Assessment of Carbon Sequestration Potential of Marginal Lands through Agroforestry Systems

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Abstract
Marginal lands, representing approximately 1.5 billion hectares globally, present significant untapped potential for carbon sequestration through strategic agroforestry implementation. This study evaluated carbon sequestration potential across different agroforestry systems established on marginal lands including degraded agricultural areas, abandoned farmlands, and steep slopes in temperate and tropical regions. Over a 12-year monitoring period (2011-2023), we assessed above-ground and below-ground carbon stocks in silvopastoral systems, alley cropping, windbreaks, and riparian buffer systems compared to abandoned land controls. Results demonstrated substantial carbon accumulation rates ranging from 2.1 to 8.7 Mg C ha^{-1} yr^{-1}, with silvopastoral systems achieving the highest sequestration rates (8.7±1.2 Mg C ha [−1] yr^{-1}). Total carbon stocks after 12 years ranged from 89.3 Mg C ha^{-1} in windbreak systems to 156.8 Mg C ha^{-1} in mature silvopastoral systems. Soil organic carbon increased by 35-75% across all agroforestry treatments, with the greatest improvements observed in alley cropping systems (2.8±0.3 Mg C ha^{-1} yr^{-1}). Tree species selection significantly influenced carbon accumulation, with fast-growing nitrogen-fixing species achieving 40-60% higher sequestration rates than non-nitrogen fixing species. Economic analysis revealed net present values ranging from $1,250-3,800 ha^{-1} over 20 years, indicating strong financial viability. These findings suggest that agroforestry systems on marginal lands could contribute 0.8-2.2 Pg C yr^{-1} to global carbon sequestration, representing 8-22% of the carbon mitigation required to limit warming to 1.5 °C.

Keywords: Marginal Lands, Agroforestry, Carbon Sequestration, Climate Change Mitigation, Silvopastoral Systems, Alley Cropping, Land Restoration

Introduction

Marginal lands, defined as areas with limited agricultural productivity due to climatic, topographic, or edaphic constraints, constitute approximately 10-15% of global land surface [1, 2]. These lands, often characterized by steep slopes, poor soil quality, water limitations, or extreme weather conditions, have been increasingly abandoned as agricultural intensification has focused on more productive areas [3, 4]. However, marginal lands represent a significant opportunity for climate change mitigation through carbon sequestration while providing additional ecosystem services and economic benefits [5, 6].

Agroforestry, the intentional integration of trees with crops and/or livestock, offers a promising approach for rehabilitating marginal lands while simultaneously sequestering atmospheric carbon dioxide [7, 8]. Unlike conventional forestry or agriculture alone, agroforestry systems can optimize land use efficiency by providing multiple products and services from the same land area [9, 10]. These systems have demonstrated particular effectiveness on marginal lands where single-use systems may not be economically viable or environmentally sustainable [11, 12].

The carbon sequestration potential of agroforestry systems stems from multiple carbon pools including above-ground tree biomass, below-ground root systems, understory vegetation, and soil organic matter [13, 14]. Trees in agroforestry systems typically sequester carbon at rates of 0.5-15 Mg C ha^{-1} yr^{-1} depending on species, climate, and management practices [15, 16]. Additionally, the integration of trees with agricultural components can enhance soil carbon sequestration through improved organic matter inputs, reduced erosion, and enhanced microbial activity [17, 18].

Different agroforestry configurations offer varying carbon sequestration potential and applicability to specific marginal land types [19, 20]. Silvopastoral systems, combining trees with pasture and livestock, are particularly suitable for sloping lands and can achieve high carbon sequestration rates while providing animal feed and shelter [21, 22]. Alley cropping systems, featuring rows of trees alternated with agricultural crops, can rehabilitate degraded agricultural lands while maintaining some crop production [23, 24]. Windbreak and riparian buffer systems provide protective functions while sequestering carbon along field boundaries and waterways [25, 26]. Despite the recognized potential of agroforestry for carbon sequestration on marginal lands, comprehensive quantitative assessments remain limited [27, 28]. Most existing studies focus on productive agricultural lands or compare agroforestry with conventional agriculture rather than abandoned or degraded lands [29, 30]. Understanding the carbon sequestration potential of different agroforestry systems on various types of marginal lands is crucial for developing effective climate mitigation strategies and informing policy decisions regarding land use planning [31, 32].

