development goals (SDGs) in the context of climate change. Observing the environmental degradation wrought by technological development and economic growth, in the second half of the 1800s he called for a revaluation of the natural world as having intrinsic worth (Cunningham, 2019). Indeed, the genetic codes of living organisms constitute the digital library of evolutionary adaptations of all life on Earth, a vast knowledge. A good deal of conservation should perhaps be done also for scientific reasons. We simply do not know enough about specific biological entities and about the web of connections that underpins our biosphere. What is clear however, is that we do not "extract" resources from an infinity pool, nor do we dump "externalities" into infinite sinks. We set agencies in motion as our actions cause reactions or responses.

Agroforestry projects based on an extensive search for maximum possible complexity do halt and reverse soil degradation, help reverse biodiversity loss, and provide some of the benefits, to a degree, provided by forests such as local climate modulation (Meyfroidt et al., 2022). Healthier ecosystems with richer biodiversity also yield greater long-term benefits such as more fertile soils, bigger yields of timber, and larger stores of greenhouse gases (UN Environment Program, 2023; Food and Agriculture Organization of the United Nations (FAO), 2024; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2016; Wilson and Lovell, 2016; van Noordwijk et al., 2021; van Noordwijk, 2021). We will always need farmland and infrastructure on land that was once forest. The open question is how ecosystems, like societies, will adapt to a changing climate (Our World in Data, 2021; World Resources Institute, 2019). If significant extensions of farmland and extensive free land area subject to human-induced degradation were converted to ambitious agroforestry schemes across scales, based on a sufficiently high number of consociated species instead of monocultures as we show in this work, a high impact in carbon sequestration, local climate modulation, land, and biodiversity restoration, could be achieved (Wilson and Lovell, 2016; van Noordwijk et al., 2021; van Noordwijk, 2021; Cunningham, 2019; Reith et al., 2020; Rodrigues et al., 2023). Actions that help reduce losses of biodiversity are found to also benefit the climate (Shin et al., 2022), and we have today unprecedented technological innovations including a digital infrastructure that could be leveraged towards SDGs (TWI2050, 2019; TWI2050, 2020).

The long-term sustainability and resilience of the system hinge on how the soil evolves and how the system responds to the increasingly frequent climate shocks and extreme climate events occurring worldwide. Our findings demonstrate the system's effectiveness in conserving soil fertility and highlight its substantial benefits in mitigating the impacts of extreme climate events. In our view, these are two of the most critical results of our research.

5 Conclusion

Our findings illustrate the robustness of this agroforestry model in integrating diverse plant species with yerba mate cultivation. We demonstrate that incorporating trees into the production of yerba mate leverages the natural synergies between different species and provides significant benefits. The system has the capacity to sustain and restore soil fertility and create a viable, sustainable long-term cultivation strategy. It also helps to restore part of the biodiversity historically typical of the region and enhances resilience to climate change.

The scale of the experiment adequately enables the acquisition of relevant data and the formulation of conclusions of general validity. Our experimental system is scalable, capable of being expanded or reduced in size, and can be managed with or without mechanization, depending on the scale. Additionally, the experiment resulted in the creation of sufficient experience to further expand this initiative. This type of knowledge can help improve land management and reverse land abandonment in the region and elsewhere (Rodrigues et al., 2023). Implementing such agroforestry systems can significantly impact carbon sequestration, local climate modulation, and land and biodiversity restoration. As climate hazards increase in frequency and intensity due to global warming, integrated sustainable agroforestry systems provide a high intrinsic value, supporting Nature's Contributions to People (NCP) and offering flexible strategies that incorporate diverse values and knowledge forms.

Overall, our study shows that well-designed agroforestry systems can sustain higher yields of yerba mate harvests while increasing SOM and improving the working environment. They prevent soil degradation, help restore degraded lands, and support greater biodiversity. These systems represent a superior, sustainable alternative to traditional monoculture practices, offering significant ecological, economic, and social benefits.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ES: Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing. CI: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing. NM: Conceptualization, Data curation, Investigation, Methodology,

Writing – review & editing. HF: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing. AW: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. NB: Writing – review & editing. PG: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. SB: Investigation, Writing – review & editing, Data curation, Formal analysis, Methodology. MG: Conceptualization, Investigation, Resources, Writing – review & editing. FW: Conceptualization, Investigation, Methodology, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1424174/full#supplementary-material

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Effects of single-tree selective harvest method on ecosystem services in a mixed temperate broadleaf forest in Iran

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Introduction: This study examines the effects of the single-tree selective harvesting method on ecosystem services in a mixed temperate broadleaf forest in Iran. Key indicators such as carbon sequestration, tree species diversity, soil nutrient cycling, and stand volume are analyzed, emphasizing their significance for sustainable forest management.

Methods: The research was conducted in four districts, each comprising two parcels: one managed using the single-tree selective harvesting method and the other serving as a control. Data on ecological and biodiversity parameters were collected, and statistical analyses, including two-way ANOVA and Principal Component Analysis (PCA), were performed to assess the impact of management practices.

Results: The findings reveal that the single-tree selective harvesting method significantly influences regulating and supporting ecosystem services. Carbon storage varied with elevation, affecting both soil and forest floor litter. Tree species diversity increased, with more species present and a reduction in dominance by certain species. However, this method also resulted in reduced stand volume in the managed areas. Elevation significantly impacted diversity indices, litter carbon storage, available potassium, and stand volume. Additionally, the interaction between management and elevation was significant for soil carbon storage, richness, diversity, total nitrogen, available potassium, and stand volume.

Discussion: The single-tree selective harvesting method appears to be a viable forest management strategy for preserving ecosystem services in mixed temperate broadleaf forests, maintaining ecosystem health without significant negative effects on soil. However, careful consideration of site-specific ecological conditions and trade-offs between provisioning and regulating services is crucial. These findings have important implications for sustainable forest management in Iran and similar forest ecosystems globally.

KEYWORDS

single-tree selective harvest method, forest management, ecosystem services, carbon storage, tree species diversity

1 Introduction

Ecosystem services are the conditions created by natural ecosystems that enhance the richness and diversity of plant and animal species, ultimately benefiting human societies (Daily, 1998). The Millennium Ecosystem Assessment (2005) categorizes ecosystem services into four groups: regulating services, supporting services, provisioning services, and cultural services (Wallace, 2007). Regulating services, such as carbon sequestration, depend on the natural processes of an ecosystem (Platon et al., 2015). Supporting services, including soil formation, originate from natural ecosystems and are essential for accessing other ecosystem services (Platon et al., 2015). Evaluating the management of natural ecosystems using ecosystem service indicators is now a critical and practical aspect of sustainable natural resource management (Grammatikopoulou and Vačkářová, 2021).

Carbon dioxide separation from the atmosphere is necessary for reducing global warming (Tong et al., 2020; Panja, 2021). Increasing forest vegetation (which plays a vital role in reducing atmospheric carbon dioxide concentrations) (Trumper, 2009; Lal, 2004) tends to be the only simple and inexpensive way to control carbon in the atmosphere.

Plant diversity is a widely used component of biodiversity in vegetation studies and an important indicator of ecological sustainability of ecosystems in environmental assessments (Pecl et al., 2017; Pollastrini et al., 2014). Forest biodiversity also affects forest growth and biodiversity mechanisms and processes, which can lead to increased biomass productivity (Zhang et al., 2010; Zou et al., 2024). This composition of tree species in forest stands plays an important role in determining the quality and quantity of litter and organic matter inputs into the forest soil, which in turn affects the nutrient cycle (Zhang et al., 2018; Carmona-Yáñez et al., 2023).

Stand volume is a basis characteristic, especially in the forest production sector (Sasanifar et al., 2019). While this characteristic is primarily considered in industrial forests for wood production, its correlation with density, tree dimensions, biomass, and habitat fertility appear to be a reliable indicator of structure in managed forest stands (Lorenz, 2010; Vafaei et al., 2017).

The success or failure of forest management methods can be determined by evaluating the rate of forest change following the implementation of various management programs (Wheeler et al., 2016; Oettel and Lapin, 2021). Therefore, in this study, the effectiveness of single-tree selective harvest method on some studied indicators of ecosystem services from temperate broadleaf forests has been investigated. On the other hand, the results will show us that in 20 years, to what extent this type of management has affected the studied characteristics of the forest. Therefore, the goals of this research were advanced by collecting data from the studied forests.

Hyrcanian forests are renowned as one of the world's oldest surviving forests, with a history spanning millions of years. These ancient forests, belonging to the Third Age of geology, harbor unique species that cannot be found anywhere else due to the limited impact of past glaciations (Sagheb Talebi et al., 2014). During the Pleistocene (Ice Age) period, all but a few broadleaf forests were lost. The Hyrcanian forests with a temperate climate were protected and survived from freezing because they were located between the mountains and the Caspian Sea. On the other hand, these forests are located in latitude belts less than 40 degrees north and at a maximum height of 5,000 m. Accordingly, the cold climate has had a more moderate effect than other forests of high latitudes. As a result, the frosts had the least effect on them. Therefore, the Hyrcanian forests can be considered the "mother" of young forests in Europe (Sagheb Talebi et al., 2014). These forests are composed of mixed deciduous trees that play an effective role in the formation of soil horizons, humus, and soil fertility through the return of leaves to the soil surface in the autumn (Sohrabi et al., 2022).

Due to being close to nature, the single-tree selective harvest method, has been used as a silviculture method for the sustainable management of forests around the world (Sagheb Talebi et al., 2014).

Numerous studies have been conducted on different management methods in Hyrcanian forests. This study specifically focuses on managing these forests using the single-tree selective harvest method. In recent years, this method has gained popularity in the Hyrcanian region of Iran, aiming to preserve the natural characteristics of the forests and maintain their asynchronous form.

The objectives of this study are, (1) to investigate the effects of single-tree selective harvest method on ecosystem services, including carbon storage, tree species diversity, the soil nutrient cycle, and stand volume in a mixed temperate broadleaf forest in Iran, and (2) Evaluating the consequences of the single-tree selective harvest method for Iran's forests and investigating its effectiveness in similar forest ecosystems.

2 Materials and methods

2.1 Study area

Shafarood Forest Company was established in 1973 with the purpose of meeting Iran's cellulosic industry's needs. It initially covered 400,000 hectares of forests in Gilan province, which is part of the Hyrcanian temperate broadleaf forests. Currently, the company manages approximately 150 thousand hectares of forests, spread across 72 districts.

In the past, the management of these forests followed the shelterwood silviculture method (from 1989 to 1998), with regenerative cutting and the first light cutting being implemented over a 10-year period. But because this cutting was done only once in light form and about 30 years ago, it did not cause any significant change in the natural structure of the forests. However, from 1996 to 2016, the management approach shifted to the single-tree selective harvest method.

2.2 Data collection

In this study, four districts were chosen from four different elevational classes within the Shafarood forests: less than 600 (0–599), 600–1,000 (600–999), 1,000–1,500 (1,000–1,499), and more than 1,500 (1,500 to the final limit of forest growth in the study area) meters above sea level (m a.s.l.). Within each district, two parcels were selected: one managed with the single-tree selective harvest method, and one serving as a control parcel. The environmental and ecological conditions, such as aspect, average slope percentage, elevational class, and tree species type, were kept similar in both parcels to ensure comparability.

The control parcels are areas where no exploitation or forest management has taken place. These parcels have not undergone any human intervention and have naturally progressed through succession.

To establish sample plots, a 100 by 200-meter inventory grid was utilized, based on previous research conducted by Khanalizadeh et al. (2020). The grid was designed using ArcGIS and overlaid onto the parcels using Google Earth. GPS coordinates for the centers of the sample plots were then recorded within the designated parcels of each district. During the field implementation of the sample plots, the centers of each parcel were determined using the GPS coordinates obtained in the previous stage.

At each sample plot center, an original plot with a circular shape and an area of 10 acres was established. A total of 30 sample plots for each district were collected (15 samples from the managed parcels and 15 samples from the control parcels). Sample collection in the study districts and parcels is presented in Table 1.

In each plot, the tree species and diameter at breast height (DBH) were measured using a caliper, with DBH classes recorded in centimeters. Furthermore, the total height of five selected trees within the sample plot was measured. These included the four closest trees in the four main directions from the plot center, as well as the thickest tree within the plot.

For soil sampling, five plots were randomly chosen from all the plots within each parcel. Soil samples were collected at a depth of 0–30 cm, following the methodology described by Barnes et al. (1997). One sample was taken from the center of each plot, while four additional samples were collected from the corners. These individual soil samples were then mixed together to create a composite sample for each selected plot. The composite samples were transferred to the laboratory for further analysis.

Similarly, within the selected plots for soil sampling, intact soil samples were extracted using a cylinder at a depth of 0–30 cm. These samples were used to determine the soil bulk density.

Within the plots designated for soil sampling, a representative portion of the litter layer was collected. The litter was carefully collected from an untouched area within each plot, following the dimensions of 50 cm by 50 cm, as described in the study by Berenguer et al. (2018). All the data of this study were collected in the summer of 2021.

TABLE 1 Measured plots in each district and parcel.

District number	Elevational range (m a.s.l.)	Parcel numbers	Sample plots number in each parcel
18	Less than 600	Parcel 19 (managed) and Parcel 17 (control)	15
17	600–1,000	Parcel 27 (managed) and Parcel 29 (control)	15
8	1,000–1,500	Parcel 12 (managed) and Parcel 13 (control)	15
5	More than 1,500	Parcel 31 (managed) and Parcel 29 (control)	15

2.3 Studied ecosystem services

In this study, we focused on analyzing two categories of ecosystem services: regulating services, specifically carbon storage, and supporting services, including the soil nutrient cycle, woody species biodiversity, and woody stem yield. We examined these services for both the managed and control parcels, as shown in Table 2. The indicators of ecosystem services were selected based on the classification outlined in the Millennium Ecosystem Assessment (2005).

2.3.1 Regulating services

2.3.1.1 Soil carbon storage

In the laboratory, we measured the percentage of soil organic carbon using the Walkley and Black method (Nelson and Sommers, 1996). Subsequently, we utilized Equation 1 to calculate the amount of organic carbon stored in the soil, expressed in tons per hectare.

$$C_C = OC\% \times Bd \times e \quad (1)$$

Where, OC represents organic carbon, Bd is the bulk density of soil, and e shows the depth of sampling soil in centimeters.

2.3.1.2 Litter carbon storage

The organic carbon content of the litter samples was determined using the combustion oven method, as described by Nilsson et al. (1999). To perform this analysis, the dried litter samples were first weighed. Subsequently, the samples were placed in an electric oven and subjected to temperatures ranging from 400 to 500°C for a duration of 4 h. After the incineration process, the samples were re-weighed to determine the weight of ash. The litter's carbon content for each area was then calculated by considering the ratio of organic carbon to organic matter (54%) and using the weight of ash and the initial weight of the samples, as outlined by MacDicken (1997).

2.3.2 Supporting service indices

2.3.2.1 Woody species diversity

Richness, diversity, and evenness indices for the woody species in the plots were calculated (with Past 4.8).

Whittaker richness presents the number of species in a plant community and is obtained by counting the number of plant species per unit (Humphries et al., 1995). The value is calculated based on Equation 2.

TABLE 2 Ecosystem service indicators and type of data.

Type of service	Ecosystem service	Unit	Type of data (indicators)
Regulating services	Carbon storage	$t\,ha^{-1}$	Soil and litter carbon
Supporting services	Woody species Diversity		Diversity, richness and evenness indicators of tree species
	Nutrient recycling	$t\,ha^{-1}$	Soil total nitrogen, total phosphorus and available potassium
	Woody stem yield	m^3	The average volume of tree trunk

$$S = N \tag{2}$$

where N is the total number of species in the reagent location.

Another indicator that is widely used in studies is the Shannon (diversity) index. The Shannon function is the most common measure of species diversity (Shannon, 1949). Equation 3 is used to calculate the Shannon-Wiener index.

$$H' = -\sum_{i=1}^{s} (p_i).(Lnp_i) \tag{3}$$

where H′ shows the Shannon-Wiener index, and Pi is the relative abundance of the *i* number of species in the sample.

The Pielou species (evenness index) was introduced in 1969 (Pielou, 1979) and varied from 0 to 1. To calculate this index, all species of a population must be identified. Equation 4 is suggested to measure this index.

$$J = \left[-\sum p_i \ln(p_i)\right] / \ln S \tag{4}$$

Where p_i is the ratio of species *i* in the population, and S is the total number of species in the sample.

2.3.2.2 Nutrient recycling

We conducted laboratory measurements of three indices: total nitrogen, using the Kjeldahl method (Bremner and Mulvaney, 1982), available phosphorus, using the Olsen method (Olsen, 1954), and available potassium, using the saturation extract method (Mehlich, 1978).

2.3.2.3 Woody stem yield

In the context of Shafaroud forests, we utilized tree-volume tariff tables to accurately assess and redefine the volume of tree trunks. This was achieved by employing recorded Diameter at Breast Height (DBH) and height values from the designated plot.

2.4 Statistical analyses

2.4.1 Comparing managed and control areas in terms of ecosystem service indices

We assessed the normality of the data distribution for each ecosystem service index using the Kolmogorov–Smirnov test. To investigate the main effects of management treatments (managed and control) and elevational ranges (less than 600, 600–1,000, 1,000–1,500, and more than 1,500 m a.s.l.), as well as their interactions, we employed a two-way ANOVA assuming normal distribution. For comparing the mean indices at the management level, we used an independent t-test, and for comparing the means among the height levels, a Duncan test was conducted (with SPSS 24).

Principal Component Analysis, or PCA, helps us reduce the dimensionality of the data while preserving its essential characteristics. Principal Component Analysis is a statistical method that transforms high-dimensional data into a lower-dimensional form while preserving the most important information. It accomplishes this by identifying new axes, called principal components, along which the data varies the most. These components are orthogonal to each other, meaning they are uncorrelated, making them a powerful tool for dimensionality reduction. PCA is most commonly firstly used when many of the variables are highly correlated with each other and it is desirable to reduce their number to an independent set. Secondly it is perfumed to distinguish the sensible variable varying among the observation. Finally, it is utilized for separation and fragmentation of various phenomena and treatments differing in view point of their measured variables (Hasan and Abdulazeez, 2021).

In this study, to identify the most significant index affected by the single-tree selective harvest method in both regulating and supporting services, we performed a principal component analysis (PCA) (with CANOVO 5). This allowed us to determine the key indicator within each service category.

3 Results

Based on the data presented in Figure 1, both the managed and control areas exhibit a J-shaped tree distribution curve. In the managed area, there is a higher number of trees per hectare in the middle diameter at breast height (DBH) classes compared to the control area. However, this trend is reversed in the larger DBH classes. Figure 1 provides a graphical representation of the number of trees per hectare in 5 cm DBH classes for both the managed and control areas.

3.1 Regulating services

3.1.1 Carbon storage

In terms of carbon storage, soil, and litter carbon storage were calculated for both regions. The two-way ANOVA results of soil and litter carbon storage indices are presented in Table 3.

The interaction between management and elevation factors has a significant impact on soil carbon storage and the elevation factor plays a more influential role on litter carbon storage. It seems that forest management had a greater effect on soil carbon than litter carbon storage. Table 4 provides a comparison of the average soil carbon storage indices resulting from the interaction of management and elevation factors.

According to the data presented in Table 4, the trend of changes in soil carbon storage is not the same with changes in altitude above sea level in both regions. Additionally, Table 5 provides the average index of litter carbon storage associated with various elevation effects.

As highlighted in Table 5, our results reveal a large increase in litter carbon storage at an altitude of 1,000–1,500 m a.s.l., which may be caused by the effect of climate or combination of tree species at this altitude.

3.2 Supporting services

3.2.1 Woody species diversity

The woody species in both managed and controlled areas are presented in Table 6. The forest stands studied in both parts are mixed broad-leaved stands. In the higher elevation, the stands are dominated by the Beech-Hornbeam mixed stands. At the lower

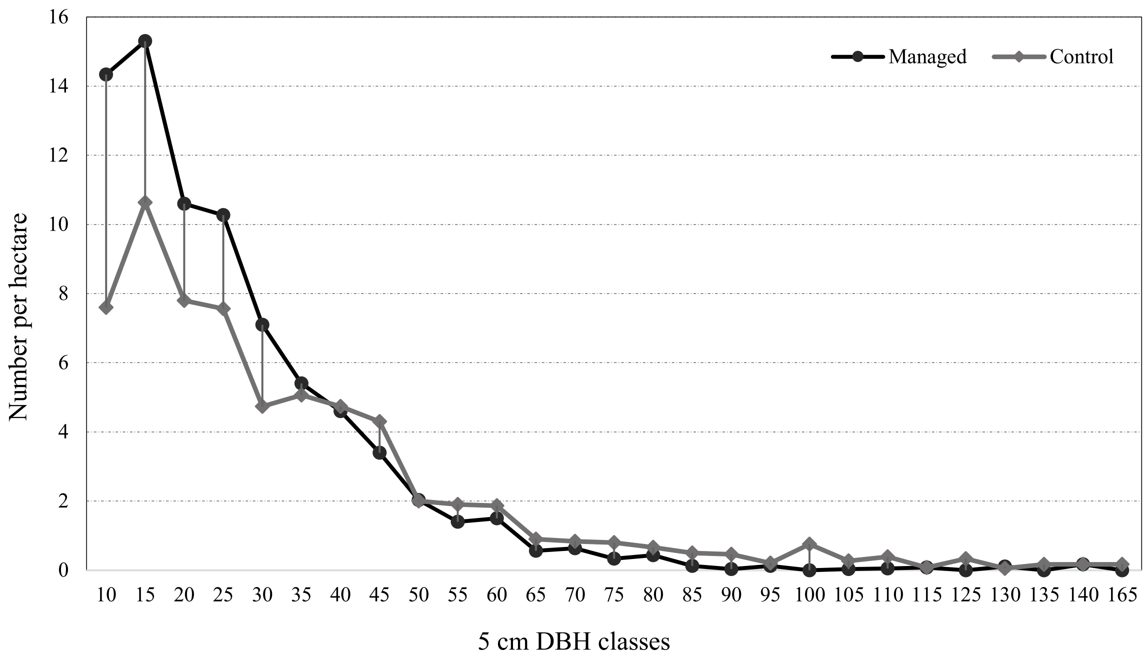

FIGURE 1
Number of trees per hectare in 5 cm DBH classes in the managed and control area.

TABLE 3 Variance analysis of changes in carbon sequestration under management and elevational range factors.

Source of variation		df	Sum of squares	Mean square	*F*	*p*
Soil carbon sequestration (t ha^{-1})	Management	1	0.25	0.25	0.00	0.98^{ns}
	Elevation	3	1,329.75	443.25	0.45	0.71^{ns}
	Management * Elevation	3	12,069.41	4,023.13	4.14	0.01*
	Error	32	31,062.52	970.70		
Litter carbon sequestration (t ha^{-1})	Management	1	0.40	0.40	0.24	0.62^{ns}
	Elevation	3	65.29	21.76	13.36	0.00**
	Management * Elevation	3	4.17	1.39	0.85	0.47^{ns}
	Error	32	52.13	1.62		

**Significant at $p < 0.01$, *Significant at $p < 0.05$, ^{ns}Not significant.

TABLE 4 Comparison of mean soil carbon related to the interaction effects of management and elevation factors using Duncan test (mean ± SE).

Area	Elevational range (m a.s.l.)	Soil carbon sequestration (t ha^{-1})
Managed	Less than 600	156.04^{ab} ± 26.63
	600–1,000	138.09^{b} ± 9.26
	1,000–1,500	143.07^{b} ± 7.83
	More than 1,500	192.67^{a} ± 11.36
Control	Less than 600	166.44^{ab} ± 12.25
	600–1,000	158.31^{ab} ± 10.50
	1,000–1,500	172.01^{ab} ± 11.63
	More than 1,500	133.74^{b} ± 13.07

^{a,b}Significant at $p < 0.05$.

elevation, the mixed stands of Carpinus-Alnus, are the dominant type. The results of two-way ANOVA for the richness, diversity, and evenness of woody species in managed and control areas are presented in Table 7.

Table 7 reveals that management exerted a predominant influence on richness and diversity metrics, whereas elevation exhibited substantial effects on richness, diversity, and evenness. Furthermore, the interaction between management and elevation demonstrated a considerable impact on richness and diversity indices. Figure 2 visually represents the average fluctuations in diversity indices of woody species attributable to the effects of management.

Figure 2 provides evidence that there are more species with higher abundance in the managed area than in the control area. Furthermore, the same conditions can be observed at an altitude of less than 600 m a.s.l. (Figure 3). The results of the interactive effects of the two studied factors are presented in Table 8.

TABLE 5 Comparison of the average litter carbon sequestration related to the main effects of elevation factors, by independent t-test (mean ± SE).

Ecosystem services	Elevational range (m a.s.l.)			
	Less than 600	600–1,000	1,000–1,500	More than 1,500
Litter carbon sequestration ($t\,ha^{-1}$)	0.45[b] ± 0.09	0.37[b] ± 0.10	3.46[a] ± 0.68	0.77[a] ± 0.37

[a,b]Significant at $p < 0.05$.

TABLE 6 Woody species registered in study area.

Number	Species name	Family	Number	Species name	Family
1	*Acer ibericum* M.B.	*Sapindaceae*	14	*Ulmus glabra Huds.*	*Ulmaceae*
2	*Fagus orientalis* Lipsky.	*Fagaceae*	15	*Juglans regia* L.	*Juglandaceae*
3	*Diospyros lotus* L.	*Ebenaceae*	16	*Gleditsia caspica Desf.*	*Fabaceae*
4	*Carpinus betulus* L.	*Betulaceae*	17	*Alnus subcordata* C.A.Mey.	*Betulaceae*
5	*Quercus castaniifolia C.A. Mey.*	*Fagaceae*	18	*Ficus carica* L.	*Moraceae*
6	*Carpinus orientalis* Mill.	*Betulaceae*	19	*Acer campestre* L.	*Sapindaceae*
7	*Parrotia persica* C.A.Mey.	*Hamamelidaceae*	20	*Pyrus glabra* Boiss	*Rosaceae*
8	*Tilia platyphyllos* Scop.	*Malvaceae*	21	*Ulmus carpinifolia* Suckow	*Ulmaceae*
9	*Acer Cappadocicum Gled.*	*Sapindaceae*	22	*Fraxinus excelsior* L.	*Oleaceae*
10	*Prunus avium (L.) L*	*Rosaceae*	23	*Acer velutinum* Boiss	*Sapindaceae*
11	*Zelkova carpinifolia* (Pall.) K. Koch	*Ulmaceae*			
12	*Sorbus torminalis* (L.) Crantz	*Rosaceae*			
13	*Quercus petraea* (Matt.) Liebl.	*Fagaceae*			

As Table 8 clarifies, the increasing trend of the studied indices with decreasing elevation factor is regular in the managed area, while there is minor irregularity in the control area.

3.2.2 Nutrient recycling

Table 9 displays the two-way ANOVA results for total Nitrogen, available phosphorus and potassium in the managed and control areas.

Based on the results reported in Table 9, it can be inferred that the interaction between management and elevation exerts a notable influence on the total nitrogen index. It seems that management has only affected available phosphorus index. Moreover, the elevation factor and the interaction between the investigated factors significantly affect the available potassium. Figure 4 graphically presents the average fluctuations in the available phosphorus index resulting from the effects of the management factor. Most likely, the lack of tree harvesting in the control area has led to an increase in available phosphorus reserves in the soil of this area. In Figure 5, the variations in the available potassium index are depicted, highlighting the influence of the elevation factor.

According to Figure 5, the process of changes in available phosphorus in relation to changes in height above sea level is not a regular process. The results of the interactive effects of the two studied factors on total Nitrogen and available phosphorus are presented in Table 10.

It can be seen that the trend of changes in total nitrogen and available potassium in both regions is decreasing in relation to the increase in altitude above sea level (Table 10).

3.2.3 Woody stem yield

The two-way ANOVA results on the mean stand volume of trees are presented in Table 11.

According to Table 11, it can be seen that stand volume has been affected by all three factors of management, height above sea level and mutual effects of both. In Figure 6, we show the mean differences in the stand volume index due to the effects of the management factor. It is understandable that the average stand volume in the control area is higher than the managed area due to the lack of wood harvesting.

Figure 7 demonstrate the mean differences in the stand volume index due to the effects of the elevation factor. At higher altitudes, for reasons such as difficult access, difficult transportation, and harsher weather, less wood is harvested, which shows that the average stand volume is the highest at an altitude of more than 1,500 m a.s.l. The results of the interactive effects of the two studied factors on the stand volume index are presented in Table 12.

The mean stand volume in both area increases based on the elevation, and this rising trend is considerable in the managed areas.

3.3 The most significantly modified indices

Principal component analysis (PCA) of the indicators examined reveals that the first three components account for 89.54% of the variance in the data, with the first and second components explaining 69.5% of the variance. Among the components, parameters with a factor load greater than 0.6, such as soil carbon storage, available potassium, total nitrogen, richness, diversity, and stand tree volume, were identified as the most influential variables affecting site differentiation.

The main component analysis is presented in Figure 8 to determine the most importantly modified indices in ecosystem services classes.

TABLE 7 Variance analysis of changes in woody species diversity indicators under management and elevational range factors.

Source of variation		df	Sum of squares	Mean square	*F*	*p*
Richness	Management	1	46.87	46.87	19.64	0.00**
	Elevation	3	271.29	90.43	37.90	0.00**
	Management * Elevation	3	33.55	11.86	4.68	0.00**
	Error	112	267.20	2.38		
Diversity	Management	1	0.71	0.71	6.13	0.01*
	Elevation	3	16.02	5.34	45.88	0.00**
	Management * Elevation	3	1.25	0.41	3.58	0.01*
	Error	112	13.04	0.11		
Evenness	Management	1	0.01	0.01	0.63	0.42^{ns}
	Elevation	3	1.05	0.35	12.80	0.00**
	Management * Elevation	3	0.19	0.06	2.31	0.08^{ns}
	Error	112	3.06	0.02		

**Significant at $p < 0.01$, *Significant at $p < 0.05$, ^{ns}Not significant.

Figure 8 depicts various indicators including GA (richness), DIV (diversity), EQU (evenness), K (available potassium), N (total nitrogen), SC (soil carbon storage), P (available phosphorus), LC (litter carbon storage), and VO (stand volume). Additionally, C1 to C4 represent the first to fourth elevation levels in the control area, while M1 to M4 represent the first to fourth elevation levels in the managed area.

Based on the analysis of this figure, the total nitrogen, soil carbon storage, available potassium, and phosphorus indices tend to be higher in the control area. Conversely, the richness and diversity indices tend to be higher in the managed area. The volume index tends to be higher at elevations above 1,500 m a.s.l. in the managed area. Litter carbon storage and stand volume show a tendency toward the control area, while the diversity and richness indices show a tendency toward the managed area.

4 Discussion

The findings of this study indicate that both the managed and control areas exhibit a J-shaped distribution curve of trees, characteristic of uneven age forests. This outcome suggests that the single-tree selective harvest method employed in the management of the studied forests did not alter their natural structure.

A similar study conducted by Moe and Owari (2020) investigated the impact of single-cutting forest management on sustainability indices in Chinese forests. Their research revealed that 50 years of forest management using the single-cutting method resulted in improved stability indices of forest stands, including a J-shaped tree distribution curve, as well as enhanced forest regeneration.

4.1 Regulating services

The soil component within ecosystems plays a pivotal role in forest environments, significantly contributing to carbon sequestration and storage (Hashimoto et al., 2009). Recent decades have seen dedicated efforts toward utilizing this resource for mitigating climate change and managing carbon. The present study's outcomes reveal that individual tree-cutting management exerts minimal impact on soil and litter carbon storage compared to control areas. Regarding carbon storage, it is necessary to understand that increased soil carbon does not necessarily imply a decrease in ecosystem health. Ecosystem management can optimize carbon sequestration by balancing carbon stocks between soil and biomass. Soils enriched with organic carbon can support greater biodiversity, improve nutrient cycling, and increase forest resilience, even if standing biomass is slightly reduced (Lin et al., 2024; Sakib et al., 2024). In this regard, it is noted that soil carbon storage declined most in the 41–50% thinned plots due to reduced carbon storage in the humus layer (Li et al., 2023). This approach highlights the importance of soils as long-term carbon sinks, contributing significantly to climate change mitigation (Deal, 2020). While our study demonstrates a redistribution of carbon from above-ground biomass to soil carbon storage, further research is necessary to measure the annual flux of carbon sequestration. This would help to clarify whether soil carbon uptake compensates for the reduced carbon stored in the stand volume.

This paper underscores the impact of elevation on litter carbon storage and the interplay between elevation and management on soil carbon storage. Observations regarding elevation's effect on litter carbon storage indicate that the most substantial values occur within the 1,000–1,500 m a.s.l. range. Significantly, this elevation range exhibits higher concentrations of available potassium, indicative of an enriched soil profile that enhances the physiological traits of tree species, consequently fostering increased litter accumulation. This increased litter volume, in turn, shows a greater share of litter carbon storage.

Rai et al. (2021) conducted a study on carbon storage in protected forests in India, encompassing both net and mixed scenarios. Their findings establish a clear correlation between elevated litter volume and increased carbon storage within ecosystems, particularly notable in mixed-species compositions. Similarly, Lee et al. (2020) examined soil and litter carbon dynamics in Korean forests, concluding that needle-leaf masses exhibit greater litter carbon sequestration compared to their broadleaf counterparts, primarily due to the larger litter volume of needle-leaf species. Conversely, the proliferation of

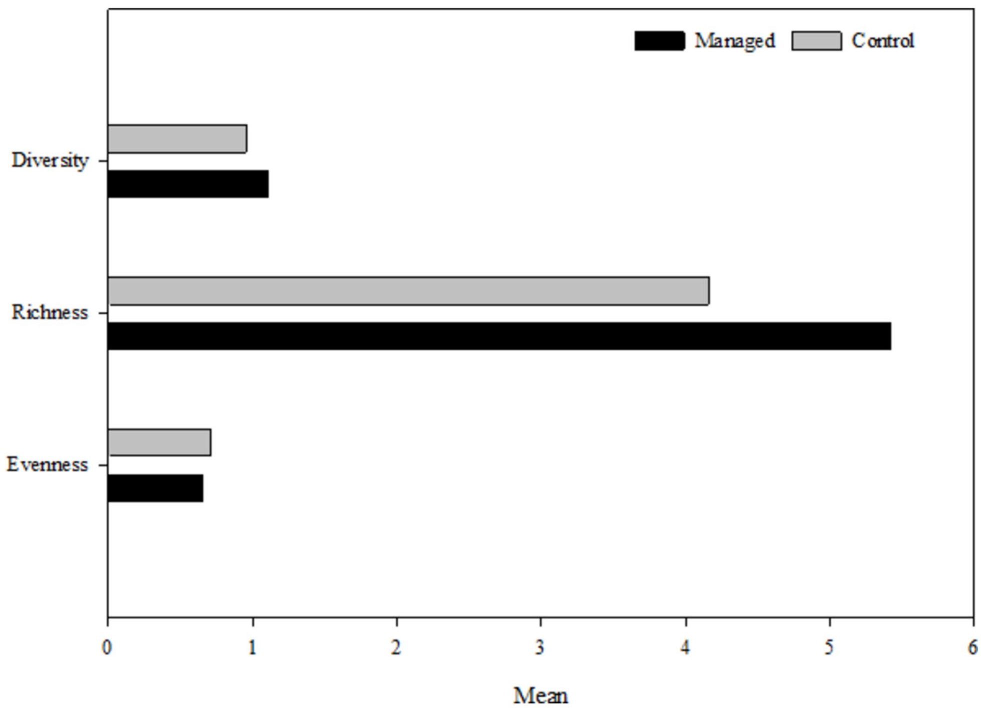

FIGURE 2
Diversity and richness indices for woody species in two managed and control area.

beech species at elevations ranging from 1,000–1,500 m a.s.l. could contribute to enhanced litter accumulation. Mölder et al. (2008) suggested that the gradual decomposition of beech tree foliage leads to thicker litter layers. As indicated by Abrari (2020), this gradual decomposition process potentially accounts for the noticeable accumulation of beech litter on forest surfaces.

Our research unveils a significant interplay between management practices and elevation, both influencing soil carbon storage. The trends in soil carbon storage across different elevations in both study areas exhibit irregular patterns. Crucially, the managed area demonstrates its highest soil carbon storage at 1500 m a.s.l., while the control area's peak value is observed between 1,000 and 1,500 m a.s.l. Lee et al. (2020) propose that variations in elevation and diverse management approaches impact tree growth parameters, including average crown diameter and diameter at breast height (DBH), thereby shaping carbon storage within litter and soil components. The pronounced net carbon index in both study regions likely enhances the carbon cycle between plants and soil, facilitating storage within plant and soil structures.

4.2 Supporting services

4.2.1 Woody species diversity

Biodiversity stands as a pivotal factor impacting forest ecosystem sustainability and performance, making its conservation decisive for sustainable forest management. This study highlights management's substantial influence on species diversity, notably affecting richness and diversity indices, with managed areas displaying higher values. Raymond et al. (2018) investigated the effects of single-cutting management in Quebec, finding that enhanced diversity and richness correlated with increased light availability due to the method. Elevated cutting intensity, light, richness, and diversity fostered non-commercial species proliferation. The study infers that single-cutting management and favorable conditions for tree species regeneration bolstered species richness and diversity. Elevation significantly impacted richness, diversity, and evenness indices, with lower elevations experiencing higher values due to native interference altering light and species regeneration dynamics.

Amini et al. (2021) explored human-made and natural illumination's effects on tree species diversity in Hyrcanian forests. Human-made illumination yielded pronounced diversity indices, possibly due to canopy gap creation. Single-cutting interventions showed minimal diversity index effects; instead, native interference and necessary cuts induced canopy changes, light alterations, and regeneration, boosting diversity indices. Management-elevation interplay influenced richness and diversity indices. Managed areas displayed increased indices with lower elevation, while control areas showed a slight rise within 1,000–1,500 m a.s.l. This corresponds to heightened indices in soil carbon storage, total nitrogen, and available potassium reported in this elevation range. These factors likely contribute to increased diversity indices in the control area at these specific elevations. Species richness and diversity all showed the highest at middle elevations in control area. In these forests, the temperature is gradually decreased and the precipitation is increased gradually along the middle altitudinal gradient. The increase in species diversity at lower elevation is due to the increase in precipitation, the decrease in that at higher elevation due to temperature limitation, and the maximum diversity at the middle elevation due to the most suitable heat and moisture conditions there (Rahbek, 1995; Colwell et al., 2004; Moradi et al., 2016). Zhang et al.

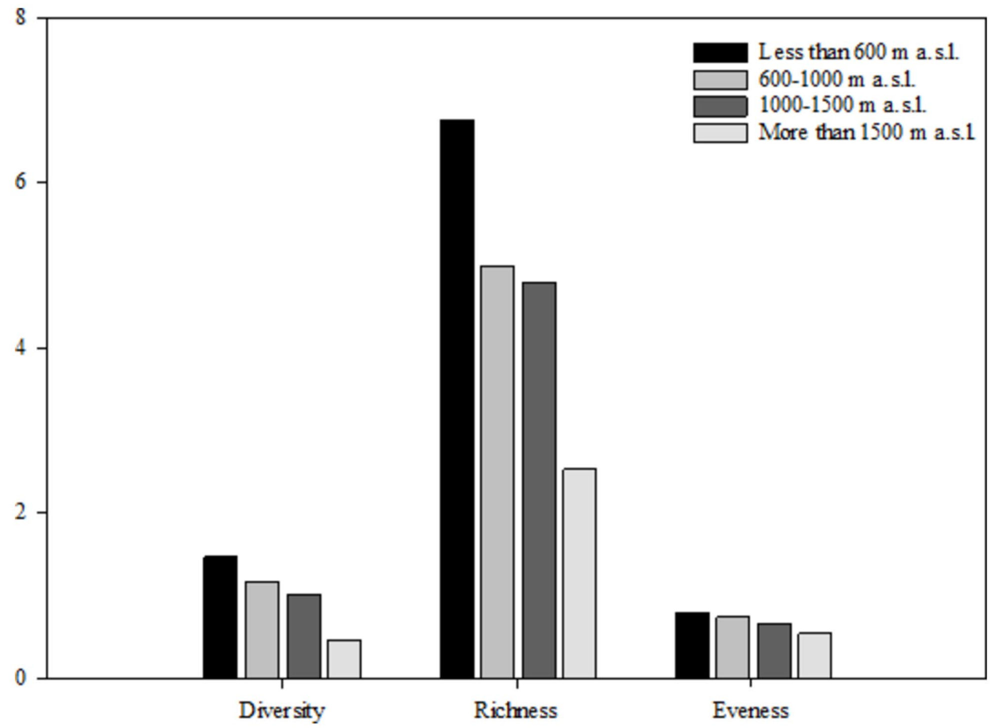

FIGURE 3
Comparison of the in woody species diversity indicators related to the main effects of elevational range, using Duncan test ([a,b]Significant at $p < 0.05$).

TABLE 8 Comparison of woody species diversity related to the interaction effects of management and elevational range using Duncan test (mean ± SE).

Area	Elevational range (m a.s.l.)	Richness	Diversity
Managed	Less than 600	$8^{a} \pm 0.63$	$1.54^{a} \pm 0.12$
	600–1,000	$6.06^{b} \pm 0.39$	$1.40^{a} \pm 0.06$
	1,000–1,500	$4.86^{cd} \pm 0.47$	$1.03^{b} \pm 0.11$
	More than 1,500	$2.66^{e} \pm 0.21$	$0.45^{c} \pm 0.04$
Control	Less than 600	$5.53^{bc} \pm 0.35$	$1.40^{a} \pm 0.06$
	600–1,000	$3.93^{d} \pm 0.31$	$0.91^{b} \pm 0.07$
	1,000–1,500	$4.73^{cd} \pm 0.43$	$1.02^{b} \pm 0.11$
	More than 1,500	$2.40^{e} \pm 0.16$	$0.47^{c} \pm 0.03$

[a,b]Significant at $p < 0.05$.

TABLE 9 Analysis of variance of total nitrogen, available phosphorus and potassium indicators for management and differences in elevation.

Source of variation		df	Sum of squares	Mean square	*F*	*p*
Total nitrogen ($t\,ha^{-1}$)	Management	1	0.34	0.34	0.03	0.86^{ns}
	Elevation	3	41.55	13.85	1.21	0.32^{ns}
	Management * Elevation	3	122.07	40.69	3.56	0.02*
	Error	32	365.50	11.42		
Available phosphorus ($t\,ha^{-1}$)	Management	1	0.001	0.001	7.73	0.00**
	Elevation	3	0.001	0.000	2.08	0.12^{ns}
	Management * Elevation	3	0.001	0.00	2.39	0.08^{ns}
	Error	32	0.006	0.00		
Available potassium ($t\,ha^{-1}$)	Management	1	0.08	0.08	0.21	0.64^{ns}
	Elevation	3	4.25	1.41	3.65	0.02*
	Management * Elevation	3	4.67	1.55	4.02	0.01*
	Error	32	12.40	0.38		

**Significant at $p < 0.01$, *Significant at $p < 0.05$, [ns]Not significant.

(2016) stated that changes in height above sea level are one of the most important factors that affect tree species diversity indices. These researchers found the highest amount of diversity in temperate forests in middle altitudes. In this study, we observed this process in the control area, which is going through its natural sequence.

4.2.2 Nutrient recycling

The findings of this study concerning nutrient cycling and supporting service indices indicate that the management factor primarily affects soil available phosphorus, resulting in higher content in managed areas compared to control areas.

The intricate process of phosphorus retrieval and recycling faces challenges due to its transformation into sediments or organic forms. Notably, the lower base density in the control region seems to stimulate greater soil respiration, leading to heightened microbial activity. Combined with increased precipitation reaching the soil surface, these factors accelerate phosphorus mineralization and its absorption by plants. Consequently, the available phosphorus content decreases in the control area's soil. The research by Chen et al. (2003)

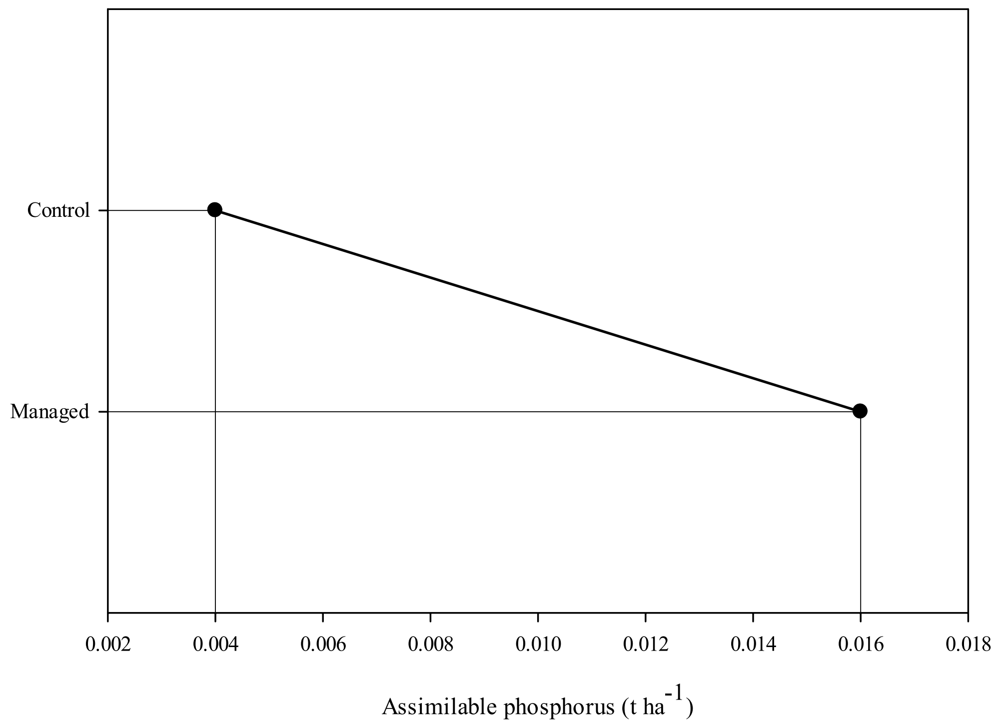

FIGURE 4
Assimilable phosphorus indices in two managed and control area.

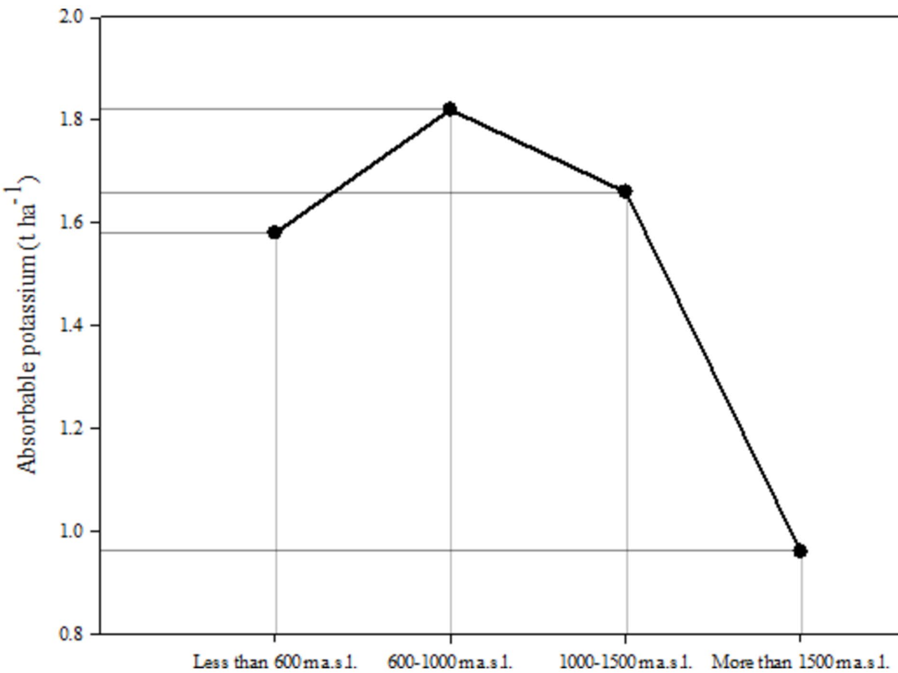

FIGURE 5
Assimilable potassium indices in elevational range.

suggests that forests with intensified microbial activity and respiration exhibit accelerated phosphorus mineralization. Therefore, it is more simply said that plant and microbial communities at P-rich sites transfer P from soil minerals into the biogeochemical P cycle. The set of mechanisms involved in this transfer is what we term P acquiring strategy. In contrast, tight P cycling is expected at sites poor in P. That means plants and microbes use P from organic sources and minimize P losses from the biogeochemical cycle (Lang et al., 2017). Apparently, this cycle is maintained in the control area and the species have taken it out of reach by consuming available phosphorus. But this problem is in a different way in the managed area, and the use of available phosphorus from the soil has decreased due to the open harvesting of trees.