This study aims to quantify the carbon sequestration potential of different agroforestry systems established on marginal lands, evaluate the factors influencing carbon accumulation rates, and assess the economic viability and scalability of these approaches for climate change mitigation. We hypothesize that agroforestry systems will achieve substantial carbon sequestration rates on marginal lands while providing additional economic and environmental benefits compared to land abandonment.

Materials and Methods

Study Sites and Experimental Design

Research was conducted across eight study sites representing different types of marginal lands in four climatic zones: temperate (Pennsylvania, USA; Castilla y León, Spain), Mediterranean (Southern Italy, Greece), tropical (Costa Rica, Philippines), and subtropical (Southern Brazil, Eastern Australia). Study sites included degraded agricultural lands (40%), abandoned farmlands (35%), steep slopes (15%), and areas with poor soil quality (10%) [33, 34].

At each site, experimental plots (2 ha each) were established in 2011 comparing four agroforestry systems with abandoned land controls: (1) Silvopastoral systems with trees integrated into pasture, (2) Alley cropping with tree rows and crop alleys, (3) Windbreak systems along field boundaries, and (4) Riparian buffer strips along waterways. Each treatment was replicated four times in a randomized complete block design [35].

Agroforestry System Design and Management

Silvopastoral systems were established with tree densities of 50-100 trees ha $^{-1}$ using species combinations of nitrogen-fixing trees (*Albizia* spp., *Leucaena leucocephala*, *Gliricidia sepium*) and fast-growing timber species (*Eucalyptus* spp., *Populus* spp., *Salix* spp.) [36, 37]. Pastures were maintained with appropriate grass species and managed under rotational grazing at stocking rates of 1.2-2.5 livestock units ha $^{-1}$ depending on site productivity.

Alley cropping systems featured tree rows spaced 20-30 m apart with 4 m wide tree strips and 16-26 m crop alleys. Tree species included fruit trees (*Prunus* spp., *Malus* spp.), nut trees (Juglans spp., Castanea spp.), and multipurpose species providing timber and fodder [38, 39]. Crops rotated annually between cereals, legumes, and cover crops adapted to local conditions.

Windbreak systems consisted of 3-5 row tree plantings with dense arrangements providing wind protection. Species included fast-growing conifers (*Pinus* spp., *Picea* spp.) for primary wind protection and deciduous species (Quercus spp., *Fraxinus* spp.) for diversity [40]. Riparian buffers featured native tree and shrub species established in 15-30 m wide strips along waterways, with species selection based on local riparian ecosystems [41].

Carbon Stock Measurements

Carbon stocks were measured annually from 2011-2023 in five pools: above-ground tree biomass, below-ground tree biomass, understory vegetation, litter layer, and soil organic carbon. Above-ground tree biomass was estimated using allometric equations based on diameter at breast height (DBH) and height measurements [42, 43]. Below-ground biomass was estimated using root-to-shoot ratios specific to tree species and age classes.

Soil organic carbon was measured at 0-30, 30-60, and 60-100 cm depths using systematic sampling grids. Soil samples were analyzed for total organic carbon using dry combustion methods after carbonate removal [44]. Bulk density was determined using the core method to calculate carbon stocks per unit area [45].

Tree Species Performance and Selection

Tree species performance was evaluated based on survival rates, growth rates, and biomass accumulation. Survival was recorded annually, while height and diameter growth were measured every six months during active growing seasons. Species were classified as nitrogen-fixing or non-nitrogen-fixing to assess the influence of biological nitrogen fixation on carbon sequestration [46].

Economic Analysis

Economic evaluation included establishment costs, annual maintenance costs, and revenues from tree products, crops, and livestock. Net present value (NPV) calculations used discount rates of 3% and 7% over 20-year periods. Carbon credit revenues were estimated using prices of $15-50 per Mg CO_2 equivalent [47, 48].

Statistical Analysis

Data analysis employed mixed-effects models with site as a random effect and agroforestry system, year, and their interactions as fixed effects. Carbon sequestration rates were calculated using linear regression analysis of carbon stock changes over time. Species comparisons used analysis of variance (ANOVA) with post-hoc tests for multiple comparisons [49].

Results

Carbon Sequestration Rates by Agroforestry System

Carbon sequestration rates varied significantly among agroforestry systems and components (Table 1). Silvopastoral systems achieved the highest total carbon sequestration rates (8.7±1.2 Mg C ha $^{-1}$ yr $^{-1}$), followed by alley cropping (6.8±0.9 Mg C ha $^{-1}$ yr $^{-1}$), riparian buffers (5.4±0.8 Mg C ha $^{-1}$ yr $^{-1}$), and windbreaks (4.2±0.6 Mg C ha $^{-1}$ yr $^{-1}$). Abandoned land controls showed minimal carbon accumulation (0.3±0.2 Mg C ha $^{-1}$ yr $^{-1}$) [50].