Elevation emerges as a critical determinant of available potassium levels within this study. Specifically, elevations between 600–1,000 m a.s.l. and 1,000–1,500 m a.s.l. display higher levels compared to both higher and lower elevations. Prior research establishes that total nitrogen and potassium are susceptible to alterations due to diverse management practices in natural ecosystems (Puladi et al., 2012). Middle elevations, relatively less impacted by native activities such as logging and livestock grazing, exhibit enhanced nutrient levels. This transformation enhances soil bioactivity and organic matter degradation, thus acting as a source of nutrients like nitrogen and potassium.

Regarding the combined effects of management strategies and elevation on soil nutrient indices, lower elevations contribute to increased available nitrogen and potassium levels in both regions, although some trends appear irregular. In managed areas, elevations below 600 m a.s.l. exhibit the highest nitrogen and potassium content. Similarly, this elevation range experiences peak values for tree species richness, diversity, and soil carbon storage. Conversely, the control area shows elevated total nitrogen and available potassium levels within the 1,000–1,500 m a.s.l. range, corresponding to the highest soil carbon storage, diversity and richness indexes. These patterns likely stem from the flow of organic matter into the soil, fostering degradation and subsequently elevating essential nutrient levels such as nitrogen and potassium. Earlier research supports the notion that heightened microbial activity, growth, and tree-related functions positively affect soil nitrogen and potassium content (Mahmoodi et al., 2020). In this case, it can be seen that the non-interference in the control area has caused a greater balance of forest stands to be observed in the middle altitudes and a greater reserve of nutrients in the soil.

TABLE 10 Comparison of mean total nitrogen and available potassium indices at different elevations in managed and control areas, using Duncan (mean ± SE).

Area	Elevational range (m a.s.l.)	Total nitrogen ($t\ ha^{-1}$)	Available potassium ($t\ ha^{-1}$)
Managed	Less than 600	$15.45^{ab} \pm 2.95$	$2.05^{a} \pm 0.26$
	600–1,000	$15.47^{ab} \pm 1.62$	$1.87^{ab} \pm 0.34$
	1,000–1,500	$13.40^{b} \pm 1.11$	$1.18^{bc} \pm 0.13$
	More than 1,500	$15.01^{ab} \pm 0.53$	$1.11^{bc} \pm 0.02$
Control	Less than 600	$13.33^{b} \pm 1.11$	$1.10^{bc} \pm 0.26$
	600–1,000	$14.84^{ab} \pm 0.99$	$1.78^{ab} \pm 0.43$
	1,000–1,500	$19.51^{a} \pm 1.34$	$2.13^{a} \pm 0.38$
	More than 1,500	$12.40^{b} \pm 1.15$	$0.81^{c} \pm 0.05$

^{a,b}Significant at $p < 0.05$.

4.2.3 Woody stem yield

In this study, the interactions between investigated factors significantly affected the stand volume of both managed and control stands. Regarding management, the control area exhibited a higher mean stand volume per hectare than the managed area. Preserving trees with substantial diameter at breast height (DBH) in the control region contributed to increased averages for DBH, basal area, and stand volume.

Regarding elevation's influence, a notable rise in mean stand volume was observed at elevations surpassing 1,500 m above sea level (m a.s.l.). Rezaei Sangdehi et al. (2020) explored the impacts of elevational gradients on Hyrcanian forests' quantitative traits, supporting our finding of increasing mean basal area and stand volume with ascending elevations. The augmentation in mean DBH and basal area values at higher elevations can be attributed to ecological shifts along the elevation gradient, encompassing changes in climate parameters, species composition (notably *Fagus orientalis* stands), and the overall Hyrcanian forest structure. As elevation rises and base density decreases, diverse species access more light and essential resources, promoting larger diameters.

Forest management, especially in single-tree selective harvest method, has been studied in relation to ecosystem health, productivity, and carbon storage. In managed forests, although a reduction in total standing volume is observed compared to unmanaged forests, this decrease is due to density regulation. Thinning practices allow growth to concentrate on a smaller number of trees, which are often of better quality and have greater growth potential. This reduction in competition among the remaining trees results in more vigorous growth, leading to better structural stability and greater resistance to diseases and pests (Li et al., 2023; Picchio et al., 2018; Lin et al., 2024). Therefore, although the total volume may be lower, productivity in terms of high-quality timber and the overall health of individual trees tend to improve (Zeller et al., 2021).

It is essential to recognize that productivity, measured in terms of standing volume, is only one indicator of ecosystem health. In managed forests, productivity manifests in other ways, such as increased species diversity, improved soil quality, and maintained carbon sequestration (Hundera et al., 2013; Nasibullina et al., 2023). Thus, even if there is a reduction in volume, the ecosystem as a whole can be considered healthier due to its balanced capacity to provide

TABLE 11 Analysis of variance of stand volume for management and differences in elevation.

Source of variation		df	Sum of squares	Mean square	F	p
Stand volume (silve)	Management	1	418,712.49	418,712.49	26.26	0.00**
	Elevation	3	361,593.49	120,531.16	7.56	0.00**
	Management * Elevation	3	415,989.94	138,663.31	8.69	0.00**
	Error	112	1,785,619.99	15,943.03		

^{a,b}Significant at $p < 0.01$.

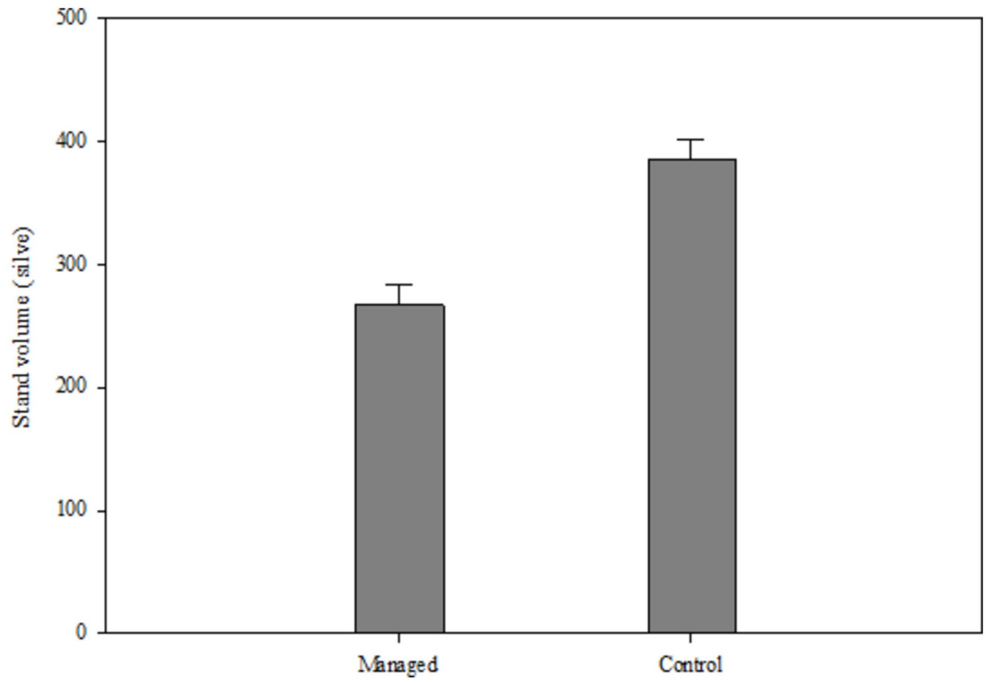

FIGURE 6
Stand volume indices in two managed and control area.

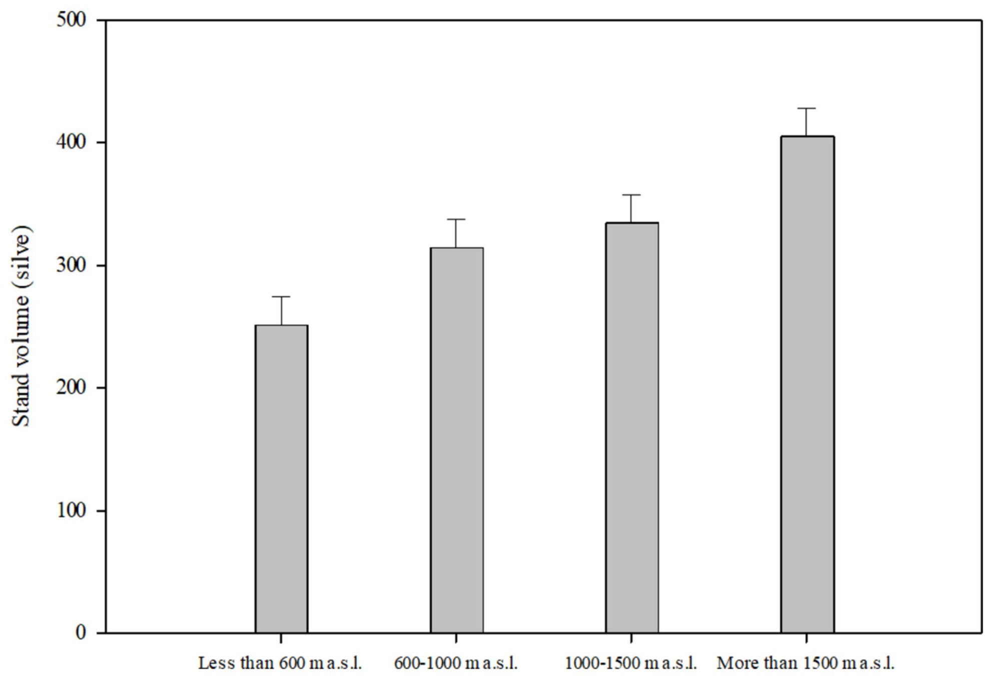

FIGURE 7
Stand volume indices in elevational range.

multiple ecosystem services sustainably (Ara et al., 2023). In summary, it is not suggested that soil carbon is superior to tree carbon, but rather that managed ecosystems can achieve a sustainable balance that favors both the growth of high-quality trees and soil carbon storage.

Lastly, considering combined management and elevation impacts on stand volume, the peak was identified at moderate elevations within the control zone. This aligns with the dominance of beech species in the control region, where preservation strategies supported larger diameters by avoiding extensive cutting

TABLE 12 Comparison of mean stand volume indice at different elevations in managed and control areas, using Duncan (mean ± SE).

Area	Elevational range (m a.s.l.)	Stand volume (silve)
Managed	Less than 600	$169.06^{d} \pm 21.32$
	600–1,000	$182.80^{d} \pm 17.77$
	1,000–1,500	$281.01^{c} \pm 26.21$
	More than 1,500	$435.73^{a} \pm 35.75$
Control	Less than 600	$333.28^{bc} \pm 28.58$
	600–1,000	$445.81^{a} \pm 40.52$
	1,000–1,500	$387.73^{ab} \pm 52.01$
	More than 1,500	$374.35^{abc} \pm 24.53$

[a,b]Significant at $p < 0.05$.

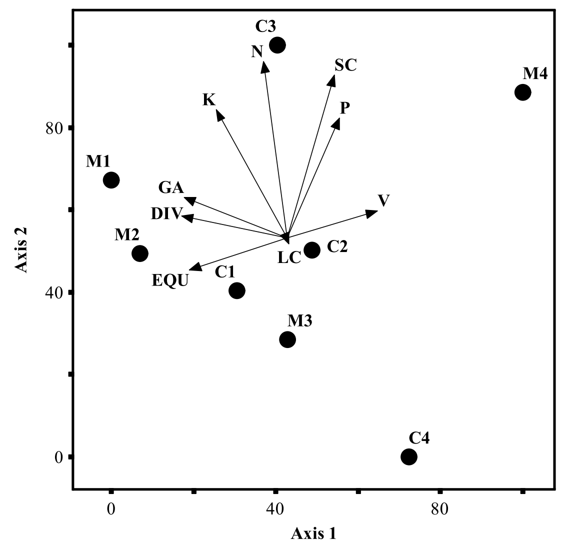

FIGURE 8
Ranking of indicators of regulating and supporting services in the space of the first and second components GA (richness), DIV (diversity), EQU (evenness), K (available potassium), N (total nitrogen), SC (soil carbon storage), P (available phosphorus), LC (litter carbon storage), and VO (stand volume); C1–C4 (control area in 4 sea level), M1–M4 (managed area in 4 sea level).

practices. On the other hand, the presence of more suitable climatic conditions in terms of temperature and precipitation in the middle altitudes has improved the conditions of the forest in this area, increasing the diversity and richness of species, soil carbon and soil nutrients, and as a result, the trees have grown better and become stronger. All these factors have finally led to an increase in the average volume of trunk wood in this part of the control area.

5 Conclusion

This study has investigated the impact of single-tree selective harvest method on ecosystem services within an Iranian mixed temperate broadleaf forest. The results of this research showed that single-tree selective harvest method in these forests did not leave an uncontrolled impact. It was found that some characteristics of the forest, such as the indices of diversity, richness and available phosphorus, have increased in the area managed in this way. These outcomes posit that this approach could serve as an effective strategy for achieving sustainable forest management objectives.

Concerning tree species diversity, the study has demonstrated that single-tree selective harvest method contributes to heightened richness and diversity of tree species in the forest. An uncontrolled increase in the diversity and richness of tree species in forest stands is not a good thing. This study showed that after 20 years, single-tree selective harvest method in these stands has not changed in a way that would take the forest out of a stable state. It is important to note that our study does not imply that the previous management regime was unhealthy. Rather, we aim to demonstrate that the single-tree selective harvest method can maintain ecosystem services such as carbon storage, species diversity, and soil nutrient cycling, offering a sustainable approach to forest management.

Although our results demonstrate a shift in carbon storage between different forest carbon pools, this study does not evaluate the rates of carbon sequestration over time. Therefore, it is not possible to determine which forest management approach is more beneficial for climate change mitigation based solely on these findings. Future research should focus on measuring carbon accumulation rates in different forest carbon pools to provide a clearer understanding of the climate-related impacts of selective forest management. More recent studies also emphasize the importance of long-term monitoring to capture changes in carbon sequestration rates across various management regimes (Jiang et al., 2020).

Our analysis reveals a redistribution of carbon storage from above-ground biomass to below-ground biomass under different forest management regimes. While this shift indicates changes in carbon allocation, it should not be interpreted as a direct improvement in ecosystem quality. To thoroughly assess ecosystem health, further research would be required, including additional variables such as biodiversity, soil stability, and nutrient cycling, which were beyond the scope of this study.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Author contributions

BK: Writing – original draft. AA: Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. AB: Project administration, Writing – original draft, Writing – review & editing. SS: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. PÁ-Á: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Policies for agroforestry, a narrative review of four 'continental' regions: EU, India, Brazil, and the United States

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Agroforestry is receiving renewed interest due to its highly diversified, multifunctional nature. With a long history and roots in many indigenous farming systems, agroforestry offers a 'win-win' for biodiversity, carbon sequestration, on-farm profitability, resilience, and social wellbeing. However, the re-integration of trees on farms goes against the previous decades' push for de-mixing, intensifying, and simplifying production methods, and farmer uptake remains low. As understanding and support for more integrated, complex farming systems builds, an enabling policy landscape is needed. This narrative policy review considers policies for agroforestry across four 'continental' regions: the EU, India, Brazil, and the United States. Using an agroecological framework, we explore the content, development, objectives, and alignment of both direct and indirect policies to provide insight into: how policies for agroforestry are currently framed; their development process; and, whether over-lapping and interconnected policy objectives are included. We find that policies for agroforestry are increasing gradually, but are typically confined to an agronomic understanding, with limited inclusion of the socio-political aspects of food and farming. Except in Brazil, policies appear to be narrow in scope, with few stakeholders included in their development. Policies do not challenge the status quo of the dominant corporate agri-food system and appear to miss the transformative potential of agroforestry. We recommend: greater coordination of policy instruments to achieve co-benefits; focused integration of agricultural and climate policies; greater inclusion of diverse stakeholders in policy development; and a widening of agroforestry systems' objectives, both in policy and practice.

KEYWORDS

agroforestry, multifunctional, sustainable food systems, policy coherence, nature-based solutions

1 Introduction

Globally, agriculture is the driving force behind several major global crises: it is responsible for an estimated 60% of terrestrial biodiversity loss due to land use change (Benton et al., 2021), as well as for 24% of greenhouse gas emissions (GHGE), 33% of soil degradation and 20% of the overuse of aquifers (UNEP, 2016). More than 60 years after the spread of the 'green revolution', 820 million people around the world are undernourished, 2 billion are deficient in micronutrients and 650 million are obese (FAO and ICRAF, 2019). When looking at the food sector from a system perspective that covers the full and complex web of activities from production, processing, transport and consumption, the global organization of our 'food system' seems highly dysfunctional. There is widespread awareness well beyond academia (Benton et al., 2021; Fanzo et al., 2021; Webb et al., 2020) that the sector needs to change its practices; evident from the significant number of reports, papers, summits, and conferences seen across civil society (WWF, GRAIN, FIAN), landworkers' organizations (LaVia Campesina), governments (UN Food Systems Summit, 2021), as well as global agribusinesses (Bayer, 2023; Cargill, 2022). However, despite broad agreement over the issues at stake, different actors have different ideas and visions for what this 'sustainable future' of the food system entails (IPES-Food and ETC Group, 2021). Calls for high-tech innovations from climate-smart and precision agriculture to organic and regenerative approaches, through to agroecology and food sovereignty, coexist and contradict. One may accuse the former innovations of being just an extension of the existing and dysfunctional, dominant agri-food system, that has expanded internationally along colonial lines (Ferrando et al., 2021), and that as a mainly 'corporate food regime' is oriented around principles of gaining profits, rather than providing nutritious food to humans (Holt-Giménez, 2019). By contrast, the latter has been criticized for being inefficient and labor and land intensive (Sanderson Bellamy and Ioris, 2017). Despite the pertaining contestation of the 'right' approach, there seems to be an unprecedented and, in general, agreed upon understanding and valuation of the links between planetary and human health (IAASTD, 2009; Willett et al., 2019; IPBES-IPCC, 2021) and in particular the impacts of climate change on sustainable food production (IPCC, 2019). This can be seen in the mainstream acceptance of concepts such as 'The Economics of Ecosystems and Biodiversity' (TEEB) and more recently 'Nature-based solutions' (NbS), which aim to make nature's 'value' to society visible.

1.1 Re-integrating planetary and human health through trees

'Nature-based solutions' (NbS) are a key concept propagated to address numerous ecological and climate challenges (IUCN, 2020; Mori et al., 2021). A broadly shared definition is that NbS are "solutions to societal challenges that involve working with nature" (Seddon et al., 2021). In the context of national climate mitigation and adaptation plans, NbS schemes, including tree planting, are championed for their capability to sequester carbon and support biodiversity while reducing the vulnerability of social-ecological systems to the impacts of climate change (Girardin et al., 2021; Roe et al., 2021). Afforestation and /or Reforestation (A/R) is one distinct NbS approach that features highly in numerous state political campaigns, Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs), as well as international initiatives (such as the Great Green Wall or the Bonn Challenge), local community projects, and corporate net-zero goals and Community Interest Companies such as Ecosia. However, 'nature-based' means different things to different people. While tree plantations may be seen as an efficient 'natural' way to adapt to and mitigate the impacts of climate change, others would reject this approach to NbS, witnessing the significant impacts on and costs to local communities, local resource right holders or the pre-existing native ecosystems (Seddon et al., 2021). The supposed potential of A/R based NbS may also distract from the need to rapidly phase out fossil fuels, protect existing ecosystems from further climate impacts or improve livelihood resilience in the face of climate shocks. There are also red flags raised around land grabbing for monoculture tree planting by corporations attempting to offset their carbon emissions, which again, often come at significant cost to local communities, local resource rights and pre-existing carbon rich biodiverse native ecosystems (Ollinaho and Kröger, 2021).

Apart from classical A/R, agroforestry systems (AFS) are another NbS that involves both trees and agricultural land use. Agroforestry is defined as "the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions" (Burgess et al., 2015). AFS as a multifunctional land-use, built on diversification and low-inputs (Hernandez-Morcillo et al., 2018), offer a set of different benefits at the farm, landscape and global levels that can: increase carbon stocks and biodiversity in agricultural systems; improve soil fertility; reduce runoff, water pollution and soil erosion; improve on-farm resilience and enhance food sovereignty (Castle et al., 2021; Jose, 2009). This 'multifunctionality' is widely recognized; indeed, AFS feature in the recent IPCC report as a sustainable land management practice that, with 'very high confidence', can "prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation" (IPCC, 2019; p. 23). Yet, despite the potential of AFS and a growing interest among policymakers, farmer uptake remains relatively low (Buratti-Donham et al., 2023).

1.2 Policies for agroforestry

Globally, barriers to scaling AF among farmers are remarkably similar. The most commonly cited issues are: unclear and deficient tenure or resource use rights; a lack of clear policies and regulations; insufficient financing (for implementation and maintenance); and a lack of knowledge and capacities (FAO, 2013; Organic Research Centre, 2021). Irrespective of regional and context dependent variations on the barriers for AF uptake, policies remain a key lever to encourage uptake and address the pertaining issues. Accordingly, it is highly relevant and interesting to understand how policies develop in this field (Westaway et al., 2023; FAO, 2013; van Noordwijk, 2019). Within the EU, the Common Agricultural Policy (CAP), for instance, has disincentivized tree planting on agricultural land until very recently. The traditional understanding of agriculture as an 'exceptional sector' plays into the non-adoption of integrated systems, like AFS. It has led to a highly compartmentalized approach in land use policies that separates agriculture for food production not only from forestry but also from interlinked objectives such as climate change mitigation or adaptation, biodiversity conservation, or public health (Candel and Biesbroek, 2016; Nilsson and Weitz, 2019; Biesbroek and Candel, 2020). This compartmentalization also inhibits effective policy integration and coherence, key concepts when attempting to address complex systems and their respective actors, disciplines and ideologies (Tosun and Lang, 2017; Runhaar et al., 2014).

Although agroforestry is considered a regenerative, agroecological approach to land management (Peredo Parada et al., 2020; Snapp et al., 2021), it can take many forms in practice. Depending on what objectives are prioritized, the transformative potential of AFS on food systems is impacted. Policies need to adopt a 'coherent' systems-thinking approach (Kuhmonen, 2018) if they are going to succeed in addressing overlapping and interconnected societal objectives. Moreover, and in line with commonly shared ideas of systems transformation and scaling, policy efforts need to open avenues for a full set of diverse practices, rather than conceptually narrowing down options to simply adding woody components, thereby missing the opportunity to change the nature of how farming as a system works.

Within this context, this paper reviews agroforestry policies in four major food producing regions of the world, with the aim to understand how these policies are being developed and with what narratives, reflecting on the scope of AFS to contribute to a fairer and more sustainable food system through the lens of agroecology as a transformational framework. Including the state and development of public policies in relation to AFS we specifically ask:

1. How is agroforestry currently framed in direct and indirect policies?
2. To what extent are policies for agroforestry aligned with other interconnected policy objectives, such as carbon sequestration, biodiversity, food security and diet related health?