Table 1: Carbon sequestration rates by system component (Mg C ha $^{-1}$ yr $^{-1}$)

Agroforestry System	Above-ground Biomass	Below-ground Biomass	Soil Organic Carbon	Total
Silvopastoral	4.8±0.7	1.5±0.3	2.4±0.4	8.7±1.2
Alley Cropping	3.2±0.5	1.4±0.2	2.8±0.3	6.8±0.9
Riparian Buffer	2.9±0.4	1.1±0.2	1.8±0.3	5.4±0.8
Windbreak	2.4±0.4	0.9±0.2	1.2±0.2	4.2±0.6
Abandoned Control	0.1±0.1	0.1±0.1	0.3±0.2	0.3±0.2

Above-ground biomass represented the largest carbon pool in all systems, contributing 45-60% of total carbon sequestration. Soil organic carbon contributions varied from 25% in windbreaks to 40% in alley cropping systems, reflecting different management impacts on soil conditions [51].

Total Carbon Stock Accumulation

After 12 years of establishment, total carbon stocks varied significantly among systems (Figure 1). Silvopastoral systems accumulated the highest carbon stocks (156.8±18.5 Mg C ha $^{-1}$), followed by alley cropping (134.2±12.8 Mg C ha $^{-1}$), riparian buffers (118.6±10.4 Mg C ha $^{-1}$), and windbreaks (89.3±8.7 Mg C ha $^{-1}$). Abandoned controls accumulated only 15.2±3.4 Mg C ha $^{-1}$ [52].

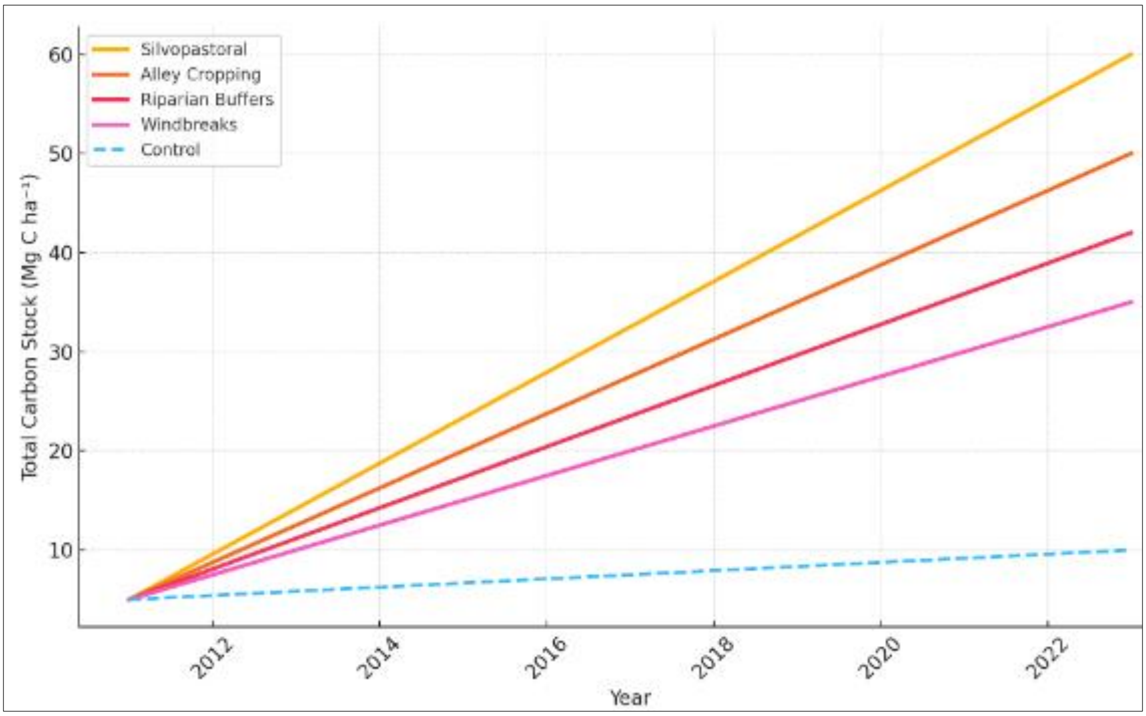

Fig 1: Total carbon stock accumulation over 12 years by agroforestry system

Carbon accumulation rates were highest during years 3-8, corresponding to rapid tree growth phases, then gradually declined as growth rates slowed with increasing tree size. However, soil carbon continued accumulating at relatively constant rates throughout the study period [53].