2 Analytical framework and methods

This research seeks to analyze public policies on or of relevance to agroforestry, their coherence and whether or not the content is narratively leaning toward a more integrated agroecological reading.

To narrow the scope of the research, four 'continental' regions were chosen for this analysis: the European Union (EU), India, Brazil, and the United States of America (U.S.A). Together, these regions represent a significant proportion of total global cropland; out of a total global cropland figure of 1.63 billion hectares, the selected regions represent about one third (0.507 billion hectares) of global cropland (Goldewijk, 2023). Given their collective contribution to global agricultural production and export (see Figure 1), and therefore their contributions to global greenhouse gas emissions (GGHE), agricultural and land use policy environments in these regions are highly relevant. Moreover, the EU, India, Brazil and the U.S.A have comparable policy models in that they all have a combination of overarching policies at the federal level (or supranational level in the case of the EU), as well as at the individual state or member state level, which can work against or in tandem with the broader policies.

Policies, both direct and indirect, were identified for each region following a 'snowball sampling' approach (Parker et al., 2019). The legislative and policy database, FAOLEX, was employed to source policies. Relevant government websites, academic and gray literature, and expert knowledge were also used to complement the list of policies. The authors define 'direct policies' to be those that specifically mention agroforestry, such as India's National Agroforestry Policy, NAP (2014) or the U.S.A's 'Agroforestry Strategic Framework 2019–2024' (2019). Given the small number of direct policies for agroforestry, 'indirect policies', such as Brazil's 'National Low Carbon Agricultural Plan' (2012) or India's 'National

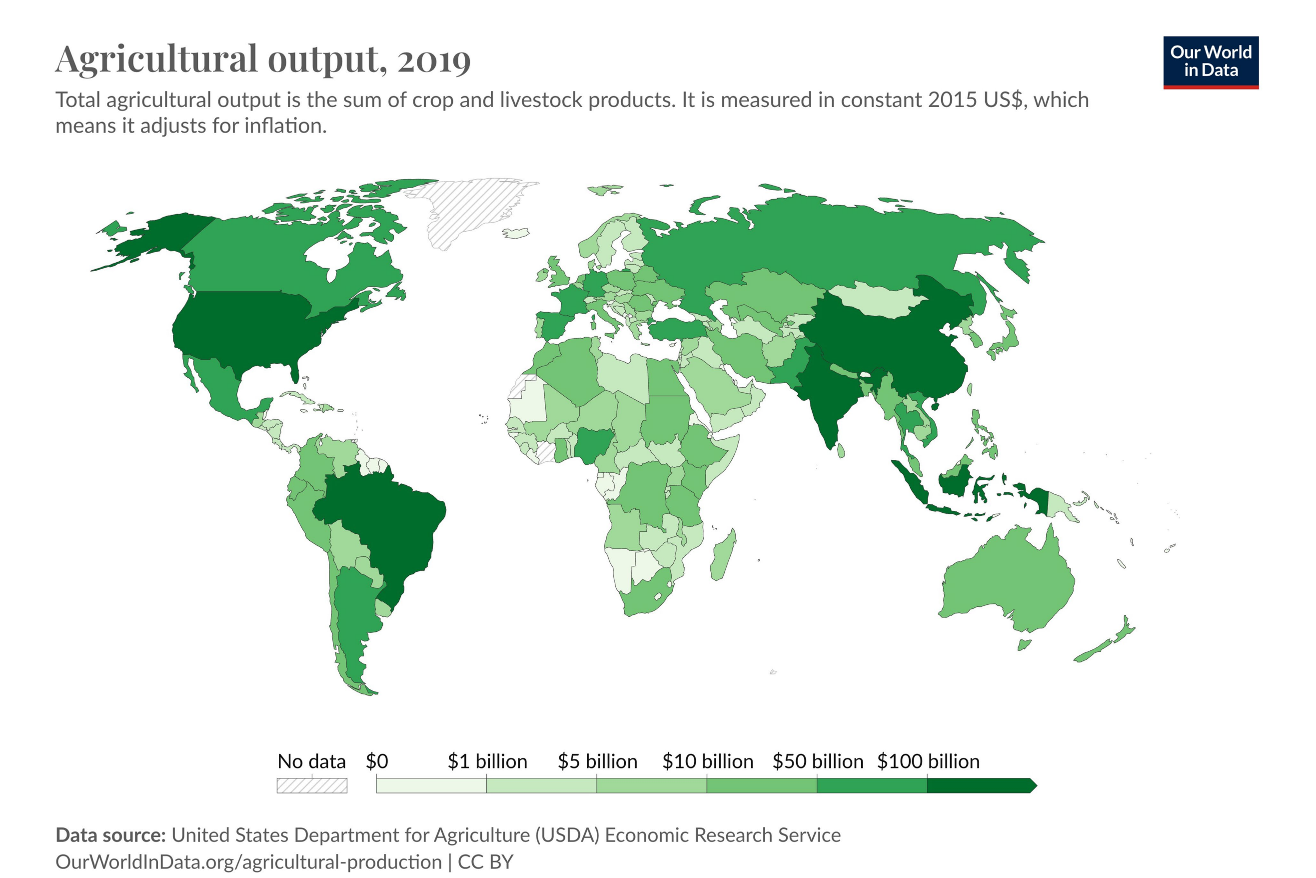

FIGURE 1
Total agricultural output as the sum of crop and livestock products in USD$ (Our World in Data, 2019).

Environment Policy' (2006) were also included. The inclusion (or exclusion) of the indirect policies was decided based on an initial assessment of the policies' perceived relevance to either agroforestry, trees on farms, agricultural production, or, where the authors considered the policy goals to overlap, such as the U.S.A's 'Agriculture Resilience Act' (2021) or India's 'Biological Diversity Act' (2002). Policies up to and including the year 2022 were included in the policy framework review. All policies included in the framework review are listed in Table 1.

To address our aims, a novel policy framework was developed (Table 2). The framework was generated inductively, informed by relevant policy literature on sustainable food systems and just transition pathways. A list of attributes in line with environmental and societal sustainability were identified and grouped into four categories: *policy development*, *subject included*, *policy goals* and *policy coherence*. In this attempt, these four categories, and the attributes within them, provide a 'picture' of the narrative leaning of the policies. *Policy development* refers to the way in which the policies appear to have been developed and how they may be operationalized. *Subject included* lists a broad range of topics related to sustainable food systems and just transitions from the literature, as well as known barriers to scaling AFS. *Policy goals* include specific benefits that AFS can contribute to (Jose, 2009) as a means to understand in what ways and for which purposes are AFS included in policies. *Policy coherence* looks at the alignment of the policies with key national and international targets (such as the Nationally Determined Contributions and SDGs) as a means to specify the extent to which different policy goals are integrated or 'coherent'. Taken together these categories provide a framework through which to assess current policies and address the two research questions listed above.

Given their relevance to the agroecological discourse on transition pathways, the High Level Panel of Experts' '13 Principles of Agroecology' (2019) serve as a basis for defining whether policies adhere to an agroecological reading or not. They were thematically grouped (see Appendix 1) and included as distinct *subject* attributes in the analysis.

An expanded definition of each attribute, its relevance and accompanying reference(s) are provided in the Supplementary materials.

The policies were reviewed using a narrative approach, using content and thematic analysis. ATLAS.ti 23 software was used to manage and code data (ATLAS.ti, 2023). Each policy was scored against each attribute, either scoring 1 for yes, 0.5 for partially or 0 for no. 'Not Applicable' and 'Not Enough Information' were also included to allow for specific instances such as a policy being created before the UN SDGs, or to highlight where there was not enough sufficient information for the authors to score the policy. An example of the coding is given in Table 3. As the review progressed, the authors adapted the framework collectively in an iterative process. When ambiguity in scoring arose, the authors collectively addressed the issue (an intercoder agreement).

3 Results and discussion

In this next section, we present our results and discuss them in the following order. We start with key figures on the agricultural sector and general AFS trends for each region. The visual representation of the policy framework review is then presented, and each region discussed in turn. Cross-cutting topics and themes are approached in a comprehensive discussion, drawing parallels from each region. Finally, limitations are presented, before concluding and providing recommendations.

3.1 Key agricultural and AFS trends across regions

Land classified as 'agricultural' in the EU spans around 157 million hectares, representing 38% of the total land area (EUROSTAT, 2023). As a sector, agriculture contributed just 1.4% to the EU's GDP in 2022 (EUROSTAT, 2023) a number which has been steadily decreasing. In 2018, the total area of agroforestry in the EU was 114,621 km2, representing 6.4% of the total utilized agricultural area (UAA), with the majority located in the Mediterranean bioregion (Rubio-Delgado et al., 2023). Silvopastoral systems are the most widespread AFS, representing 81% of the total agroforestry area and 5% of UAA. The EU has direct policies both at the regional and individual member state (MS) level to support AFS. Yet, despite the existence of policy support, there has been a low degree of farmer uptake for direct AF measures, and subsequently large leftover budgets for such measures that could have been allocated to maintaining and increasing AFS (Mosquera-Losada et al., 2016). In fact, there has been a 47% decline in AFS in Europe (Rubio-Delgado et al., 2023) between 2009 and 2018 despite the CAP providing for AFS since 2007.

The U.S.A is the second-largest agricultural trader in the world, after the European Union (USDA, 2022). According to the USDA, agriculture, food and related industries contributed 5.2% toward GDP in 2019. 44.36% of the U.S.A.'s land mass is registered as agricultural land (World Bank Group, 2021). Figures for AFS as a land use do not yet exist, however, according to the 2017 Census of Agriculture (COA), 1.5% of all farm operations responded that they had at least one agroforestry practice on their farm (Smith et al., 2022). AFS, in the more traditional sense of perennial polycropping systems, have been used by Indigenous and First Nation peoples in the U.S.A for centuries. AFS were first formally recognized in the U.S.A in the 1930s in the form of windbreaks (Jose and Udawatta, 2021). The U.S.A. does not have direct national policies for AFS at the federal level but supporting policies can be found at the state level.

In India, agriculture is the largest source of livelihoods, contributing to about 17% of GDP and employing roughly 47% of the total national workforce (Ministry of Labor and Employment, 206). As the Indian economy has diversified, agriculture's contribution to GDP has declined. Current estimations of AFS as a land use vary substantially (Sharma et al., 2017). Taking FAO's figures that agricultural land in India represents 60% of the total land area alongside the Central Agroforestry Research Institute of India's estimations that AFS make up 8.65% of agricultural land, we can estimate 14.41% of utilized agricultural area is AFS. India was the first country to introduce a National Agroforestry Policy, NAP (2014), but no direct regional or state policies were identified.

Brazil, the world's fifth-largest country in both area and population, accounts for the largest share of arable land and the

TABLE 1 The 33 documents included in the policy framework review.

Region / country	Name of policy (year of adoption)	Binding instrument in law (laws, acts, decrees)	Non-binding instrument (communications, strategies, plans)
EU	Common Agricultural Policy (2013)	X	
	European Green Deal (2019)		X
	EU Biodiversity Strategy for 2030 (2020)		X
	Farm to Fork Strategy (2020)		X
	EU Forest Strategy for 2030 (2021)		X
India	National Forestry Policy (1988)	X	
	National Agricultural Policy (2000)		X
	Biological Diversity Act (2002)	X	
	Forest Rights Act (2006)	X	
	National Environment Policy (2006)		X
	National Policy for Farmers (2007)		X
	National Biodiversity Action Plan (2008)		X
	Green India Mission (2010)		X
	National Agroforestry Policy (2014)		X
	Agricultural Export Policy (2017)		X
	Nationally Determined Contribution (2022)		X
United States	National Environmental Policy Act (1969)	X	
	The National Forest Management Act of (1976)	X	
	Farm Bill Agricultural Improvement Act (2018)	X	
	Agroforestry Strategic Framework (2019–2024)		X
	Agriculture Resilience Act (2021)	X	
	Nationally Determined Contribution (2021)		X
	USDA Food System Transformation Framework (2022)		X
Brazil	National Family Farming Policy (2006)	X	
	National Forest Code (2012)	X	
	National Low Carbon Agricultural Plan “Plano ABC” (2012)		X
	National Agroecology and Organic Agriculture Policy (2013)	X	
	National Integrated crop-livestock-forestry systems Policy (2013)	X	
	National Adaptation Plan to Climate Change (2016)		X
	National Plan for Native Vegetation Recovery (2017)		X
	National Food Acquisition Program (2021)	X	
	Nationally Determined Contribution (2022)		X
	National Agribusiness Financing Plan “Plano Safra” (2022–2023)		X

TABLE 2 Policy framework developed by authors, with attributes grouped into four thematic categories.

Thematic categories	Attributes
Policy development	Policy is legally binding
	Cross-ministerial collaboration
	Farmers, practitioners, and food system experts consulted
	Indigenous knowledge / ways of knowing, included or referred to
	Development of targets based on holistic food systems approach
	Specific objectives / key metrics included
Subject included	Land tenure
	Land access
	Water access
	Farm succession
	Financing for agroforestry
	Knowledge and training
	Deforestation
	Emissions reduction included in relation to policy ambition
	Support for new entrants
	Fair employment
	Territorial or landscape approach encouraged
	HLPE environmental
	HLPE social
	HLPE economic
	HLPE political
Policy goals	Contribute to an agroecological transition
	Carbon sequestration
	Biodiversity preservation & conservation
	Soil health
	Improve air and water quality
	Flood mitigation
	On-farm resilience
	Food security and nutrition
	Inclusion of cultural ecosystem services
Policy coherence	Links to climate goals / NDCs
	Links to UN SDGs
	Links to biodiversity priorities
	Links to other agricultural and environmental state policies
	Intersectionality
	Diet related health

fourth-largest agricultural land globally (2.3 million sq. km; World Bank Group, 2021). Brazilian agriculture and livestock (including processing and distribution) contributed to almost 25% of the national GDP in 2022 (CEPEA, 2022). AFSs are increasing; there was a 67% increase from 8.4 to 13.1 million hectares between 2006 and 2017 (Manzatto et al., 2019), however, this represents just 5% of total farmed land (Schuler et al., 2022; Alexandre et al., 2021). Brazil does not have direct national policies for AFS, but indirect policies at the state level include AFS as a management practice.

3.2 Regional policy framework analysis

Policies relating to AFS are increasing gradually over time, our analysis yielded 16 out of 33 policies created after 2015. More recent policies include a greater diversity of policy goals, such as carbon sequestration, improving air and water quality, and biodiversity preservation and conservation. Issues around land tenure and access (known barriers to scaling AFS) are for the most part, not included. Notably, the UN SDGs are also largely absent within the policies

TABLE 3 Intercoder agreement on codes (with example) allocated to each policy attribute.

Code	Definition	Example from data
1	Yes	EU Forestry Strategy for 2030 (EU, 2021)—this scored 1 for attribute 'deforestation' as the policy mentions deforestation multiple times as well as its commitment to ensure that any products sold on the EU market, originating from the EU or globally, will not contribute to deforestation.
0.5	Partially	Green India Mission (India, 2010)—this scored 0.5 for attribute 'Indigenous knowledge/ ways of knowing included or referred to' as the policy only makes one mention in section 4.3 whereby "Traditional Ecological Knowledge of communities, along with forestry science and state-of-the-art technology would improve the Mission interventions"
0	No	National Adaptation Plan to Climate Change (Brazil, 2016)—this scored 0 for attribute 'Policy is mandatory' as the policy explicitly mentions its purpose whereby "The purpose of the Brazilian Federal Government's National Adaptation Plan, hereinafter referred to as the National Adaptation Plan (NAP) is to guide initiatives for management and reduction of long-term climate risks, as established in Ministry of Environment (MMA) Order 150 of 10th of May 2016, published in the Official Gazette (DOU) of 11th May 2016."
NI	Not enough information	When not enough information is found in the document, we asserted the value NI.
NA	Not applicable	National Environment Policy Act (U.S.A, 1969)—this scored NA for attribute 'Links to UN SDGs' as the policy was written before the UN SDGs

reviewed. A policy summary matrix is used to visualize the results from the policy framework analysis (Figure 2).

In terms of *policy development*, Brazil scored highest, with strong cross-ministerial collaboration and stakeholder consultation. Policies in the EU appear to have specific objectives and key metrics included, but only partially consult with key actors. The only attribute not fulfilled in India in *policy development* was the development of policies with a holistic food systems approach. In the U.S.A, consultation with stakeholders is minimal. None of the regions have addressed either partially or in full all subjects, however financing for agroforestry was addressed in full in at least one policy for all regions. Brazil has included the majority of *subject* attributes (13 out of 14), followed by India (10), the EU (6), and the U.S.A (5). The High Level Panel of Expert's (HLPE) attributes scored low across all regions: 'environmental' was addressed in full in just one policy in India; 'social' addressed in full in three policies in Brazil and one in India; 'economic' was only partially addressed or not at all in all regions and 'political' only addressed in full in two policies in Brazil.

Brazil is the only region that fulfills the agroecological transition attribute, and the only region with at least one policy addressing each *policy goals* attribute. The EU appears to address provisioning ecosystem services, with at least one policy either partially or fully addressing carbon sequestration, biodiversity preservation and conservation, soil health, air and water quality and flood mitigations. According to our analysis, policies in the U.S.A appear not to demonstrate coherence; with only one policy fully addressing climate goals. The other three regions have addressed most of the *policy coherence* attributes. Brazil, India, and the EU have policies linked to biodiversity priorities. Despite many of the assessed policies dated post 2015, (the date of the UN SDGs), only the EU has developed policies in line with these goals.

Figure 3 visualizes the total scores of each region and each attribute, which enables some additional trends to be observed in the data. Seemingly, the more agronomic or environmental attributes such as carbon sequestration, biodiversity and air and water quality are more readily included than the socio-economic or political attributes such as land tenure, access to land or fair employment. Interestingly, food security and nutrition scores higher than flood mitigation and on-farm resilience across the regions. For the most part, Brazil is the highest contributor across attributes, followed by India and the EU with the U.S.A the lowest contributor across attributes. Attributes in the *policy coherence* category are represented the least, with minimal links to climate goals or NDCs or the UN SDGs, though links to other agricultural and environmental state policies are included in all regions except the U.S.A.

3.2.1 European union

The Common Agricultural Policy (CAP) is the primary legislation guiding EU agricultural production. The CAP is renewed every 6 years and represents 40% of the total EU budget. The CAP primarily functions through direct subsidies based on the size of land or heard, and through rural development subsidies. In 2019, farmers received €38.2 billion in direct payments and €13.8 billion in rural development subsidies (European Parliament, 2021). Over the last decade, the policy environment for AFS across the EU has been growing. While the EU has defined AF as "land use systems in which trees are grown in combination with agriculture on the same land," (European Parliament, 2020), the minimum and maximum number of trees per hectare can be defined by each MS. This could be seen as positive as it gives each MS the opportunity to take into account their own realities, yet, it has resulted in a huge variety of definitions, which is suggested to negatively impact uptake and go as far as disincentivizing AFS (EURAF, 2020).

Within the 2007–2013 period, only five EU MS directly supported AF within the CAP (Belgium; France; Hungary; Italy; and Portugal), while the 2014–2020 CAP saw an additional three (United Kingdom; Greece; and Spain). Some Member States (MS) like Hungary supported AF across the entire country, while in places like the UK and Italy, it was only supported in certain regions. AFS were also supported indirectly within Pillar II of the 2014–2020 Rural Development Plans (RDPs) through 22 other Measures (EURAF, 2020), and through the CAP's Statutory Mandatory Regulations (SMRs), Good Agricultural and Environmental Conditions (GAECs) and Ecological Focus Areas (EFAs).

In the recent CAP (2023–2027), AFS can be directly supported as part of the 'Eco-schemes', a novel instrument which is voluntary for farmers but is ring-fenced by 25% of the Pillar 1 direct payment budget. These schemes prioritize the protection of the environment and climate through a list of possible practices that can be implemented by MS at their own discretion. These include the expansion of organic farming practices, integrated pest management, agroecology, animal welfare, the protection of water resources and soil, and many others.

10.3389/fsufs.2024.1417740

FIGURE 2
Policy summary matrix showing the results of the policy framework analysis. Regions and corresponding policies are shown along the horizontal axis; attributes and their respective categories are shown along the vertical axis. Shaded boxes represent each policies' score as the key denotes.

However, only four countries have included an agroforestry related Eco-scheme (Czech Republic; Germany; Greece; and Portugal). AFS also find direct and indirect support through the Eco-schemes that have been implemented by MS on landscape features (Belgium Flanders; Bulgaria; Croatia; Estonia; France; Hungary; Italy; Ireland; Lithuania; Netherlands; Romania; Spain; and Portugal). In general, the types of policies that appear to be most beneficial to the protection and expansion of AFS are the ones that support traditional systems, the implementation of new systems and the yearly support for the management of those new systems. From the data gathered, this type of policy support is only found in France and Portugal.

As the CAP continues to evolve and the EU makes ambitious targets such as '30 by 30' (the worldwide initiative for governments to designate 30% of Earth's land and ocean areas as protected areas by 2030) and 'net-zero by 2050' (net-zero carbon emissions by 2050), AFS are indirectly supported, to a limited extent, outside the

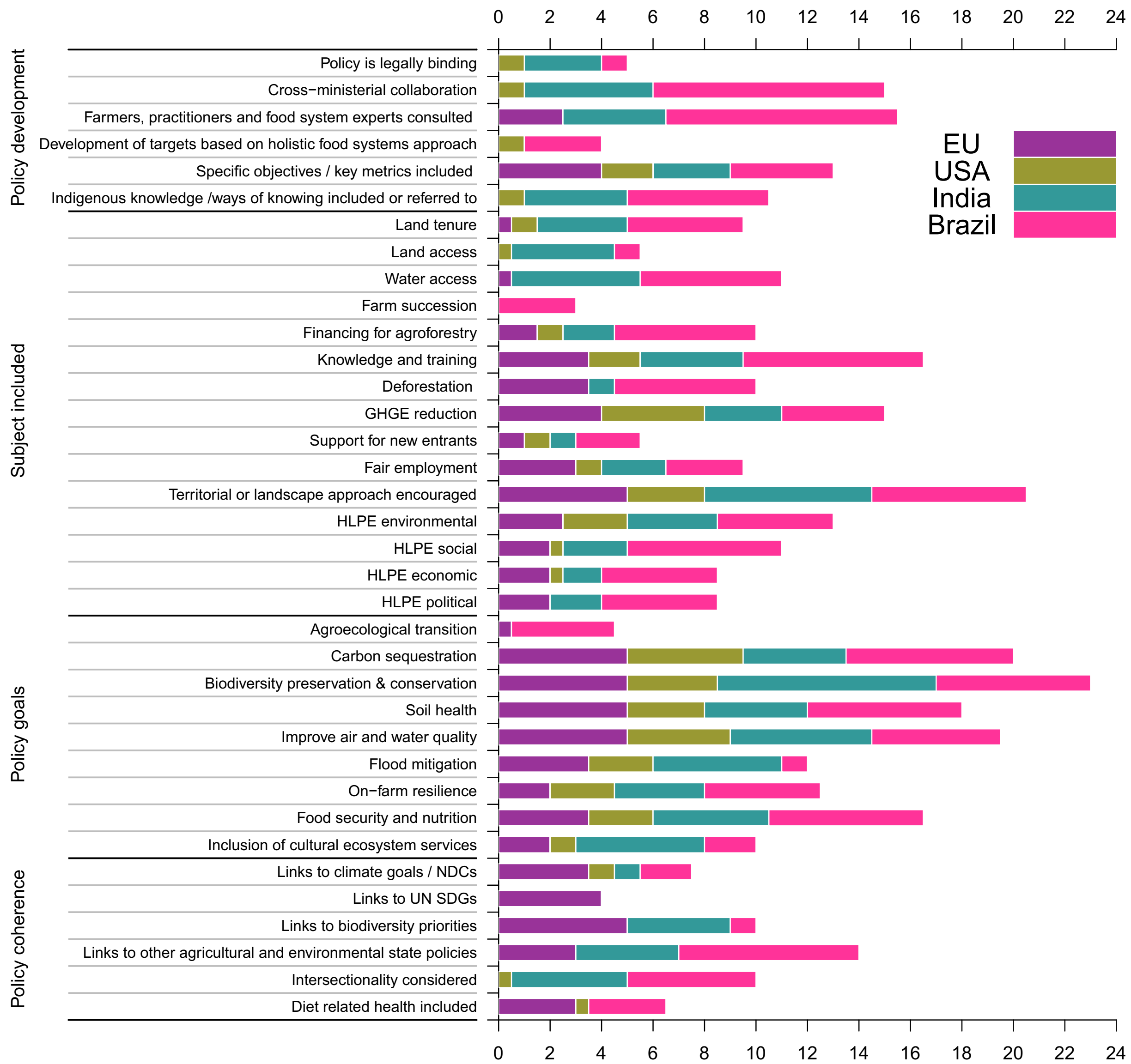

FIGURE 3
Total scores by region and for each attribute in the policy analysis framework.