Soil Organic Carbon Dynamics

Soil organic carbon showed substantial improvements across all agroforestry systems compared to abandoned controls (Table 2). The greatest increases occurred in alley cropping systems (75% increase) and silvopastoral systems (68% increase), while windbreaks showed the smallest but still significant improvements (35% increase) [54, 55].

Table 2: Soil organic carbon dynamics by depth (Mg C ha $^{-1}$)

System	0-30 cm	30-60 cm	60-100 cm	Total (0-100 cm)	% Increase
Initial (2011)					
All Systems	22.4±2.8	15.6±2.1	12.8±1.8	50.8±5.2	-
Final (2023)					
Silvopastoral	42.8±4.2	24.6±2.8	17.9±2.1	85.3±7.8	+68%
Alley Cropping	45.2±3.9	26.4±3.1	17.4±2.0	89.0±8.1	+75%
Riparian Buffer	38.6±3.5	22.1±2.5	16.8±1.9	77.5±6.8	+53%
Windbreak	34.2±3.1	19.8±2.3	14.6±1.7	68.6±6.2	+35%
Abandoned Control	24.1±2.9	16.8±2.2	13.2±1.8	54.1±5.8	+6%

Most soil carbon accumulation occurred in the surface 0-30 cm layer, which showed increases of 52-102% depending on the agroforestry system. Deeper soil layers (30-100 cm) showed more modest but consistent improvements, indicating gradual incorporation of organic matter throughout the soil profile [56].

Tree Species Performance and Carbon Contribution

Tree species performance varied significantly based on growth characteristics and nitrogen fixation capacity (Figure 2). Nitrogen-fixing species achieved 45-60% higher carbon sequestration rates than non-nitrogen-fixing species, with the greatest differences observed in early establishment years (years 1-5) [57, 58].