CAP. Within the EU Biodiversity Strategy for 2030 for example, AF is mentioned directly twice and indirectly through landscape features, which are an inherent part of AF. In the Farm-to-Fork Strategy, AF is mentioned once. In these documents AFS is mentioned as an opportunity for tree planting, as well as a system that represents strong benefits for biodiversity, people, and climate. Within the primary European Green Deal Strategy document, AF is mentioned just once. Within the EU Forest Strategy for 2030, it is mentioned multiple times. However, most of these European Green Deal strategies contain measures that are vague, leaving implementation and assessments to the discretion and ambition of individual MS.

The EU shows relatively robust *policy coherence* (Figure 2) with various policies cross-referencing each other as a source of guidance, for example on reforestation and biodiversity in both agricultural and environmental policies. This is perhaps unsurprising given the interconnected nature of the policies reviewed; the Farm to Fork Strategy being a sub-strategy of the Green Deal for example. The Green Deal in particular is explicit in its integrated ambition: "All EU actions and policies will have to contribute to the European Green Deal objectives. The challenges are complex and interlinked." Additionally, most of the policies had at least partial links to climate goals, NDCs, and UN SDGs. Intersectionality was not considered in any of the policies and diet related health was referenced only in the three documents reviewed of the EU Green Deal.

The EU scored quite highly across all attributes, prioritizing carbon sequestration, biodiversity preservation and conservation, air quality improvement, food security, and to a lesser extent, flood mitigation, on-farm resilience and cultural ecosystem services. All policies reviewed demonstrated partial inclusion of 'farmers, practitioners and food system experts consulted' but none suggested cross-ministerial collaboration and reference to knowledge co-creation was minimal. The consideration of the social components of a fair food system was also lacking, especially on matters of access to land or water, or farm succession (Figure 2). However, support for new entrants was partially considered within the CAP and EU

Forestry Strategy. There was partial inclusion of all four themes of the HLPE's Principles for Agroecology across the policies reviewed, except for 'social' in the CAP, and 'economic' and 'political' in the EU Forestry Strategy. Direct policies for AFS often include aspects of biodiversity, soil health and improved animal health and welfare, but minimal inclusion of social aspects such as land tenure or access. Additionally, most policies focus on the farm or plot level. There is limited indication to suggest that the policies are transformative or have an agroecological leaning.

3.2.2 United States

Farmers in the U.S.A have typically received very high levels of federal support, not dissimilar to the EU. US agricultural policy follows a 5-year legislative cycle that is commonly known as the US 'Farm Bill'. The Farm Bill governs farming, food and nutrition, and rural communities, as well as aspects of bioenergy and forestry. In the 2014 Farm Bill however, direct payments and subsidies were completely removed, though price support still exists for some products, such as diary. The Farm Bill instead moved toward providing subsidized insurance for yield and loss.

Policy support for AF is found at the federal level, mainly through the USDA Farm Service Agency (FSA) and the National Agroforestry Centre (NAC). However, there is no direct federal or state policy for AF. The FSA's support comes mainly in the Conservation Reserve Program (CRP), which started in the 1985 Farm Bill (Smith et al., 2022). Windbreaks, shelter belts, living snow fences and riparian buffers all fall under the CRP. Given that most of the public funds for AF systems come from the CRP, a common misconception in the US is that AF is a conservation practice with additional benefits, as opposed to a production practice (Chenyang et al., 2021). In 2011, the USDA launched its Agroforestry Strategic Framework 2011–2016 which outlines the mission, goals, and approach to AF with contributions from 8 agency members of the USDA AF Executive Steering Committee (AESC), the USDA Interagency Agroforestry Team (IAT) and the National Agroforestry Centre (NAC). However, there is limited policy information or details on the financing of AF, and a formal AF policy in the US is still lacking. The USDA budget for AF (2011–2012) was $333 million, less than 1% of the total USDA budget. In addition to minimal financial support, the dominance of leased land (39%) represents a key barrier to farmers wanting to convert to AFS.

The NAC defines AF in the Agroforestry Strategic Framework as "the intentional integration of trees or shrubs with crop and animal production to create environmental, economic, and social benefits" (National Agroforestry Centre, 2019, p. 2), going on to say, "agroforestry provides opportunities to integrate productivity and profitability with environmental stewardship to support healthy, sustainable agriculture systems, economies, and communities" (P3). However, this is not benchmarked in any way and is left to the reader to define for themselves what 'healthy, sustainable agriculture systems, economies, and communities' might be. This is tacitly echoed by the omission of many of the *subject* attributes related to the socio-economic such as 'HLPE social', 'land tenure' or 'fair employment' or policy goals such as UN SDGs, scoring '0' (Figure 2). The stated goals within the Agroforestry Strategic Framework are broad and not quantifiable.

In terms of *policy coherence*, the policies reviewed for the US score very low (Figure 2). There appears to be minimal alignment of national and international targets. Only one policy, 'Agricultural Resilience Act' (2021) scores a '1' for 'Links to climate goals'. There are no links to biodiversity priorities or other agricultural and environmental state policies within the dataset. One policy scores '0.5' for 'Diet related health' (USDA's Food System Transformation Framework) and another (2018 Farm Bill) scores '0.5' for 'Intersectionality considered'.

The US scores are low for many of the *policy development*, *subject* and *policy goal* attributes (Figure 2). There was not enough information to score most of the policies on whether farmers or practitioners had been consulted, nor whether there was cross ministerial collaboration. Only one policy reviewed (NDC) scored '1' for the inclusion or referral to indigenous knowledge or ways of knowing. Land and water access were not mentioned across all policies. Carbon sequestration and improving air and water quality were the highest scoring attributes across the policies. The more recent Agriculture Resilience Act (2021) scored highest across attributes, in particular the *policy goals* section, omitting only an explicit goal of an agroecological transition. Seemingly the policies reviewed do not have a narrative leaning toward agroecology, instead focusing on the agronomic benefits of AFS. Only the USDA's Food System Transformation Framework (2022) partially included HLPE 'economic', 'social' and 'environmental' themes but not 'political'.

3.2.3 India

In line with Indian federalism, individual states hold considerable constitutional responsibility for the agricultural sector policies. Nonetheless, the central government develops national approaches to policy and provides funds for implementation at state level. The central government is responsible for a few relevant policy areas, like international trade. In 2020, the Government of India (GOI) amended three key trade and farming bills with an ambition of doubling farmers' income by the year 2022 and securing supply. However, these amendments were met with huge resistance by farmers, protesting from August 2020 until December 2021. The three amendments essentially aimed at deregulating the agricultural sector and to encourage farmers to sell directly to large buyers (companies, retailers, etc.). The strong resistance to these amendments led the government to suspend the laws for 18 months and form a new committee with representatives from the government and farmers to discuss the concerns.

In 2014, India became the first country in the world to issue a nationwide policy for AF, the National Agroforestry Policy, NAP (2014). The Ministry of Agriculture has the mandate for AF in India with an Agroforestry Mission located within the Department of Agriculture and Cooperation. AF is defined in the NAP as "a land use system which integrates trees and shrubs on farmlands and rural landscapes to enhance productivity, profitability, diversity, and ecosystem sustainability." However, most Indian farmers have been hesitant to adopt AFS on a large scale due to financial issues, tenure, delayed incomes and increasing legal complications which hinder complexity, especially with regards mixing 'agriculture' and 'forestry' (Chavan et al., 2015). Considering India has been investing into AF research for over 30 years and has a substantial national AF policy in place since 2014, the lack of uptake and overall land use is noteworthy. This could be explained by the minimal inclusion of knowledge and training, financing or farm succession as subjects included within policies. Land tenure, a known hurdle in AFS is included within the National Farmers Policy (2007), the Forest Rights Act (2006) and is referred to as 'critical issue' within the NAP (2014), whereby states should "simplify regulations related to forestry, land use and land tenure" (page 11).

In terms of *policy coherence*, four of the more recent policies National Policy for Farmers (2007), National Biodiversity Action Plan (2008), National Environmental Policy (2006) and the NAP (2014) make direct links to other agricultural and environmental state policies. For example, the NAP is recognized as a critical pathway to meeting the National Forestry Policy (1988) ambition of increasing forest or tree cover to 33% from the present level of less than 25% (National Agroforestry Policy, NAP, 2014, page 1). There is little substantial reference to climate change despite the relevance for food security of the country (IFPRI, International Food Policy Research Institute, 2022). Only the Green India Mission (2010) establishes direct links directly to climate goals or the NDCs.

India's policies could be said to have an agroecological leaning, especially the more recent policies such as Forest Rights Act (2006) and the National Policy for Farmers (2007). Many of the 'sign post' attributes such as cultural ecosystem services, territorial or landscape approach, access to land and water, land tenure and food security and nutrition are included fully or partially across Forest Rights Act (2006), National Policy for Farmers (2007), National Biodiversity Action Plan (2008) and Green India Mission (2010). Additionally, indigenous knowledge or ways of knowing is also included or referred to in just over half of the policies.

3.2.4 Brazil

In the Brazilian federalism, the central government possesses the authority to formulate national policies, and to create funding mechanisms for their implementation in states. Historically, support for the agricultural sector and policymaking itself has mirrored the priorities or agenda of elected officials. In the early 1950s, the National Agricultural Policy Commission (CNA, 2024) was created, during the presidency of Getulio Vargas (Brasil, 1951). Over a decade later, in 1964, the Land Statute (*Estatuto da Terra*) came to govern national agricultural policies (Brasil, 1964), and provided the foundation for important sector developments. Namely, the establishment of a national credit system, the development of minimum prices policies, and the creation of two public institutions, one for agricultural research (Embrapa), and the other for technical assistance (Emater). In 1991, the reformulation of agricultural policies culminated in the Agricultural Policy Law, that defines guidelines, objectives and the institutional competencies of the national agricultural policy to this day (Brasil, 1991).

During a 13-year period with the Worker's Party (PT) in power (2003–2016), financial support for the agricultural sector has seen its highest figures, following a tendency that started in 1995, with strong vein to subsidized credit, especially for small-scale and family farming. During the presidency of Lula, the Agroecology and Organic Farming policy (Brasil, 2003) was passed, and the National Plan for Agriculture and Livestock "*Plano Safra*" was created. The plan plays a fundamental role in guaranteeing agricultural production and development in the country by financing small-, medium- and large-scale farmers. During the presidency of Dilma Roussef, the amount of funding has peaked in 2014 (de Souza et al., 2020), and the National Crop-Livestock-Forest Integration Policy was passed, representing the first step toward policies on integrated land-use systems. That AFS doubled almost between 2006 and 2017 is seen as a result of supporting policies and public recognition of agroforestry (Manzatto et al., 2019).

Despite general criticism over low levels of support and protection for agriculture, the *Plano Safra* 2022/2023 has increased the maximum resources for family farming by 36%, and better agricultural insurance conditions, compared to the previous plan (OECD, 2020; Brasil, 2022a, 2022c). However, the largest part of funding is given to agribusiness, while family farming represent less than 18% of the total amount. In theory, the plan supports 'sustainable' practices, but the budget for Agroecology and Organic Agriculture was considerably reduced by about 75% (Brasil, 2022b), decision that can be associated with the agenda of the elected president Bolsonaro. The *Plano Safra 2023/2024* has reached the largest volume of resources in the history of agricultural policy, introducing measures to enhance the socio-environmental aspects of agricultural production and deter illegitimate practices in credit allocation (Harfuch and Lobo, 2024; Brasil, 2024). The latest plan provides the cheapest loans for day-to-day expenses in agroecological based farming or systems shifting to organic methods (Brasil, 2024).

Although there exists no direct national policy on agroforestry, AFS are supported through different policies, across levels and sectors but are predominantly subject to forest legislation. For example, the Brazilian Forest Code considers AFSs as beneficial for society, if practiced by farm-based agriculture or by traditional peoples in small-scale farms, and if the cultivation practice does not compromise the ecological function of the area (Brasil, 2012, Article 3). Under the law, AFS's are listed as a management practice for degraded land restoration, eligible for funding (Forest Code Article 42), accepted to be implemented in the Legal Reserve (Forest Code, Article 66), and incentivized to be implemented in degraded and expropriated land (Brasil, 2013). Moreover, AFSs are listed as a fundable item in the National Program for Strengthening Family Farming under the funding program Pronaf ABC+ Bioeconomia. Under the term "farming-livestock-forest integration" funding is available for restoring degraded pasture (Brasil, 2024, 2022a,b,c). Accordingly, family-based farmers may apply to finance investment projects that aim to implement, utilize and/or recover AFSs. Listed also as a restoration strategy, AFSs have legal basis to be used in the restoration of part of the permanent preservation areas (APP), and in the totality of the legal reserves (RL; Brasil, 2012).

Brazil ranks highest among the four regions assessed in this study with regard to *policy coherence*. 15 states of the country have public policy interfacing with the National Plan for Agroecology and Organic Production (PNAPO; IPEA, 2017). AF is a technique that benefits pollinators and other types of beneficial fauna, according to the National rules for Organic Production Systems. Brazil's legal framework is robust and, in principle, operates synergistically. The connection between policies pertaining to agroforestry lies more in how these policies are put into practice and executed rather than their conceptualization. To exemplify, the PNAPO is directly linked to the National Farming Policy, prioritizing the beneficiaries of the latter for the implementation of agroecological and organic practices. For Agroforestry, the National Low Carbon Agricultural Plan (*Plano ABC*) is at the forefront, having scored the highest among all policies in the country. The *Plano ABC* stands alone nationwide with the link to the UN SDGs, and alongside the National Adaptation Plan to Climate Change 2016 are the two policies with links to Climate Goals and the country's NDC.

With dedicated policies for agroecology and organic production systems, Brazil's policies do seem to have a narrative leaning toward agroecology, unique from the other regions. Of the 10 policies analyzed, seven presented partial or full compliance with the HLPE attributes. Policies advocate for the provisioning of food through agroecological practices among small-holder farmers. The law mandates that a minimum of 30% of the food in school programs must come from small-scale farmers (Brasil, 2009). Farmers must be registered in the Environmental Rural Registry (CAR) to be able to access any funding lines for agricultural production, which is a topic addressed in half of the policies analyzed in our study. A resilient food system rooted in agroecological practices is both a solution and a counterpoint to the dominant food production system, a major contributor to the country's GEEs and negative externalities (Brazil, 2016).

3.3 What can we learn from the four regions?

Taken together, the results from the four regions offer an interesting snapshot of current policies relating to AFS. It is not possible to compare across regions directly, given the diverse contexts, policies and scope, but it is possible to draw some insight when considering the results as a whole.

3.3.1 Collaboration may lead to greater policy coherence

From the attributes chosen, the two categories of *policy development* and *coherence* score lower than *content* or *goals*, with *goals* seemingly scoring the highest out of the four and *coherence* the lowest (Figure 3). This is perhaps unsurprising given that policies, by their nature, are often trying to achieve specific goals and are frequently developed in sectoral silos, with little cross-ministerial collaboration (Muscat et al., 2021). However, policy coherence is critical if we are to address the negative externalities of the food system (De Schutter et al., 2020) and successfully integrate land and climate issueswhich have risen in part, due to the siloed ways policies have been developed (Buckwell et al., 2017). There is perhaps a slight trend toward greater policy coherence in the more recent policies (Figure 2), which is encouraging and should be built on. It is not possible to say from the data whether increased cross-ministerial collaboration and the inclusion of farmers, practitioners and food-system experts directly leads to greater policy integration, however for the U.S.A, low scores within *policy development* match with low scores for *coherence*. The results for Brazil on the other hand could highlight how increased cross-ministerial collaboration results in greater coherence, particularly when looking at links to other agricultural and environmental state policies (Figure 2). Brazil was also unique in taking a food systems approach in the development of The National Food Acquisition Program, which addresses affordability, supply chains and human health. Further, Brazil carried out consultations with relevant actors in all the policies assessed. This would be in line with thinking that inclusion of a greater diversity of stakeholders within the policy process results in more effective policies (IPCC, 2019; Parsons and Barling, 2022). In contrast, in the EU, knowledge co-creation across sectors and ministries played no role beyond limited consultation with relevant stakeholders. A surprisingly small number of policies link directly to climate goals or NDCs; some of the more recent policies make direct links, but overall this integration is not explicit. As for diet-related health, most regions do not make the link between AFS and the potential for improved nutrition or health, except the EU, where three of the five policies do include diet-related health objectives.

3.3.2 Policy inconsistencies may hinder AFS uptake

Despite regions scoring higher for *coherence*, inconsistencies and contradictions exist both within and across policies reviewed. For example, while CAP direct payments (under Pillar 1) follow a per-hectare income support, CAP Rural Development funding (under Pillar 2), is based on the provision of public goods, a direct contradiction. Specifically, for AFS, up until the most recent CAP, there were official guidelines for how many trees could be planted per hectare, which have remained in MS RDP's when defining AF. Therefore, although AF is in theory supported, it is within an environment that creates challenges for entry and experimentation, which makes it harder for the expansion of AFS championed within the Biodiversity and Forestry Strategies, for example. In Brazil, the integrated crop-livestock-forestry systems (ILPF) and agroforestry have been addressed as if they were interchangeable, however, in practice, the integration of trees and agriculture within ILPF systems are mostly separated spatially and temporally, not configuring an AFS (AFS), leading to overestimations. In the US, the 2018 Farm Bill did not address controversial issues related to pesticide use and regulation which have been linked to environmental and public health concerns. While the 2018 Farm Bill included some provisions for climate change and the promotion of soil health and carbon sequestration practices, there was no cohesive approach to address the sector's significant contributions of GHGE. Provisions made within the 2021 Agricultural Resilience Act however, are much more ambitious and robust, including setting specific targets for farmland preservation and reducing agricultural land conversion to development. However, depending on how these goals are implemented, the possibility of this conflicting with the 2018 Farm Bill's provisions for land-use decisions and property rights is high.

These examples of policy inconsistencies confirm the need for better mechanisms to balance trade-offs and competing policy goals in complex, so-called 'wicked problems' (Candel and Biesbroek, 2016; Holt et al., 2016). Only with better ways to reconcile competing objectives and see across multiple policy domains, will we be able to address the whole and see opportunities for co-benefits across policy objectives. More broadly—these inconsistencies might allude to the different and contesting voices, ideas and philosophies often hidden in published policy documents, made evident in Anderson and Maughan's mapping of the HLPE process for agroecology (Anderson and Maughan, 2021), who highlighted how our positionalities and philosophies shape divergent understandings and ultimately, end up in policy, financing, decision making and methods.

3.3.3 Policies for agroforestry lean toward agronomic reading of NbS concept

The majority of policies included in this review lean toward an agronomic understanding of AFS as a NbS, favoring policy goals and subjects linked to environmental objectives such as carbon sequestration, biodiversity preservation and conservation, air and water quality and flood mitigation. Objectives linked to diet, health, access to land and water are less frequently included as a possible co-benefit of AFS. This could be explained in part by the predominant focus in the literature of 'provisioning' ecosystem services AFS offer (Jose and Udawatta, 2021) and the prevailing methods used to measure and assess land use systems, which often favor direct, tangible benefits such as yield, biodiversity, carbon sequestration etc., often leaving out the intangible social co-benefits.

Many of the policies reviewed contain specific and obvious biases toward classic neo-liberal growth strategies and the dominant corporate agri-food sector. Despite the Farm to Fork Strategy stating that "The EU will support the global transition to sustainable agri-food systems, in line with the objectives of this strategy and the SDGs.

Through its external policies, including international cooperation and trade policy, the EU will pursue the development of Green Alliances on sustainable food systems with all its partners in bilateral, regional, and multilateral fora" (page 18), the EU has not shown willing to fundamentally reassess supply-side policies or re-negotiate Free Trade Agreements. Likewise in the USDA's Food System Transformation Framework (2022), a pledge of up to $300 million toward an "Organic Transition Initiative to provide comprehensive support for farmers to transition to organic production" is given. Yet, there are limited provisions given toward pesticide regulations. The 2018 Farm Bill did not address controversial issues related to pesticide use and regulation; omitting to include measures to restrict the use of certain pesticides that have been linked to environmental and public health concerns. In the context of Brazil, the decision to implement a fourfold reduction in the budget allocated to Agroecology and Organic Agriculture undermines the ambition set out in the Act (2013). Policies continue to send conflicting signals and appear to tacitly support the status-quo.

3.3.4 Lack of legal obligations may inhibit tangible action

Thirteen of the 34 policies included in this study are legally binding, meaning there is no legal obligation for the mandates in the other 21 policies to be met. Even if metrics and goals are included, governments are not legally bound to implement them. Many of the regional frameworks and strategies by definition are not designed to be legally binding, rather included or implemented by national legislation, as is the case for the EU, reflected in only one legally binding policy instrument (CAP). Given the studied countries and their combination of both federal and state (or member state for the EU) policies, it could be interesting to compare these findings with smaller countries with just national policies to see what extent they were legally binding or not.

3.3.5 People and practitioners are absent within policy

For the most part, the EU, and the U.S.A, the two 'higher income' regions included in this review do not include the framework of intersectionality in their policies (The U.S.A Farm Bill scores 0.5, all others 0). Taking an intersectional approach to policymaking and policy analysis requires identifying, understanding, and addressing the structural inequalities in a given context that account for these different lived experiences and inequalities (Munro et al., 2014; Mitra and Rao, 2019; Runnymead, 2017). This omission of intersectionality within the policy arena is unsurprising but noteworthy. Brazil and India, which both score higher on in terms of wealth inequalities, both have four policies that include intersectionality. This could be perhaps due to a greater recognition of the diverse countries' demographics, including a stronger recognition of indigenous and traditional peoples and cultures. Other lowest scoring attributes include farm succession, support for new entrants and, surprisingly, links to the UN SDGs.

3.3.6 Current framing of agroforestry systems misses its transformational potential, far from radical roots of agroecology

All the attributes chosen can add up to give a 'picture' of how policies relating to agroforestry are being framed and the transformability of AFS as a NbS in its current conceptualization within policy. Seemingly, the policies reviewed within Brazil and the EU score higher across the four attribute categories than the US or India (Figure 1). Given that both the EU and Brazil have in part come out in direct support for food system change and more specifically, agroecology, this is perhaps to be expected. While Brazil is the only region reviewed with a specific and direct policy for agroecology: The National Agroecology and Organic Agriculture Policy (2013), the EU has supported agroecology as a tool within other policies (i.e., the goal in the Green Deal for uptake of agroecology and as one tool out of the many offered within the CAP eco-schemes). It must be noted however, that policies included for both the EU and Brazil are overall, more recent than for the US or India. For the EU in particular, policies are from 2014 onwards, when arguably, government priorities around many of the issues included in the *policy goals* and *subject* attributes, can be said to be higher than in for example, the late 60s in the U.S.A (National Environmental Policy Act 1969). None of the EU policies make direct claims to an agroecological transition, although two of the EU policies (CAP 2014–2020 and Biodiversity Strategy 2020) are partially linked to an agroecological transition since they financially support agroecology in their legislation or include specific targets and policy goals to increase agroecology. Brazil is the region with the highest score for this attribute, with four policies committing to this as an ambition. In fact, Brazil stands alone in having a specific Agroecology and Organic Farming Policy (2013). Further, one of the purposes of the National Food Acquisition program (2021) is to "promote and produce organic and agroecological food." Similarly, the National Low Carbon Agricultural Plan (Plano ABC) indicates the alignment between the latter with other credit lines of the Plano Safra; observing purposes, financeable items and interest rates practiced, specifically mentioning agroecology. Except for Brazil, this lack of explicit commitment to agroecology and low representation of its principles within the policies reviewed is perhaps unsurprising, given the majority of democracies included are proponents of conventional agriculture, who seemingly doubt the viability of agroecology (Bellwood-Howard and Ripoll, 2020).