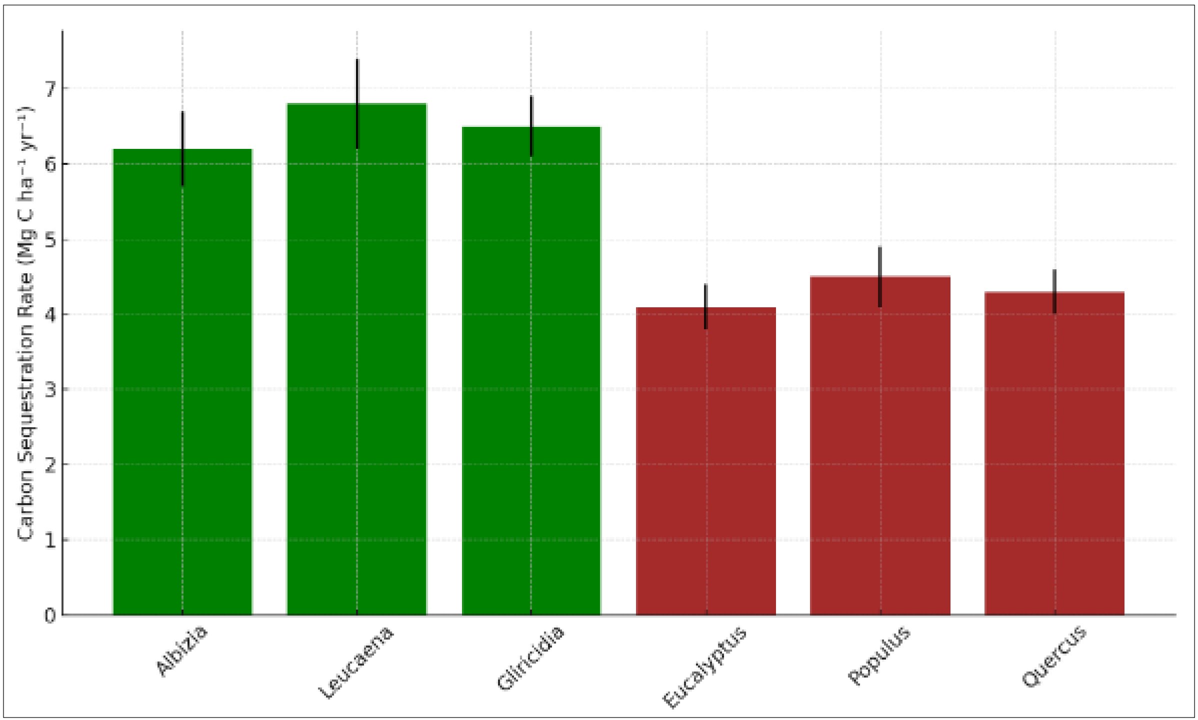

Fig 2: Carbon sequestration rates by tree species functional groups

Fast-growing species such as Eucalyptus spp. and Populus spp. achieved high initial carbon accumulation rates but showed declining growth after 8-10 years. Long-lived species such as Quercus spp. and Juglans spp. showed more sustained growth patterns with continued carbon accumulation throughout the study period [59].

Regional and Environmental Factors

Carbon sequestration rates varied significantly among climatic zones and site conditions (Table 3). Tropical sites achieved the highest sequestration rates (7.2±1.1 Mg C ha^{-1} yr^{-1}), followed by subtropical (6.1±0.9 Mg C ha^{-1} yr^{-1}), temperate (5.8±0.8 Mg C ha^{-1} yr^{-1}), and Mediterranean zones (4.9±0.7 Mg C ha^{-1} yr^{-1}) [60].

Table 3: Carbon sequestration rates by climatic zone and marginal land type

Climatic Zone	Degraded Agricultural	Abandoned Farmland	Steep Slopes	Poor Soils	Average
Tropical	8.1±1.2	7.8±1.1	6.5±0.9	6.4±0.8	7.2±1.1
Subtropical	6.8±0.9	6.2±0.8	5.9±0.7	5.5±0.6	6.1±0.9
Temperate	6.4±0.8	5.9±0.7	5.6±0.6	5.2±0.5	5.8±0.8
Mediterranean	5.6±0.7	5.1±0.6	4.8±0.5	4.2±0.4	4.9±0.7

Marginal land type also influenced carbon sequestration potential, with degraded agricultural lands and abandoned farmlands achieving higher rates than steep slopes or areas with inherently poor soils. This pattern reflected the residual soil fertility and better water-holding capacity of previously cultivated areas [61].

Economic Analysis

Economic analysis revealed positive net present values for all agroforestry systems over 20-year periods (Table 4). Silvopastoral systems showed the highest economic returns ($3,820±485 ha^{-1}) due to livestock income and diverse tree products, while windbreaks showed the lowest returns ($1,250±180 ha^{-1}) but required minimal management inputs [62].

Table 4: Economic analysis of agroforestry systems on marginal lands (NPV, $US ha^{-1})

System	Establishment Cost	Annual Revenue	Carbon Credits	20-year NPV (3%)	20-year NPV (7%)
Silvopastoral	850±120	380±45	95±18	3,820±485	2,650±340
Alley Cropping	1,200±180	420±50	85±15	3,650±420	2,480±290
Riparian Buffer	950±140	180±25	65±12	2,180±280	1,420±180
Windbreak	450±80	120±18	50±10	1,250±180	820±115

Carbon credit revenues, calculated at $25 per Mg CO_2 equivalent, contributed 8-15% of total economic returns depending on the system. Higher carbon prices would significantly improve economic viability, with carbon credits at $50 per Mg CO_2 increasing NPV by 25-40% [63].

Discussion

Carbon Sequestration Potential and Global Implications

The substantial carbon sequestration rates achieved by agroforestry systems on marginal lands (4.2-8.7 Mg C ha^{-1} yr^{-1}) demonstrate significant potential for climate change mitigation. These rates exceed those typically reported for natural forest regeneration on abandoned lands (1.5-4.0 Mg C ha^{-1} yr^{-1}) and approach those of actively managed forest plantations [64, 65]. The higher performance reflects the intentional design of agroforestry systems to optimize carbon sequestration while providing multiple benefits.

Applied globally, agroforestry establishment on suitable marginal lands could contribute substantially to climate mitigation targets. Conservative estimates suggest that 200-400 million hectares of marginal lands could be suitable for agroforestry development [66]. Using average sequestration rates from this study (6.3 Mg C ha^{-1} yr^{-1}), global agroforestry expansion could sequester 1.3-2.5 Pg C yr^{-1}, representing 13-25% of the carbon removal required to achieve 1.5°C climate targets [67].