3.4 Study limitations

The study faces several limitations that require acknowledgment and should be considered if the policy analysis framework is to be repeated for other regions or NbS. The authors recognize the selection of policies included is subjective and admit possible omissions due to the challenges of navigating complex and disparate government websites, as well as incomplete information on FAOLEX. The EU policies reviewed were notably more recent and fewer in number, potentially skewing the comparative analysis. The novel policy analysis framework developed in this review focusses on *positive* attributes for sustainable food system change and just transition pathways. The authors did not look for those attributes that might act as counterweights to this end goal, which could be developed in a future framework. Finally, the authors recognize their geographic locations and positionalities based in Europe and Brazil, with India and the U.S.A. being more 'unknowns'.

4 Conclusion and recommendations

This paper set out to review agroforestry policy and policies related to agroforestry in four 'continental' regions, in an attempt to give an overview of what policies have been developed for AFS and with what narratives and objectives. The framework constructed in this study proved to be insightful and can be replicated to other regions, countries or indeed other NbS. The thematic categories of policy *development, content, goals* and *coherence* highlighted: the on-going gap between land and climate policies; the apparent improvement of coherence when more stakeholders are involved; and the normative leaning of AFS to address just agronomic issues without considering broader, interconnected issues such as diet related health.

Our analysis shows that despite mounting evidence for the severity of the climate crisis and its impact on food and agriculture, policy is lagging, with inconsistencies and contradictions making scaling back the negative externalities of agriculture and scaling up promising approaches, such as AFS, increasingly difficult. The link between agriculture and climate (both in terms of its impacts to and fragility in the face of), is not sufficiently reflected in recent policies within this review. The policies do not question the basis of the conventional agri-food system and for the most part, are based on growth strategies and neo-liberal trade policies. The development of agroforestry policy, despite having decades worth of supportive evidence is lagging, with minimal care given to financial incentives, knowledge, or training. Land tenure and access rights remain unaddressed across most policies, despite this being a well-documented barrier to scaling of AFS globally. Across the regions reviewed, policies for agroforestry are increasing gradually, but appear to be confined to an agronomic understanding of the practice. The focus is primarily on the provisioning of ecosystem services these systems can offer, as opposed to seeing it as a tool for food system change or linking with other policy objectives around health and improved livelihoods.

Improving policy coherence is critical as we seek to address the multiple, interconnected crises of climate change, biodiversity loss and inequality. Assessing the degree to which key policies for agroforestry and agriculture are aligned with national and international targets, such as the UN SDGs or NDCs, revealed how few policies consider multiple aims across policy domains. The EU policies tend toward greater coherence, perhaps given their specific relevance to the subject and more recent development. Seemingly, there is a big opportunity for AFS, and agriculture more broadly, to be firmly integrated into key targets around biodiversity loss, carbon emissions and diet related health.

Proponents and practitioners of AFS must focus on the practical translation of practice into policies, while policy and decision makers need to embed AFS within a diverse set of policy domains. We recommend: greater coordination of policy instruments to achieve co-benefits; focused integration of agricultural and climate policies; greater inclusion of diverse stakeholders in policy development; and a widening of AFS objectives both in policy and practice.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RV: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. F-EM-d-O: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. JB-D: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. JE: Software, Visualization, Writing – review & editing. SR: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1417740/full#supplementary-material

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Appendix 1

Principle	FAO's 10 elements	Scale application*	Category
Improve resource efficiency			
1. Recycling. Preferentially use local renewable resources and close as far as possible resource cycles of nutrients and biomass.	Recycling	FI, FA	Environmental
2. Input reduction. Reduce or eliminate dependency on purchased inputs and increase self-sufficiency	Efficiency	FA, FO	Environmental
Strengthen resilience			
3. Soil health. Secure and enhance soil health and functioning for improved plant growth, particularly by managing organic matter and enhancing soil biological activity.		FI	Environmental
4. Animal health. Ensure animal health and welfare.		FI, FA	Environmental
5. Biodiversity. Maintain and enhance diversity of species, functional diversity and genetic resources and thereby maintain overall agroecosystem biodiversity in time and space at field, farm and landscape scales.	Part of diversity	FI, FA	Environmental
6. Synergy. Enhance positive ecological interaction, synergy, integration and complementarity among the elements of agroecosystems (animals, crops, trees, soil and water).	Synergy	FI, FA	Environmental
7. Economic diversification. Diversify on-farm incomes by ensuring that small-scale farmers have greater financial independence and value addition opportunities while enabling them to respond to demand from consumers.	Part of diversity	FA, FO	Economic
Secure social equity/responsibility			
8. Co-creation of knowledge. Enhance co-creation and horizontal sharing of knowledge including local and scientific innovation, especially through farmer-to-farmer exchange.	Co-creation and sharing of knowledge	FA, FO	Social
9. Social values and diets. Build food systems based on the culture, identity, tradition, social and gender equity of local communities that provide healthy, diversified, seasonally and culturally appropriate diets.	Parts of human and social values and culture and food traditions	FA, FO	Social
10. Fairness. Support dignified and robust livelihoods for all actors engaged in food systems, especially small-scale food producers, based on fair trade, fair employment and fair treatment of intellectual property rights.		FA, FO	Economic
11. Connectivity. Ensure proximity and confidence between producers and consumers through promotion of fair and short distribution networks and by re-embedding food systems into local economies.	Circular and solidarity economy	FA	Economic
12. Land and natural resource governance. Strengthen institutional arrangements to improve, including the recognition and support of family farmers, smallholders and peasant food producers as sustainable managers of natural and genetic resources.	Responsible governance	FA, FO	Political
13. Participation. Encourage social organization and greater participation in decision-making by food producers and consumers to support decentralized governance and local adaptive management of agricultural and food systems.		FO	Political

*Scale application: FI, field; FA, farm, agroecosystem; FO, food system. Source: derived from High Level Panel of Experts (2019).

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Adaptive agroforestry—mitigating climate change impacts by farmers' perception in different climate conditions in Iran

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Introduction: Developing countries are particularly vulnerable to climate change (CC), thereby impacting food production and altering the species composition to deliver essential services. Sustainable land-use systems, such as agroforestry, have emerged as adaptive solutions to climate change. Agroforestry, which integrates trees and shrubs with crops or livestock, offers multiple benefits, including enhanced production, improved soil and water conservation, and increased carbon sequestration. A study assessing the impact of CC on agroforestry was carried out in Iran, spanning across semi-arid, semi-humid, and humid climates.

Methods: Data were collected from 204 households using surveys to understand the socioeconomic characteristics, land use, and agroforestry.

Results and discussion: The results indicated significant differences in farming experience and land holdings ($p < 0.01$) across regions. Agroforestry was more prevalent in semi-arid regions, with alley cropping being the most common practice. Farmers' attitudes toward continuing agroforestry were positive, although there was a general lack of information about the practice. The primary sources of information were other farmers and extension experts. Species diversity in agroforestry varied by region, with apples, walnuts, and poplars being the most common in semi-arid regions, while species diversity was generally lower in humid regions. To mitigate the impacts of climate change, adaptation strategies, such as altering crop and tree species to those more resilient to climate change, have been employed. The farm size assigned for the agroforestry systems in the semi-arid region was 0.86 ha, which was higher than that assigned in other regions. Farmers in the semi-arid regions rely on a greater diversity of species to mitigate CC impacts than those in other regions. This approach enhances the sustainability of agroforestry by optimizing resource use and maintaining agricultural productivity.

KEYWORDS

agroforestry, climate change (CC), semi-arid region, species diversity, Iran

Introduction

Climate change (CC) refers to long-term shifts in temperature and weather patterns, primarily driven by human activities such as burning fossil fuels, which release greenhouse gases and contribute to global warming. This poses serious threats to agriculture, potentially reducing productivity on a global scale. While agriculture contributes 14% of human-caused greenhouse gas emissions, it also holds potential for mitigating CC through practices that enhance carbon sequestration in soil and biomass (Reppin et al., 2020). CC poses a serious threat to developing countries, impacting both food production and the capacity of natural ecosystems to provide products and services (Manaye et al., 2021). changes in temperature and precipitation patterns are projected to reduce crop yields, increase the prevalence of agricultural pests and diseases, and lower the quality of animal fodder (Skendžić et al., 2021; Alotaibi, 2023). These impacts are significantly concerning since agriculture is the main livelihood for many impoverished people in rural areas of developing countries. These populations typically have limited access to financial or biophysical resources for adapting to CC.

In light of these challenges, there has been an increasing recognition of the need for sustainable land-use systems that can help address both the economic and ecological impacts of CC. This is particularly urgent in arid and semi-arid regions, where droughts and famines have been aggravated by climate shifts in recent decades (Kumar et al., 2022b; Rathore et al., 2023; Motaghed et al., 2024). These systems must respond flexibly to rapid changes in economic and ecological conditions while preserving or restoring soil and water resources. An agroforestry system is a solution to reduce and adapt to the effects of CC (Reppin et al., 2020). Globally, agroforestry offers a sustainable and potential solution by increasing carbon reserves and potentially improving agricultural productivity. This approach can help countries like Ethiopia fulfill their commitments to forest restoration and smart agriculture, meeting the needs of vulnerable populations in changing climatic conditions (Manaye et al., 2021). Climate change also exacerbates its own effects. For instance, in the East Usambara Mountains of Tanzania, farmers used to have two growing seasons per year for crops, but recently, they have only one. Farmers report that decreasing humidity and increasing temperatures in mountainous areas are changing species compositions, with mango and citrus trees currently thriving in areas where they previously could not (Reyes, 2008). Such changes highlight the need for adaptive strategies to integrate agroforestry into broader land management practices.

Agroforestry is a form of sustainable land use that combines trees and shrubs with crops or livestock, enhancing and diversifying production while preserving natural resources (Molua, 2005; Rathore et al., 2023). Agroforestry, characterized by the growth of various woody perennials associated with crops, is a suitable alternative in areas where traditional land-use practices involve periodic clearing and cultivation. It helps control soil erosion, reduces environmental degradation through biological interactions among trees, crops, and livestock, and increases income from agricultural land (Rasul and Thapa, 2006; Kumar et al., 2022a). The multifunctional nature of agroforestry can address several problems simultaneously (Reyes, 2008; Mbow et al., 2014a). Agroforestry species improve microclimatic conditions and reduce the risk of food shortages due to reduced yields and low production for smallholder farmers. In various regions, agroforestry has been shown to increase farmers' income by growing multipurpose tree species alongside crops. Perennial woody plants help reduce global warming through carbon sequestration and improve aesthetic values (Rasul and Thapa, 2006; Babu et al., 2023). Due to the numerous benefits of agroforestry, many landowners in temperate regions have adopted these systems, achieving notable success in North America and Europe. Common agroforestry methods in the temperate regions include mixed cultivation, pasture forestry, forest understory agriculture, windbreaks, and riparian buffer strips (Molua, 2005). Common agroforestry systems in the temperate regions and Iran include alley cropping, silvopasture, forest farming, windbreaks, riparian buffers, and traditional home gardens. These systems enhance productivity, biodiversity, and resilience in temperate areas by integrating trees with crops and/or livestock. Similarly, in Iran's temperate and mountainous regions—such as the Caspian forests and Arasbaran—the use of fruit and nut trees (such as walnut, apple, and hazelnut) alongside annual crops, livestock grazing under forest cover, and the maintenance of windbreaks and shelterbelts are widespread. Traditional agroforestry practices in Iran, including orchard-based farming, garden-forests (Baq-e-Estan), and mixed tree-crop systems, reflect deep-rooted ecological knowledge and play a vital role in supporting rural livelihoods, conserving biodiversity, and adapting to climate variability.

While agroforestry has proven beneficial in many regions, the extent and nature of its impacts can vary depending on the system components and regional conditions. A variety of researchers have focused on the services provided by other systems of agroforestry (Newaj et al., 2013; Gomes et al., 2020; Niether et al., 2020; Papa et al., 2020; Reppin et al., 2020; Duffy et al., 2021; Manaye et al., 2021; Ariza-Salamanca et al., 2023). For example, Gomes et al. (2020) discussed the potential of agroforestry to mitigate these effects, maintaining approximately 75% of the area suitable for coffee production. In addition, Niether et al. (2020) confirmed that agroforestry contributed significantly to food security and diversified income sources. The strategic use of mixed cropping and marginal planting can enhance tree diversity in the arid ecosystems of Ethiopia (Manaye et al., 2021). Ariza-Salamanca et al. (2023) found that considering only available land use that does not contribute to deforestation would significantly reduce the suitable area by 14.5%. Regarding shade trees, their models indicate that 50% of the 37 shade tree species studied will experience a reduction in geographic range by 2040, and this reduction may reach 60% by 2060 in West Africa.

In recent decades, human activities due to industrialization and urbanization have accelerated CC, affecting all aspects of human life. These activities have also impacted agriculture, natural resources, and forests. Currently, to combat the negative effects of CC, many initiatives based on the knowledge of rural communities are being implemented. In Iran, agroforestry has been practiced since ancient times as an important economic and ecological solution to mitigate and adapt to CC. However, due to the diversity in agroforestry system components, it is essential to identify optimal systems. The role of different agroforestry systems in protecting plant diversity and forest structure has not been directly compared in many cases with high agricultural activity. Different land uses impose various costs and benefits on society through positive and negative externalities, such as soil erosion and environmental degradation. Therefore, policymakers need to understand which land-use systems best improve the livelihoods of rural people while reducing adverse environmental impacts. It is also crucial to identify what motivates farmers to transition from unsustainable to sustainable land-use activities (Rasul and Thapa, 2006). Understanding farmers' motivations to transition from unsustainable to sustainable practices, as well as the costs and benefits associated with different land-use systems, is crucial for informing policy decisions aimed at enhancing rural livelihoods and environmental resilience.

While extensive research has highlighted the potential of agroforestry as a sustainable land-use system to mitigate and adapt to climate change (CC), there remains a significant gap in understanding the optimal components and regional variations of agroforestry systems, especially in regions with high agricultural activity such as Iran (Nemati and Ghanbari, 2025). While agroforestry has been proven effective in temperate regions and some tropical areas, its applicability in arid and semi-arid regions, such as parts of Iran, remains underexplored, particularly in terms of how specific agroforestry practices can be tailored to local climatic and socioeconomic conditions. Furthermore, there is a lack of comprehensive studies comparing the role of different agroforestry systems in ecological and economic outcomes, particularly concerning the protection of plant diversity and forest structure. Although some studies have examined the economic and environmental benefits of agroforestry, little attention has been given to the motivations and challenges that farmers face when transitioning from unsustainable to sustainable land-use practices. This gap is critical, as understanding these drivers is essential for designing policies and interventions that encourage agroforestry adoption at a larger scale. Additionally, the long-term impact of agroforestry on local food security, especially in the face of CC-induced challenges such as reduced crop yields and increased pest prevalence, has not been sufficiently explored. The interaction between climatic changes, adaptation strategies, and agroforestry adoption also requires deeper investigation, particularly regarding how farmers in different regions of Iran have adapted their practices over the past three decades. To fill these gaps, future research should focus on identifying regional variations in agroforestry knowledge, understanding the socioeconomic motivations of farmers, and evaluating the effectiveness of various agroforestry components in addressing ecological and economic challenges in climate change.

Therefore, the primary objective is to investigate the role of agroforestry in mitigating and adapting to the effects of CC. In addition, in this research, we aim to (i) identify various agroforestry systems and their components, (ii) analyze regional variations in agroforestry knowledge sources, (iii) eventually evaluate farmers' motivations and challenges in agroforestry adoption, and finally (iv) analyze climatic changes over the past 30 years and adaptation strategies of farmers with CC. These objectives collectively address key issues of food security, rural livelihoods, and sustainable land use in Iran, while also providing a framework for promoting agroforestry as a climate-resilient strategy applicable in broader contexts.

Methods and materials

Study area

The present study was conducted in three climates: semi-arid, semi-humid, and humid to show the effects of climate change on agroforestry. For this purpose, the three provinces of East Azerbaijan (Ahar County and Varzaqan County) in the semi-arid region of Azerbaijan, Kermanshah (Paveh County) in the semi-humid climate of Zagros, and Mazandaran (Kalardasht County) in the humid environment of the Hyrcanian region were selected (Table 1; Figure 1). In East Azerbaijan, located in a semi-arid zone, the climate is characterized by hot, dry summers and cold winters, with annual precipitation ranging from 300 to 400 mm. The soils in this region are predominantly lithosols and regosols, which are nutrient-poor and prone to salinity in the absence of irrigation. In contrast, Kermanshah, specifically Paveh County in the semi-humid Zagros region, experiences cooler temperatures, with annual precipitation ranging between 600 and 800 mm. This region supports more fertile soils such as luvisols and cambisols, which retain moisture and are suitable for a wider variety of crops. Finally, Kalardasht in Mazandaran, located in the humid Hyrcanian region, enjoys mild temperatures and abundant rainfall (1,200–2,000 mm annually), resulting in highly fertile cambisols and fluvisols enriched with organic matter, making it ideal for agriculture such as rice and citrus cultivation. Each region's soil and climate distinctly influence their agricultural potential and vegetation types, ranging from arid, sparse vegetation in East Azerbaijan to lush, forested areas in Mazandaran.

Data collection

This research was conducted in several stages. Initially, a rapid preliminary assessment was conducted to identify farms with various agroforestry systems in each region. Based on the diversity of agroforestry systems in each region, a specific number of households were randomly selected from each system for evaluation.

TABLE 1 Climatic information of the three selected regions.

Region	Precipitation (mm)	Elevation (m)	Average temperature (°C)	Main activity	Main product	Sample size
SA – Azerbaijan	310–450	1,360	21.9	Farming and animal husbandry	Wheat and apple	78
SH – Kermanshah	670	1,540	15	Farming and animal husbandry	Pomegranate, walnut, mulberry, and pea	70
HU – Mazandaran	450	1,250	12	Farming, tourism, and gardening	Wheat, hazel, and walnut	56

SA, semi-arid; SH, semi-humid; HU, humid.

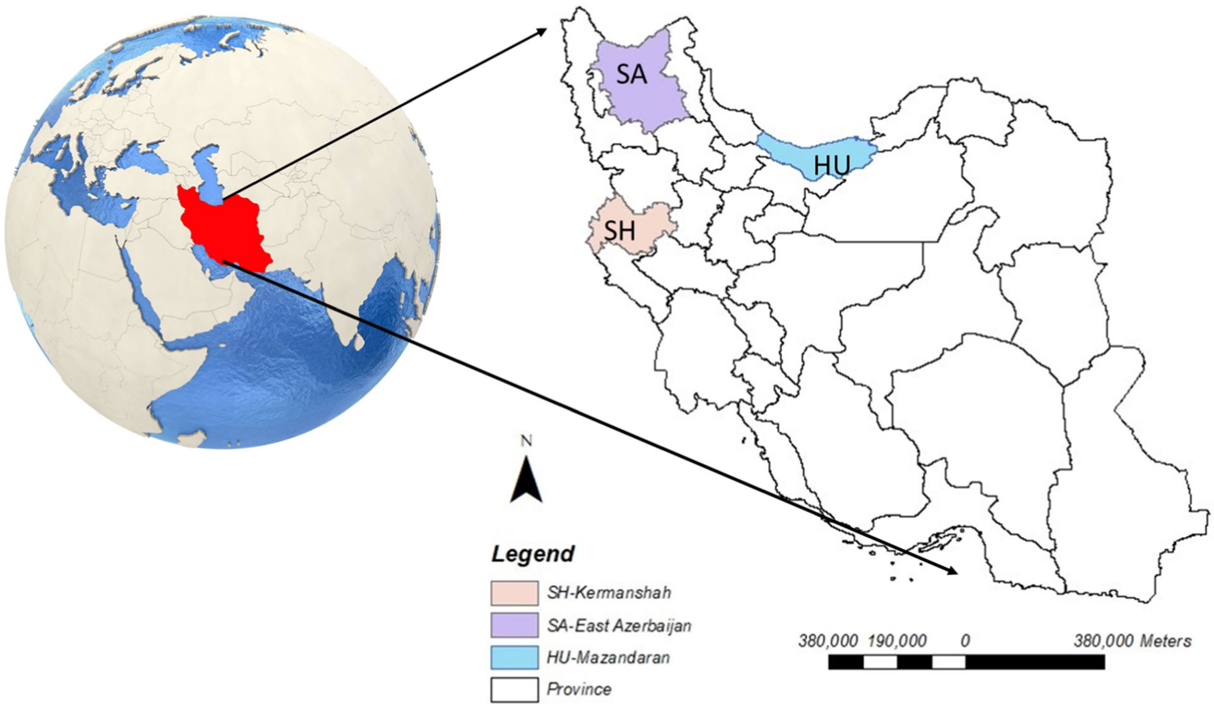

FIGURE 1
Location of the study area in three selected regions.

In the next step, a survey was conducted among households. Before beginning the interviews, farmers were informed about the objectives of the study. After obtaining their consent to participate, the interviews proceeded. Fourteen interviews were conducted using a pretested questionnaire to refine unbiased questions; however, after explaining the research aims, 14 farmers declined to participate. In total, we filled out 204 questionnaires from farmers. The interviews focused on gathering information on household use and benefits of on-farm trees and their role as a source of livelihood in household use and commercialization. Both quantitative and qualitative questions were used to collect information from the sample households (Bukomeko et al., 2019; Reppin et al., 2020). The average time of a face-to-face interview was between 45 and 65 min. The content validity of the questionnaire was confirmed by a panel of academic and executive specialists, who provided feedback regarding the suitability of each question. The questionnaire's reliability was assessed using the Cronbach's alpha coefficient for related criteria, which was 0.78. A five-point Likert scale (answer scale: 1: very low, 2: low, 3: average, 4: high, and 5: very high) was used to quantify the responses.

The main questions addressed personal characteristics, occupation, farm details, types of species, costs, incomes, types of harvested products, methods of selling, changes in species and products over time, and factors affecting production levels. Each farmer was also asked to prepare a list of most important tree species regarding each climate. The research instrument was divided into demographic and socioeconomic characteristics, agroforestry activities, motivations, problems, and climate change adaptation strategies. These sections addressed key research questions by linking farmers' demographic profiles to their agroforestry practices and the socioeconomic factors influencing these practices. For instance, farmer's average age and experience, along with educational background and landholding size, were analyzed to determine their impact on agroforestry adoption and management. Each section of the instrument was designed to collect data directly related to the research questions concerning the demographic and socioeconomic influences on farmers' activities. For instance, differences in farmers' age, experience, and education were associated with variations in agroforestry management and decision-making. Information on land holdings and cooperative membership provided context for analyzing economic resilience and resource access. Over time, information on shifts in species and products showed how farmers adapted their practices to cope with environmental and market changes, highlighting the constantly evolving nature of agroforestry systems. Overall, the comprehensive design of the instrument enabled a nuanced analysis of how various factors impact agroforestry practices, ensuring that the results reflect a broad spectrum of influences and outcomes (Figure 2).

Data analysis

Descriptive statistics were employed to analyze household data, revealing the uses and benefits of different tree species. To test differences between groups based on various farm and household characteristics, tests such as the Chi-squared and analysis of variance (ANOVA) tests were performed at a significance level of 5%. After the ANOVA test, we carried out a *post-hoc* test to determine which region is different from the other. Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) software version 20 IBM (Reppin et al., 2020).

Results

Demographic and socioeconomic characteristics of farmers

The socioeconomic characteristics of the respondents were identified as key factors influencing farmers' activities. Specifically, variables such as age, experience, and household size significantly impact the management of agroforestry systems. In this section, we provided some information about these factors. The mean age of household-head farmers was 52.3 years; the youngest household head interviewed was 24 years of age, and the oldest was 81 years of age. The maximum years of farming experience of farmers were approximately 65 years, with an average of 26 years (Table 2). There was a significant difference among farmers in age and farming experience ($p < 0.01$).

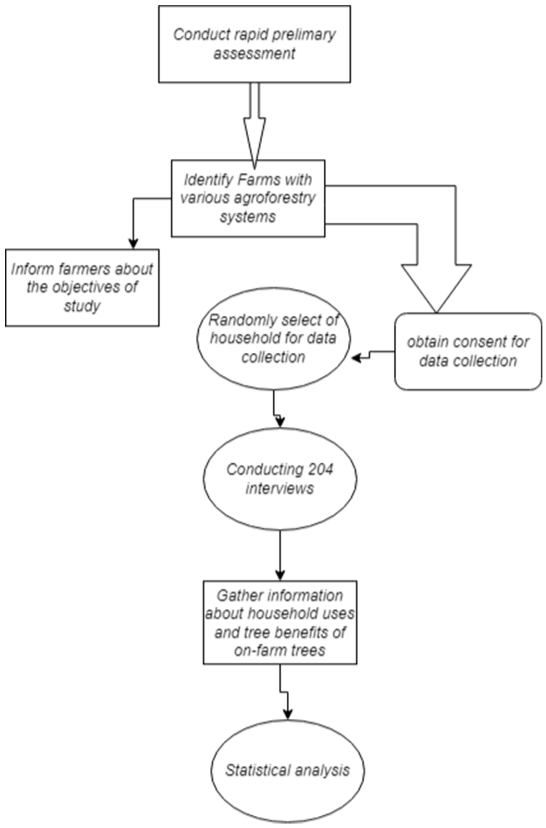

FIGURE 2
Flowchart for the research steps.

Nearly 91% of farmers were male-headed and 9% female-headed; 90% of respondents were married; and 10% of them were single. In addition, 72% of respondents had other income sources in addition to farming. Just 28% were active in farming. Furthermore, 66% of farmers had permanent residency status in the villages, and the remaining 34% had seasonal residency (Table 3).

The average length of schooling for farmers was 9–12 years. However, the level of education varied across different regions, ranging from no formal education in the SA and SH regions to the highest level of education with 18–22 years of schooling. The results showed that 46% of farmers in the SA region had 1–5 years schooling, approximately 40% of those in the SH region had 16–18 years of school education, and 31% in the HU region had 9–12 years of school education (Table 4).

The average household's land holding for irrigation farming land was 1.6 ha (standard deviation [SD] = 2.5), ranging from zero to 15 ha. The average rain-fed farming land was 3.5 ha. The average distance to the farming area from respondents' residences was 1.7 km (Table 5). All types of land holding were significantly different among regions. All items differed significantly ($p < 0.01$) across climate regions.

Only 15% of respondents were members of cooperatives, with membership rates ranged from 22% in the SH region to 7% in the HU region (Table 6).

Different irrigation methods were used by farmers in different climate regions. Almost all farmers did not use modern irrigation methods for farming in the SA and SH regions, whereas nearly one-third (29.6%) of farmers irrigated with sprinkler irrigation (Table 7).

TABLE 2 Descriptive statistics of respondents in different climate regions using Duncan's test.

Factor	Region	*N*	Min.	Max.	Mean	SD	*F*	Sig.
Age (year)	SA	78	32	81	51.6[b]	12.9	9.24	<0.01**
	SH	66	24	68	48.4[b]	10.2		
	HU	56	30	80	57.8[a]	13.3		
	Total	200	24	81	52.3	12.7		
Household size (individual)	SA	76	1	11	4.2	1.9	0.26	0.770[ns]
	SH	68	2	6	4.1	1.0		
	HU	56	0	8	4.0	2.0		
	Total	200	0	11	4.1	1.7		
Farming experience (year)	SA	78	7	65	33.3[a]	15.7	18.02	<0.01**
	SH	64	2	45	23.4[b]	14.3		
	HU	44	3	60	17.0[c]	14.7		
	Total	186	2	65	26.0	16.3		

[ns]Non-significant difference. **Significant difference at α = 0.01. *N*, number; Min, minimum; Max, maximum; SD, standard deviation; Sig, significant level; SA, semi-arid; SH, semi-humid; HU, humid. Alphabet a and b shows significant difference between two regions.

TABLE 3 Socioeconomic characteristics of respondents in different climate regions.

Factor		Frequency mean (%)		
Marital status	Region	Single	Married	Total
	SA	8 (10)	70 (90)	78
	SH	10 (15)	58 (85)	68
	HU	2 (4)	48 (96)	50
	Total	20 (10)	176 (90)	196
Gender	Region	Male	Female	Total
	SA	78 (100)	0 (0)	78
	SH	50 (76)	16 (24)	66
	HU	48 (96)	2 (4)	50
	Total	176 (91)	18 (9)	194
Main job	Region	Farming	Non-farming	Total
	SA	56 (72)	22 (28)	78
	SH	22 (34)	42 (66)	64
	HU	8 (14)	48 (86)	56
	Total	86 (43)	112 (57)	198
Other income source	Region	Yes	No	Total
	SA	44 (56)	34 (44)	78
	SH	50 (75)	16 (25)	66
	HU	48 (92)	4 (8)	52
	Total	142 (72)	54 (28)	196
Residence status	Region	Permanent	Seasonal	Total
	SA	56 (74)	20 (26)	76
	SH	32 (53)	28 (47)	60
	HU	38 (70)	16 (30)	54
	Total	126 (66)	64 (34)	190

SA, semi-arid; SH, semi-humid; HU, humid.

TABLE 4 Educational level of respondents in different climate regions.

Region	Education level (year)							
	No literacy	1–5	5–9	9–12	14–16	16–18	18–22	Total
SA	0 (0)	34 (46)	12 (16.2)	12 (16.2)	12 (16.2)	4 (5.4)	0 (0)	74 (100)
SH	0 (0)	12 (17.1)	6 (8.5)	4 (5.7)	18 (25.7)	28 (40)	2 (2.8)	70 (100)
HU	10 (19)	4 (8)	8 (15)	16 (31)	10 (19)	4 (8)	0 (0)	52 (100)
Total	10 (5.1)	50 (25.5)	26 (13.3)	32 (16.3)	40 (20.4)	36 (18.4)	2 (1)	196 (100)

Data in parentheses show the frequency percentage. SA, semi-arid; SH, semi-humid; HU, humid.

Agroforestry activities

Nearly half of the farmers (46%) did agroforestry in their lands in the SA region. This ratio was 31% in the SH region and 22.5% in the HU region. There was a decreasing trend with challenging climate conditions (Figure 3). The results showed that the average farm size assigned to the agroforestry system was 0.6 ha, varying from 0–3 ha. The highest farm size of agroforestry was observed in the SA region with 0.86 ha (Table 8). Agroforestry farm size (ha) per farmer was significantly different across climate regions ($F = 23.27$, $p < 0.001$).

Alley cropping was the most common form of agroforestry in all three climate regions. Aquaforestry had the lowest representation among agroforestry and was not practiced in the SA and SH regions (Figure 4). There was a significant difference in the types of agroforestry practiced among the different climate regions ($p < 0.01$).

Nearly all farmers expressed an intention to continue practicing agroforestry. However, there was a significant difference in their willingness to recommend agroforestry to other farmers ($p < 0.001$). The results showed that farmers did not have much information on agroforestry (3.5 ± 1.24) (Table 9).

TABLE 5 Access to farm land among farmers in different climate regions using Duncan's test.

Capital	Region	*N*	Min.	Max.	Mean	SD	*F*	Sig.
Irrigation farm land (ha)	SA	78	0	15	2.5[a]	3.1	14.64	<0.01**
	SH	24	0	2	0.7[b]	0.6		
	HU	36	0.03	0.35	0.2 [b]	0.1		
	Total	138	0	15	1.6	2.5		
Rainfed farming land (ha)	SA	78	0.5	16	4.6[a]	3.8	15.4	<0.01**
	SH	18	0.2	5	1.3[b]	1.4		
	HU	14	0.02	1	0.3 [b]	0.3		
	Total	110	0.02	16	3.5	3.7		
Garden lands (ha)	SA	74	0.1	10	1.3[a]	1.9	10.53	<0.01**
	SH	60	0.02	3	0.7[b]	0.7		
	HU	46	0.02	1	0.2[b]	0.2		
	Total	180	0.02	10	0.8	1.4		
Number piece of land	SA	76	1	30	10.7[a]	7.3	63.25	<0.01**
	SH	36	1	5	1.8[b]	1.1		
	HU	46	0.02	6	1.3[b]	1.1		
	Total	158	0.02	30	6.0	6.9		
Barren land (ha)	SA	58	0	10	3.1[a]	2.3	6.49	<0.01**
	SH	8	0	1.5	0.6[b]	0.6		
	HU	4	0.5	1	0.8[b]	0.3		
	Total	70	0	10	2.6	2.3		
Distance farming with village (km)	SA	76	0.5	5	2.3[a]	1.0	37.7	<0.01**
	SH	52	0.8	5	1.9[a]	1.2		
	HU	52	0	3	0.7[b]	0.8		
	Total	180	0	5	1.7	1.2		

**Significant difference at α = 0.01. *N*, number; Min, minimum; Max, maximum; SD, standard deviation; Sig, significant level; SA, semi-arid; SH, semi-humid; HU, humid. Alphabet a and b shows significant difference between two regions.

TABLE 6 The cooperative membership of farmers in different climate regions.

Region	Yes	No	Total
SA	10 (14)	60 (86)	70 (100)
SH	14 (22)	48 (78)	62 (100)
HU	4 (7)	50 (93)	54 (100)
Total	28 (15)	158 (85)	186 (100)

Data in parentheses show the frequency percentage. SA, semi-arid; SH, semi-humid; HU, humid.

TABLE 7 Irrigation method by farmers in different climate regions.

Region	Traditional/flooded	Sprinkler irrigation*	Dripped system	Other	Total
SA	74 (44)	0 (0)	4 (40)	0 (0)	78 (100)
SH	60 (35.7)	2 (11.12)	4 (40)	0 (0)	66 (100)
HU	34 (20.3)	16 (88.88)	2 (20)	2 (100)	54 (100)
Total	168 (100)	18 (100)	10 (100)	2 (100)	198 (100)

Data in parentheses show the frequency percentage. *Sprinkler irrigation is a method of applying irrigation water, which is similar to natural rainfall. SA, semi-arid; SH, semi-humid; HU, humid.

Farmers had access to information from different sources (Figure 5). Other farmers (39.5%) in the SA and HU regions were the primary sources of information, and in the SH regions, farmers got their information on agroforestry from extenders and experts (69%). In total, extenders and experts (46%) and other farmers (41%) were two important sources of information.

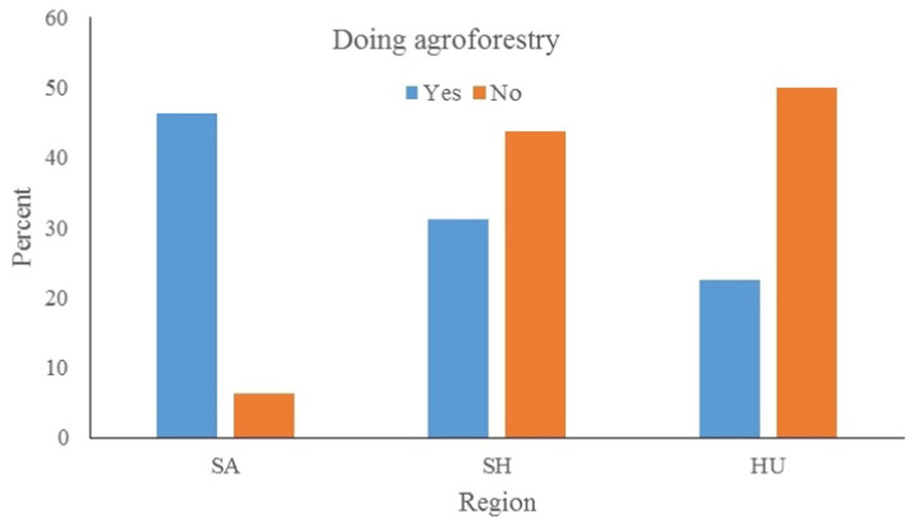

FIGURE 3
The distribution of agroforestry systems across climate regions. SA, semi-arid; SH, semi-humid; HU, humid.

TABLE 8 Agroforestry farm size (ha) per farmer across climate regions using Duncan's test.

Region	*N*	Min.	Max.	Mean	SD	*F*	Sig.
SA	74	0	3	0.86[a]	0.56	23.27	<0.01**
SH	28	0.1	2	0.41[b]	0.5		
HU	36	0.03	1	0.22[b]	0.22		
Total	138	0	3	0.6	0.56		

**Significant difference at α = 0.01. *N*, number; Min, minimum; Max, maximum; SD, standard deviation; Sig, significant level; SA, semi-arid; SH, semi-humid; HU, humid. Alphabet a and b shows significant difference between two regions.

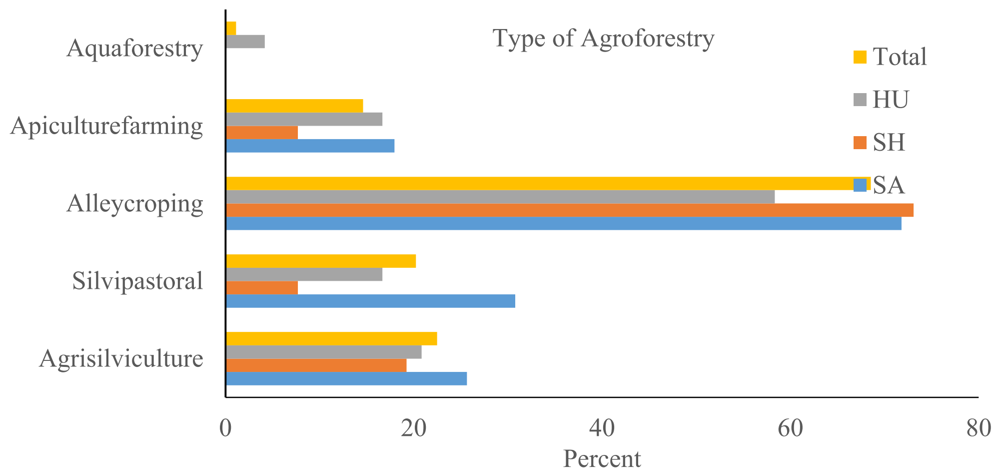

FIGURE 4
Type of agroforestry systems in different climate regions. SA, semi-arid; SH, semi-humid; HU, humid.

Notably, 17 and 14 tree species were planted in the agroforestry systems of the SA and SH regions, respectively. In the SA region, three species, apple, walnut, and poplar, were the primary species cultivated, while in the SH region, walnut, fig, and pomegranate were the three main species planted by farmers. The diversity of species planted in the HU region was very low. Of the five species planted in the HU region, poplar, walnut, and peach were three planted (Table 10).

Farmers followed a different purpose by planting trees in agroforestry. In all regions, the priority for farmers was providing food (70%) for their subsistence. The following preferences were selling timber (27.7%) and shading (23%) (Figure 6).

TABLE 9 Farmers' attitudes to agroforestry in different climate regions using Duncan's test.

Factor	Region	*N*	Mean	SD	*F*	Sig.
Tending to continue agroforestry	SA	78	4.6	0.75	3.86	0.023[ns]
	SH	52	4.2	1.25		
	HU	48	4.7	1.03		
	Total	178	4.5	1.01		
Recommend to other farmers to use agroforestry	SA	78	4.5[b]	0.79	10.2	<0.01**
	SH	52	4.3[b]	1.21		
	HU	44	5.1[a]	0.82		
	Total	174	4.6	0.99		
Information about agroforestry	SA	78	3.7 [a]	0.98	20.73	<0.01**
	SH	52	3.9[a]	1.08		
	HU	52	2.6[b]	1.34		
	Total	182	3.5	1.24		

[ns]Non-significant difference. **Significant difference at α = 0.01. Answer scale: 1: never, 2: very low, 3: low, 4: average, 5: high, and 6: very high). *N*, number; Min, minimum; Max, maximum; SD, standard deviation; Sig, significant level; SA, semi-arid; SH, semi-humid; HU, humid. Alphabet a and b shows significant difference between two regions.

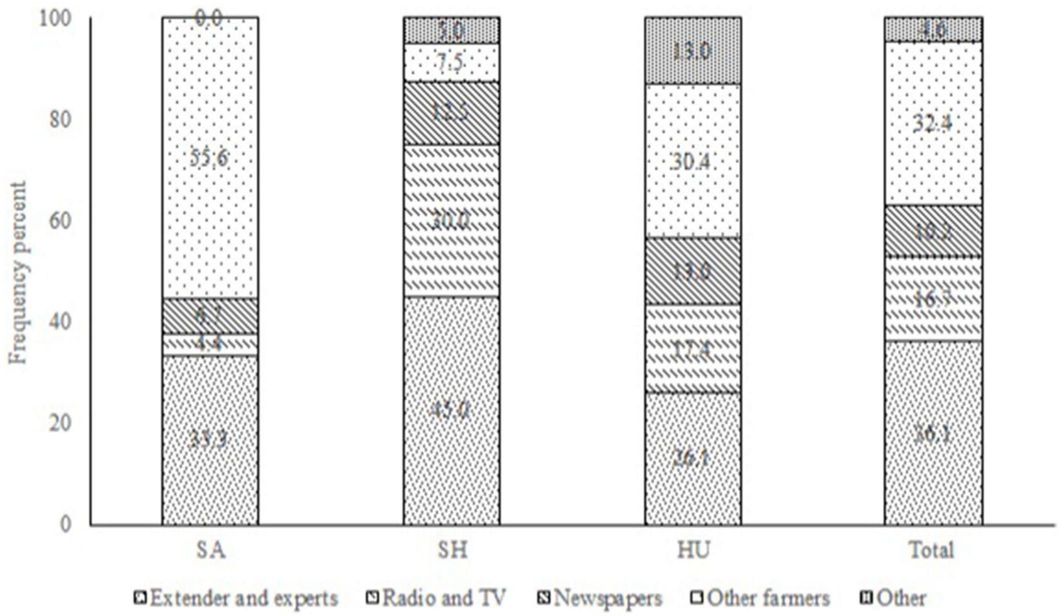

FIGURE 5
Source of information on agroforestry across climate regions. SA, semi-arid; SH, semi-humid; HU, humid.

Farmer's motivations

Farmers had different motivations for doing farming based on the agroforestry system. Although they had multiple purposes of doing agroforestry, increasing income (3.7 ± 1.1) and employment (3.3 ± 1.1) were two main motivating factors among farmers to do agroforestry. Wood (2.4 ± 1.2) and manure (2.3 ± 1) production were two other less important motivating factors of farmers (see Supplementary materials). Some motivational factors were significantly different among the studied regions. Water storage, creating employment, manure production, medicinal uses, and wood production significantly differed among the three climate regions. Similar to all production activities, farmers face some problems and obstacles in agroforestry. Governmental support (4.1 ± 1.1) and lack of efficient budget (4 ± 1.2) were the two main problems and obstacles in agroforestry. Lack of efficient land, lack of efficient information, and lack of education for farmers were three other factors among the challenges faced by farmers (Table 11).

Climate change adaptation

Climate change affects all dimensions of farmers' lives, and they experience its impacts in various ways. Increasing temperature

TABLE 10 Type of planted species at the agroforestry systems across climate regions.

Row	Species	Average per ha (%)*			
		SA	SH	HU	Total
1	Sour cherry (*Prunus cerasus*)	12 (7.32)	0 (0)	2 (7.14)	14 (5.43)
2	Peach (*Prunus persica*)	4 (2.44)	0 (0)	4 (14.28)	8 (3.1)
3	Almond (*Prunus amygdalus*)	4 (2.44)	4 (6.06)	0 (0)	8 (3.1)
4	Apple (*Malus domestica*)	44 (26.83)	0 (0)	0 (0)	44 (17.05)
5	Cherry (*Prunus avium*)	10 (6.1)	0 (0)	0 (0)	10 (3.87)
6	Plum (*Prunus domestica*)	4 (2.44)	0 (0)	0 (0)	4 (1.55)
7	Mulberry (*Morus alba*)	2 (1.22)	10 (15.15)	0 (0)	12 (4.65)
8	Nectarine (*P. persica* var. *nucipersica*)	2 (1.22)	0 (0)	0 (0)	2 (0.77)
9	Walnut (*Juglans regia*)	32 (19.51)	10 (15.15)	4 (14.28)	46 (17.82)
10	Pear (*Pyrus communis*)	4 (2.44)	4 (6.06)	0	8 (3.1)
11	Apricot (*Prunus armeniaca*)	12 (7.31)	0 (0)	0 (0)	12 (4.65)
12	Poplar (*Populus* sp.)	16 (9.75)	2 (3.03)	16 (57.14)	34 (13.18)
13	Ash (*Fraxinus excelsior*)	4 (2.44)	2 (3.03)	0 (0)	6 (2.32)
14	Elm (*Ulmus glabra*)	2 (1.22)	0 (0)	0 (0)	2 (0.77)
15	Willow (*Salix alba*)	8 (4.87)	0 (0)	0 (0)	8 (3.1)
16	Fig (*Ficus cariaria*)	0 (0)	10 (15.15)	0 (0)	10 (3.87)
17	Ailantus (*Ailanthus altissima*)	0 (0)	2 (3.03)	0 (0)	2 (0.77)
18	Persimmon (*Diospyros kaki*)	0 (0)	2 (3.03)	0 (0)	2 (0.77)
19	Olive (*Olea europaea*)	0 (0)	4 (6.06)	0 (0)	4 (1.55)
20	Orange (*Citrus sinensis*)	0 (0)	2 (3.03)	0 (0)	2 (0.77)
21	Lemon (*Citrus limon*)	0 (0)	2 (3.03)	0 (0)	2 (0.77)
22	Pomegranate (*Punica granatum*)	0 (0)	10 (15.15)	0 (0)	10 (3.87)
23	Grape (*Vitis vinifera*)	0 (0)	2 (3.03)	0 (0)	2 (0.77)
24	Pine (*Pinus eldarica*)	0 (0)	0 (0)	2 (7.14)	2 (0.77)
25	Rose (*Rosa* sp.)	2 (1.22)	0 (0)	0 (0)	2 (0.77)
26	Quince (*Cydonia oblonga*)	2 (1.22)	0 (0)	0 (0)	2 (0.77)
–	Total	164 (100)	66 (100)	28 (100)	258 (100)

*Data in parentheses show the frequency percentage of species rather than the total frequency of species in the region. SA, semi-arid; SH, semi humid; HU, humid.

(4 ± 1.7) and droughtiness (4 ± 1) were the two primarily perceived impacts, as reported by farmers (Table 12).

One adaptation strategy to coping with and mitigating climate change impacts was changing species. Farmers have changed crop species for several reasons, including low water demand, better adaptation, and improved efficiency. Traditional species cultivated in the past are replaced with new species (see Supplementary materials). For example, Barley has been replaced with alfalfa, pea, modified barley and wheat, and medicinal plants because of low water demand, adaptation, and change in efficiency. A similar strategy has been implemented for tree species planted in agroforestry. Some regions have replaced some high water demand species such as apple with walnut. Some farmers have changed grape species to fig, pomegranate, and pear for their adaptability and low water demand. Farmers have used other species, such as mulberry, olive, and pomegranate due to their adaptation, change in efficiency, and low water demand (Table 13).