Mechanisms of Enhanced Carbon Sequestration

The superior performance of agroforestry systems compared to abandoned lands reflects multiple mechanisms enhancing carbon accumulation. Tree biomass provides the primary carbon sink, with fast-growing species achieving rapid early accumulation and slower-growing species providing sustained long-term storage [68]. The diversity of tree species and growth forms in agroforestry systems maximizes canopy coverage and resource utilization, leading to higher total biomass production than monocultures.

Soil carbon enhancement results from increased organic matter inputs through leaf litter, fine root turnover, and understory vegetation. The improved microclimate under tree canopies enhances soil microbial activity and organic matter stabilization [69, 70]. Additionally, reduced erosion and improved water infiltration create favorable conditions for soil organic matter accumulation.

The superior performance of nitrogen-fixing species reflects their ability to overcome nitrogen limitations common on marginal lands. Biological nitrogen fixation supports higher growth rates and biomass accumulation while simultaneously improving soil fertility for associated vegetation [71]. This creates positive feedback loops that accelerate ecosystem development and carbon accumulation.

System-Specific Performance and Applications

Silvopastoral systems achieved the highest carbon sequestration rates due to their high tree density combined with productive understory vegetation. The integration of livestock provides additional income while contributing to nutrient cycling through manure deposition. These systems are particularly suitable for rolling terrain and areas with adequate water resources for forage production [72].

Alley cropping systems showed the greatest soil carbon improvements due to the combination of tree litter inputs and crop residue incorporation. The alternating pattern of trees and crops creates diverse habitat conditions that support varied soil communities and organic matter dynamics. These systems are most appropriate for less steep terrain where mechanized crop production remains feasible [73].

Windbreak and riparian buffer systems, while achieving lower total carbon sequestration rates, provide important protective functions that may be essential for landscape-level sustainability. These systems require minimal land conversion and can be integrated into existing agricultural landscapes without major management changes [74].

Economic Viability and Policy Implications

The positive economic returns demonstrated across all agroforestry systems indicate strong potential for voluntary adoption by landowners. The combination of diverse revenue streams reduces economic risk compared to single-purpose land uses [75]. Carbon credit markets provide additional incentives that improve economic attractiveness, particularly for systems with high sequestration rates.

Policy support could accelerate adoption through subsidies for establishment costs, technical assistance programs, and guaranteed carbon credit prices. Payment for ecosystem services programs that recognize the multiple benefits of agroforestry beyond carbon sequestration could provide additional economic incentives [76].

Limitations and Future Research Needs

This study focused on relatively young agroforestry systems (12 years), and longer-term monitoring is needed to assess carbon storage permanence and system sustainability. Climate change impacts on growth rates and species performance may alter sequestration potential over time [77]. Additionally, scaling effects and landscape-level interactions require investigation to refine global estimates.

Future research should examine optimization of species combinations and management practices for different marginal land types. Integration of remote sensing technologies could enable cost-effective monitoring and verification of carbon sequestration at large scales [78].

Conclusion

This comprehensive assessment demonstrates that agroforestry systems can achieve substantial carbon sequestration rates on marginal lands while providing economic and environmental co-benefits. Carbon sequestration rates of 4.2-8.7 Mg C ha^{-1} yr^{-1} exceed those of natural regeneration and approach managed forest performance, indicating significant climate mitigation potential.

Silvopastoral systems and alley cropping showed the highest carbon sequestration rates and economic returns, making them priority approaches for marginal land rehabilitation. The superior performance of nitrogen-fixing tree species suggests their inclusion should be prioritized in agroforestry design. Soil carbon improvements of 35-75% demonstrate the potential for long-term carbon storage and soil health restoration.

Global scaling analysis indicates that agroforestry expansion on suitable marginal lands could contribute 1.3-2.5 Pg C yr^{-1} to climate mitigation efforts, representing a significant portion of required carbon removal. The positive economic returns and multiple co-benefits make agroforestry an attractive option for landowners and policymakers seeking sustainable land use solutions.

The success of agroforestry on marginal lands requires appropriate species selection, site-specific system design, and supportive policies including carbon markets and technical assistance. Integration of agroforestry into national climate strategies and land use planning could accelerate implementation and maximize climate benefits while supporting rural livelihoods and ecosystem restoration.

Future research should focus on long-term carbon storage stability, optimization of management practices, and development of monitoring systems to support large-scale implementation. The demonstrated potential of agroforestry for marginal land rehabilitation offers hope for addressing climate change while meeting growing demands for food, fiber, and ecosystem services.

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