Discussion

The findings from our study reveal significant regional variations in the sources of information that farmers rely on for agroforestry. In the SA and HU regions, 39.5% of farmers reported that other farmers were their primary source of information. This reliance on peer networks highlights the importance of social interactions and community-based learning in agricultural settings. Peer-to-peer knowledge exchange is often perceived as more practical and trustworthy, as it involves sharing firsthand experiences and locally adapted practices (Hermans et al., 2017). Such informal networks can play a crucial role in spreading innovative practices and encouraging the adoption of agroforestry among farmers who might be skeptical of external advice (Franzel et al., 2014).

In contrast, in the SH region, 69% of farmers obtained their information from extenders and experts, highlighting the essential role of formal agricultural extension services in this region. Extenders

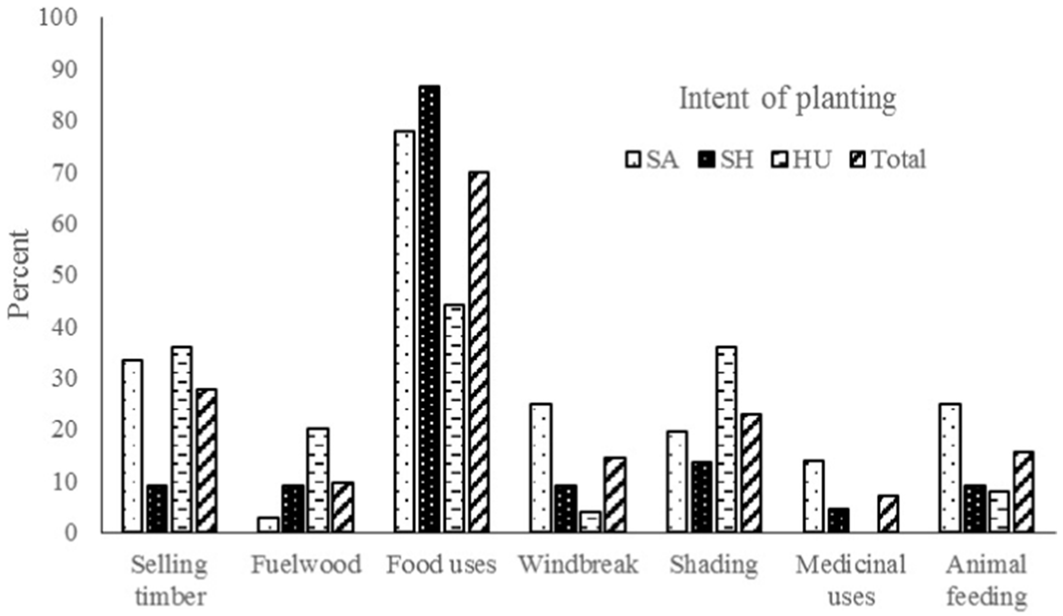

FIGURE 6
Intent of planting tree species based on the agroforestry systems across climate regions. SA, semi-arid; SH, semi-humid; HU, humid.

and experts accounted for 46% of the overall information sources, indicating their significant influence across the study areas. These professionals provide scientifically validated and comprehensive information, which is essential for addressing complex agroforestry issues and promoting sustainable practices (David and Asamoah, 2011). The regional difference suggests that, where extension services are well-established and accessible, farmers are more likely to trust and rely on these sources. These insights emphasize the need for a balanced approach to agricultural extension that integrates both informal peer networks and formal expert advice to address the various informational needs of farmers across different regions (Davis et al., 2012).

In the agroforestry systems of the SA, SH, and HU regions of Iran, 17, 14, and 5 species have been planted, respectively. All trees planted in the agroforestry have a special benefit and function. Although farmers had multiple purposes for practicing agroforestry, increasing income and employment emerged as the primary motivation factors for doing agroforestry. The ecological benefits of agroforestry activities such as ecosystem fixation, water storage, and soil quality were categorized as the second priorities of farmers. Some other researchers have mentioned similar benefits to the farmer communities (Lasco et al., 2016; Swamy and Tewari, 2017). Lasco et al. (2016) identified seven tree species planted in the agroforestry in Bohol, Philippines. In addition, Swamy and Tewari (2017) have stated that farmers are exploiting the benefits of agroforestry, providing a buffering effect against climate change in the arid and semiarid regions. In agroforestry, the species and diversity of tree species are critical in not only determining the income but also adapting to climate variability. This finding aligns with our results of planting more species in the SA and SH regions rather than the HU region. The potential of agroforestry can only be realized when the barriers to its implementation are addressed through the most efficient solutions. The recognition of agroforestry as a mitigation strategy under the Kyoto Protocol has enhanced its credibility as an adaptation strategy among local communities (Hernández-Morcillo et al., 2018).

The results of this study highlight that farmers have diverse purposes for planting trees in agroforestry, with primary focus on subsistence needs. Across all surveyed regions, the primary priority for farmers was to provide food (70%), highlighting the vital role of agroforestry in enhancing food security. This finding aligns with existing research indicating that agroforestry can significantly contribute to household food supplies by integrating tree crops with food crops and livestock (Mbow et al., 2014a). The secondary preferences of selling timber (27.7%) and providing shade (23%) reveal that farmers also recognize the economic benefits and the microclimate regulation that trees offer. Selling timber presents a valuable income source, while shade is crucial for protecting crops and livestock from extreme weather, thereby supporting overall farm productivity and resilience (Garrity, 2004; Yadav et al., 2024).

Farmers' motivations

The results revealed insightful findings regarding the motivations and challenges faced by farmers engaged in agroforestry. Farmers' motivations for adopting agroforestry were multifaceted, with income generation (3.7 ± 1.1) and employment opportunities (3.3 ± 1.1) being the primary driving forces. These motivations align with common expectations in agroforestry adoption, as the practice often offers economic benefits and improved livelihoods for rural communities. In particular, income and employment creation are often emphasized in studies like those by Arimi and Omoare (2021), highlighting the potential of agroforestry to help farmers combat climate change while also providing a reliable income source. However, wood (2.4 ± 1.2) and manure (2.3 ± 1) production, though beneficial, were reported as

TABLE 11 Problems and obstacles in implementing agroforestry systems across different climate regions using Duncan's test.

Problem	Region	*N*	Mean	SD	*F*	Sig.
Lack of governmental support	SA	78	3.8[a]	1.2	16.65	<0.01**
	SH	52	3.8[b]	1.2		
	HU	52	4.8[a]	0.5		
	Total	182	4.1	1.1		
Lack of education for farmers	SA	78	3.7	1.1	4.35	0.016[ns]
	SH	52	3.4	0.8		
	HU	50	3.2	1.0		
	Total	180	3.5	1.0		
Lack of efficient information	SA	76	3.7[a]	1.0	13.12	<0.01**
	SH	52	3.4[b]	1.0		
	HU	50	2.8[c]	0.9		
	Total	178	3.4	1.0		
Lack of efficient land	SA	74	3.1[c]	1.3	43.46	<0.01**
	SH	52	3.9[b]	1.2		
	HU	54	4.9[a]	0.5		
	Total	180	3.9	1.3		
Lack of an efficient budget	SA	78	3.4[c]	1.1	22.66	<0.01**
	SH	52	4.1[b]	1.4		
	HU	54	4.7[a]	0.7		
	Total	184	4.0	1.2		
Lack of information from the composition of the tree plus crops	SA	78	3.6[a]	1.1	17.54	<0.01**
	SH	52	3.3[a]	1.0		
	HU	50	2.5[b]	0.6		
	Total	180	3.2	1.1		
Not using updated research	SA	74	3.7[a]	1.1	19.63	<0.01**
	SH	52	3.2[b]	1.0		
	HU	46	2.6[c]	0.6		
	Total	172	3.2	1.1		

[ns]Non-significant difference. **Significant difference at α = 0.01. Answer scale: 1: very low; 2: low, 3: average, 4: high, and 5: very high. N, number; SD, standard deviation; Sig, significant level. SA, semi-arid, SH, semi-humid, HU, humid. Alphabet a and b shows significant difference between two regions.

less important motivating factors. This could suggest that farmers prioritize immediate financial returns and livelihood benefits over secondary benefits like wood or manure, which might not be as directly associated with their economic survival. This finding could be contextualized by the study by Felton et al. (2023), which indicates that, while agroforestry offers multiple benefits, some are viewed as secondary or long-term benefits that may not outweigh the immediate need for income and job creation. On the flip side, farmers also face significant challenges in agroforestry. The two biggest obstacles were government support (4.1 ± 1.1) and the lack of an efficient budget (4 ± 1.2). This finding resonates with broader challenges in agroforestry adoption, as governmental support is often crucial in terms of policy frameworks, financial incentives, and technical assistance. The economic barriers, including insufficient budget allocation, were echoed in studies such as Schaffer et al. (2024), which suggest that the success of agroforestry depends on substantial government investment and support for farmers to overcome the costs of transitioning to these systems. Furthermore, the lack of efficient land, the lack of efficient information, and the lack of efficient education were significant hurdles. Farmers may not have access to land suitable for agroforestry or the information needed to implement these systems effectively. This finding reflects a common challenge in promoting agroforestry, as highlighted in the study by Arimi and Omoare (2021), where insufficient knowledge and lack of technical support hinder farmers' ability to maximize agroforestry's potential. Understanding these multifaceted motivations is crucial for developing tailored extension services and policies that support farmers' immediate and long-term goals, ensuring the success and sustainability of agroforestry.

Governmental support

Farmers involved in agroforestry, such as those in other agricultural activities, encounter various challenges that hinder their productivity and sustainability. The most significant

TABLE 12 The impacts of climate change perceived by farmers during the recent years across climate regions using Duncan's test.

Impact	Region	*N*	Mean	SD	*F*	Sig.
Increasing temperature	SA	76	3.9[b]	0.9	6.729	<0.01**
	SH	54	4.7[b]	1.07		
	HU	40	3.2[a]	1.2		
	Total	170	4.0	1.7		
Change of precipitation type	SA	78	3.6[b]	1.1	5.029	<0.01**
	SH	54	3.8[b]	0.8		
	HU	26	3.0[a]	1.1		
	Total	158	3.5	1.1		
Change of precipitation amount	SA	78	4.1[a]	0.9	21.18	<0.01**
	SH	52	3.8[a]	1.0		
	HU	20	2.6[b]	0.7		
	Total	150	3.8	1.0		
Changing of the season time	SA	76	3.5[a]	1.1	8.27	<0.01**
	SH	54	3.3[a]	0.9		
	HU	24	2.6[b]	0.7		
	Total	154	3.3	1.0		
Frostbite	SA	78	4.0[a]	0.9	12.91	<0.01**
	SH	54	3.8[a]	1.1		
	HU	28	2.8[b]	1.4		
	Total	160	3.7	1.1		
Droughtiness	SA	74	4.3[a]	0.7	28.22	<0.01**
	SH	54	4.0[a]	1.0		
	HU	22	2.7[b]	0.9		
	Total	150	4.0	1.0		

[ns]Non-significant difference. **Significant difference at $\alpha = 0.01$. Answer scale: 1: very low, 2: low, 3: average, 4: high, and 5: very high. *N*, number; SD, standard deviation; Sig, significant level; SA, semi-arid, SH, semi-humid, HU, humid. Alphabet a and b shows significant difference between two regions.

obstacles identified in this study were the need for more governmental support (4.1 ± 1.1) and a lack of efficient budget (4 ± 1.2). This finding is consistent with previous research, which highlights that inadequate financial backing and policy support are significant constraints in the successful implementation and scaling up of agroforestry (Mbow et al., 2014a). Governmental support is crucial for providing the necessary resources, subsidies, and incentives to encourage farmers to adopt and sustain agroforestry. Without sufficient budget allocation, farmers struggle to invest in essential inputs and technologies, which can severely limit the potential benefits of agroforestry (Garrity, 2004).

In addition to financial and policy-related challenges, farmers face practical obstacles such as a lack of efficient land, a lack of information, and a lack of education. These factors are necessary to enable farmers to implement and manage agroforestry effectively. Limited access to suitable land restricts the extent to which farmers can engage in agroforestry, especially in densely populated areas or regions with land tenure issues (Franzel, 1999). Moreover, the lack of efficient information and education indicates a gap in knowledge transfer and capacity building. Farmers need comprehensive and accessible information on best practices, benefits, and management techniques of agroforestry to make informed decisions (Ajayi et al., 2006). Extension services and educational programs play a vital role in addressing this gap by providing tailored training and resources to equip farmers with the necessary skills and knowledge (Scherr and Sthapit, 2010). The reliance on extension services in the SH region can be mitigated by further elaboration upon improvements in these services, such as increasing their accessibility in remote areas, improving the quality of training, or tailoring advice to local agroecological conditions. Addressing these obstacles through targeted interventions can enhance the adoption and effectiveness of agroforestry, contributing to improved livelihoods and environmental sustainability.

In addition, climate change education can be incorporated into school and university curricula to help people understand this issue and also teach people how to cope with climate change (Hossain et al., 2016; Ghanbari et al., 2019). This information is essential for planners, extensionists, and NGOs to improve responses to further incidences of climate change and thus reduce the resulting difficulties. Finally, the adaptation projects should be contextualized according to the communities and ecosystems around them. Training programs for agroforestry managers and developing safe economic routes are key solutions to promote sustainable agroforestry.

TABLE 13 Changing tree species and climate change by farmers across climate regions.

Tree planted past	How many years ago	Tree planted recently	Reason for change
Plum	4	Cherry	Adaptation and low water demand
Apple	3	Walnut	low water demand, adaptation, and change in efficiency
Cherry	13	Persimmon	Adaptation
Grape	5	Fig	Adaptation and low water demand
Grape	5	Pomegranate	Adaptation and low water demand
Grape	5	Pear	Adaptation and low water demand
Poplar	17	Modified poplar	Change in efficiency
Native walnut	10	Modified walnut	Adaptation and change in efficiency
Plum	5	Poplar	Change in efficiency
Plum	15	Poplar	Adaptation and change in efficiency
Pomegranate	20	Olive	Adaptation and change in efficiency
Pomegranate	20	Mulberry	Adaptation and low water demand
Poplar	11	fruit trees	Change in efficiency
Poplar	15	Walnut	Adaptation and change in efficiency
Walnut	4	Mulberry	Adaptation and change in efficiency
Walnut	4	Orange	Adaptation and change in efficiency
Walnut	4	Lemon	Adaptation and change in efficiency
Walnut	14	Mulberry	Change in efficiency and low water demand
Walnut	14	Pomegranate	Change in efficiency and low water demand
Walnut	15	Pomegranate	Adaptation and change in efficiency
Walnut	15	Mulberry	Adaptation
Walnut	15	Mulberry	Change in efficiency
Walnut	15	Pomegranate	Adaptation and change in efficiency
Walnut	30	Pomegranate	Adaptation
Willow	5	Poplar	Change in efficiency

Climate change adaptation

As other researchers stated over the last decade, however, there has been a recognition that increasing temperatures, carbon dioxide levels, and changes in humidity and rainfall could affect agroforestry systems (Mbow et al., 2014b; Hariyanto et al., 2025). Climate change may shift ecological zones in tropical mountains and affect tree species distributions. Additionally, higher temperatures and increasing rainfall would increase the prevalence of coffee tree pests (Watts et al., 2022). Drought could decrease cacao yields by reducing the production of cacao pods per tree (Jaramillo et al., 2013). Due to the mentioned effects of CC, farmers attempt to adapt themselves to it. Besides, drought is considered another sign of climate change. Gateau-Rey et al. (2018) found that drought conditions could increase mortality rates in both cacao trees and their shade trees in Brazil, implying that tree shading may not be effective against drought. Adaptation to climate change is a two-step process that requires rural communities to first perceive climate change and then respond to the changes in the second step (Asrat and Simane, 2018; Rodríguez-Barillas et al., 2024). Changing cropping species by planting drought-resistant crop varieties was a vital adaptation strategy. As found in a study by Watts et al. (2022), agroforestry was mainly negatively affected by climate change. Climate change, manifested through increased temperature, changes in rainfall amounts and intensity, and drought, may hinder agroforestry farmers' climate resilience in dealing with declining ecosystem services. Emphasis on more drought-resistant crops in arid and semi-arid regions could help in reducing vulnerability to climate change (Rodríguez-Barillas et al., 2024). Generally, there is a shift from water-intensive to less water-intensive crops. A similar practice has been followed by farmers of the Barind region of Bangladesh who have cultivated a drought-tolerant rice variety to combat climate changes (Hossain et al., 2016). Furthermore, the shift in cropping practices was primarily from low economic yield and high water demand crops to crops with higher efficiency and low water demand. Changing cropping patterns has been noted as an adaptation strategy in Isfahan, Iran, and the Barind region of Bangladesh (Morid and Massah Bavani, 2010; Hossain et al., 2016). In addition, Kattumuri et al. (2017) reported that farmers in the semi-arid regions of Karnataka in India adopted shifting cropping pattern practices to cope with current climate risks. It was found to be the best possible strategy to mitigate the negative impacts of climate change (Morid and Massah Bavani, 2010). Saffron plantation has been expanded across Iran, especially the semi-arid region of Iran and Azerbaijan, as their response to water deficiency that villages face (Ghanbari et al., 2021).

In addition to changes in crop products, changes in tree species have been implemented to mitigate the climate change impacts. Swamy and Tewari (2017) mentioned that local communities had developed tree-based systems to reduce climate change risks. The tree component in agroforestry serves an important role in the conservation of fauna diversity, provision of ecosystem services (e.g., provision of food, fuel wood, improving crop productivity, increasing cash income, etc.), and inclusion of climate regulation services (Mulatu and Hunde, 2019). The functional diversity of trees led to planting and replacing different species in the agroforestry. In other parts of arid regions of the World, tree diversity can enhance food security and income in the arid ecosystems of Ethiopia (Manaye et al., 2021). We found similar results in this research, where the number of tree species in the agroforestry systems in the semi-arid region was higher than that in semi-humid and humid regions. Greater diverse species provide higher income sources, which will lead to an increase in their adaptability and the financial sustainability of farmers. As Santos et al. (2022) stated, Mediterranean agriculture urges alternatives, and agroforestry could be a key element among the tools to fight contemporary environmental challenges, such as climate change, water scarcity, and food security (Tramblay et al., 2020). Concerning biodiversity, trees in agricultural landscapes appear particularly efficient in contributing to biodiversity conservation, while environmentally valuable and economically profitable (Kay et al., 2019; Santos et al., 2022). Interestingly, our findings revealed that the number of tree species in agroforestry systems within the semi-arid region was higher than those observed in semi-humid and humid regions, indicating that more diverse species may contribute to a broader range of income sources. This result contrasts with many previous studies, which typically report greater species richness in more humid environments due to more favorable growing conditions and higher ecological productivity (Jose, 2012; Nair, 2012). In contrast, our results suggest that, in semi-arid regions, farmers may intentionally cultivate a wider array of drought-tolerant and multipurpose tree species to diversify income and mitigate environmental risks such as drought and soil degradation. This adaptive strategy may reflect a response to harsher climatic conditions, where species diversity becomes a form of livelihood insurance rather than a product of ecological abundance. Similar findings were reported in some case studies from dry regions of sub-Saharan Africa and Central Asia, where agroforestry diversity was driven more by the socioeconomic necessity and traditional knowledge than by climatic potential (Garrity, 2004). Therefore, the relationship between climate conditions and agroforestry diversity appears to be context-dependent, influenced not only by biophysical factors but also by farmers' strategies, cultural practices, and resource needs.

Farmers have employed various adaptation strategies to cope with and mitigate the impacts of climate change, with one notable strategy being the alteration of crop and tree species. This approach involves replacing traditional species with those that are more resilient to changing climatic conditions. For example, barley, which was historically cultivated, has been replaced by alfalfa, pea, bred barley, wheat, and medicinal plants. These replacements were driven by factors such as low water demand, better adaptation to the changing climate, and increased efficiency (Palombi and Sessa, 2013). This strategic shift not only helps in conserving water but also ensures that the crops can thrive under new environmental conditions, thereby maintaining agricultural productivity and sustainability.

Similarly, a comparable strategy has been adopted for tree species within agroforestry. Species with high water demand such as apple have been replaced with walnut in certain regions, reflecting a shift toward species that require less water and are better adapted to the prevailing climate (Nair, 2012). Additionally, some farmers have transitioned from grape cultivation to fig, pomegranate, and pear due to adaptability and lower water requirements. Other species, such as mulberry, olive, and pomegranate, have also been favored for their efficiency and adaptation to the new climatic conditions. These changes are indicative of farmers' proactive measures to ensure the sustainability of their agroforestry in the face of climate change (Lin, 2011). By selecting species that are better suited to the evolving environment, farmers can mitigate the adverse effects of climate change, optimize resource use, and sustain their livelihoods.

Conclusion

The study highlights significant regional differences in the sources of information that farmers in Iran rely on for agroforestry. In the semi-arid (SA) and humid (HU) regions, farmers primarily depend on peer networks (39.5%), emphasizing community-based learning. In contrast, in the semi-humid (SH) region, 69% of farmers rely on agricultural extension services and experts, reflecting the role of formal sources in areas with well-established services. The research also shows that agroforestry practices in Iran vary by region, with semi-arid areas exhibiting the highest species diversity. Farmers' motivations for agroforestry are driven by economic, ecological, and subsistence needs, with food security being the top priority, followed by income and employment benefits. However, challenges such as lack of government support, lack of an efficient budget, and lack of efficient land, lack of information, and lack of education hinder agroforestry adoption. Addressing these issues through targeted interventions, including better government support, budget allocation, and educational programs, is essential for successful agroforestry implementation. The study also emphasizes the need for integrating both informal peer networks and formal expert advice to meet the diverse informational needs of farmers.

Adaptation strategies, such as using climate-resilient crop and tree species, help mitigate climate change impacts and ensure agroforestry sustainability. The research highlights agroforestry's potential in enhancing food security, combating climate change, and improving rural livelihoods. To scale agroforestry, overcoming barriers to information, financial resources, and education is crucial, alongside incorporating these systems into national policies for sustainable land use and climate mitigation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Dr. Rasoul Zavareghi, University of Tabriz; Dr. Attaollah Nadiri, University of Tabriz; and Dr. Jalal Shiri, University of Tabriz. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because we got permission from people orally before asking questions.

Author contributions

SG: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. MJ: Conceptualization, Methodology, Writing – review & editing. JG: Conceptualization, Data curation, Writing – review & editing. IE: Conceptualization, Formal analysis, Methodology, Writing – review & editing. PÁ-Á: Conceptualization, Formal analysis, Supervision, Writing – original draft. SS: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. MA: Data curation, Methodology, Writing – original draft. LE: Data curation, Formal analysis, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2025.1473355/full#supplementary-material

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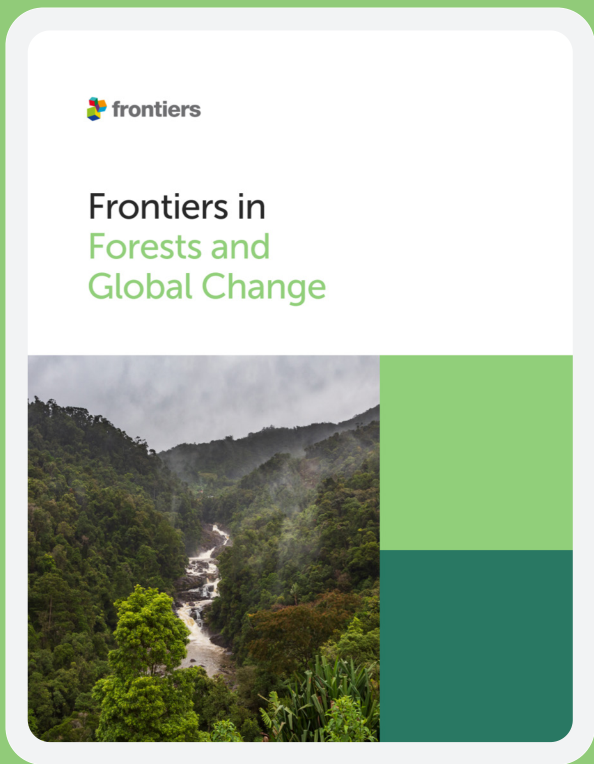

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