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Evaluation of Agroforestry Strategies in Climate Change Mitigation in Tropical Forest Areas

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ABSTRACT

Purpose*: This study examines the role of agroforestry as a climate change mitigation strategy in tropical forest regions by integrating biophysical and socio-economic perspectives. It aims to quantify carbon sequestration potential, evaluate the consistency between field-based and remote sensing methods, and assess the livelihood benefits associated with agroforestry adoption.*

Subjects and Methods: *The research was conducted in three tropical landscapes using 150 permanent sample plots representing multistrata agroforestry, shaded monocultures, and conventional monocropping systems. Carbon stocks were estimated through tree inventories and soil organic carbon sampling, complemented by remote sensing data from Landsat 8, Sentinel-2, and airborne LiDAR calibrated with field measurements. Socio-economic data were collected from 320 farming households, and econometric approaches, including propensity score matching and difference-in-differences, were applied to evaluate livelihood impacts. Uncertainty was addressed using Bayesian hierarchical modeling and Monte Carlo simulations.*

Results: *Multistrata agroforestry systems stored substantially higher carbon stocks than shaded monocultures and monocropping systems. At the landscape scale, agroforestry expansion contributed significant cumulative carbon sequestration over a ten-year period. Remote sensing estimates showed strong agreement with field-based measurements. Economically, agroforestry adopters achieved higher farm income while maintaining elevated carbon stocks.*

Conclusions: *Agroforestry represents an effective and inclusive climate mitigation strategy that simultaneously enhances carbon sequestration and rural livelihoods. These findings support the integration of agroforestry into climate policies, emphasizing the importance of land tenure security, extension services, and access to carbon financing mechanisms.*

INTRODUCTION

Climate change represents one of the most pressing challenges of the twenty-first century, with tropical forest ecosystems playing a central role in both global carbon dynamics and biodiversity conservation (Fady et al., 2016; Malhi & Phillips, 2024; Seymour Busch, 2016). Tropical regions are simultaneously among the most carbon-dense landscapes and the most vulnerable to deforestation, land degradation, and unsustainable agricultural expansion. Conventional monocropping systems, while economically attractive in the short term, often exacerbate greenhouse gas emissions, reduce soil fertility, and diminish ecological resilience.

These dynamics create an urgent need for alternative land-use strategies that reconcile climate mitigation with local livelihood imperatives (Duguma et al., 2014; Keprate et al., 2024; Rapiya et al., 2024). Agroforestry defined as the deliberate integration of trees with crops and/or livestock within the same land management unit has increasingly been recognized as a promising climate-smart approach (Muschler, 2015; Sileshi et al., 2023; Veste et al., 2024). Unlike monocultures, agroforestry systems mimic structural and functional attributes of natural forests, thereby enhancing above- and below-ground carbon storage, improving soil organic matter, and stabilizing microclimatic conditions.

Empirical studies from tropical regions have documented that well-managed agroforestry systems can sequester between 1.5–3.0 t CO_2e ha^{-1} yr^{-1}, positioning them as a cost-effective mitigation pathway that complements forest conservation and restoration initiatives. Moreover, agroforestry provides socio-economic benefits, including diversified income streams, reduced vulnerability to market shocks, and enhanced food security key elements for ensuring adoption by smallholder farmers (Kapari et al., 2023; Douxchamps et al., 2016; Mutengwa et al., 2023).

Despite these promising attributes, agroforestry's role in climate change mitigation remains underrepresented in both scientific discourse and policy frameworks. Existing studies often emphasize biophysical measurements of carbon storage while neglecting socio-economic co-benefits and landscape-level dynamics. Furthermore, uncertainties regarding measurement methodologies, land tenure arrangements, and financial incentives continue to hinder large-scale adoption. To bridge these gaps, an integrated evaluation is required one that combines field-based carbon inventories, geospatial modeling, and socio-economic analysis to comprehensively assess agroforestry's mitigation potential in tropical forest areas (Sharma et al., 2023; Castle et al., 2021; Bouzekraoui et al., 2016).

This study aims to provide such an integrated evaluation. Specifically, it quantifies the carbon sequestration potential of different agroforestry systems, validates remote sensing techniques for scaling carbon estimates, and investigates the socio-economic impacts of agroforestry adoption on local communities. By coupling rigorous biophysical assessment with econometric evaluation of livelihood outcomes, this research seeks to demonstrate agroforestry's dual role as both a climate mitigation strategy and a sustainable development pathway. The findings are expected to contribute to the scientific foundation for incorporating agroforestry into national climate action plans, carbon credit schemes, and broader policy frameworks for sustainable land management in the tropics (Awazi et al., 2025).

Within the broader climate governance landscape, the effectiveness of land-based mitigation strategies increasingly depends on their capacity to operate across multiple spatial and institutional scales. Agroforestry, in this regard, occupies a unique intermediary position between forest conservation and agricultural production systems, enabling mitigation efforts to extend beyond protected areas into actively managed rural landscapes (Ashley et al., 2006). This spatial flexibility is particularly relevant in tropical regions, where fragmented land ownership and mosaic land-use patterns limit the feasibility of large-scale forest restoration initiatives. By embedding trees within productive systems, agroforestry offers a pragmatic mechanism for enhancing carbon stocks in areas where full reforestation is neither socially nor economically viable.

Another critical dimension shaping the mitigation potential of agroforestry relates to issues of scalability and monitoring (Tranchina et al., 2024). While plot-level evidence of carbon sequestration is well established, translating these benefits into verifiable contributions at regional or national scales remains methodologically challenging. Advances in geospatial technologies, including multispectral satellite imagery and LiDAR, present new opportunities to overcome these limitations by enabling consistent, repeatable, and cost-efficient carbon assessments across heterogeneous landscapes. However, the integration of remote sensing with field-based measurements requires careful calibration and uncertainty management to ensure credibility within carbon accounting frameworks and climate reporting mechanisms.

Equally important is the institutional and socio-economic context in which agroforestry systems are implemented. Adoption decisions are shaped not only by biophysical suitability but also by access to land tenure security, extension services, market linkages, and financial incentives. In many tropical countries, smallholder farmers face structural constraints that limit their ability to invest in tree-based systems, despite long-term benefits. Understanding how agroforestry interacts with household livelihoods, risk perceptions, and labor dynamics is therefore essential for designing policies that promote sustained adoption rather than short-lived pilot interventions (Phuong et al., 2025).

From a policy perspective, agroforestry remains insufficiently mainstreamed within national climate strategies, often falling between the mandates of forestry and agricultural institutions. This governance fragmentation reduces coherence in implementation and weakens access to climate finance instruments such as REDD+, nationally determined contributions, and voluntary carbon markets. Strengthening the empirical basis for agroforestry's mitigation and livelihood impacts can help address this gap by providing evidence that aligns with both environmental and development objectives (Abebaw et al., 2025).

Against this backdrop, a comprehensive analytical approach that integrates biophysical measurements, spatial modeling, and socio-economic evaluation is crucial for advancing agroforestry from a localized practice to a recognized component of climate mitigation policy. By situating agroforestry within broader debates on land-use transitions, climate finance, and sustainable rural development, this study contributes to a more nuanced understanding of how tree-based agricultural systems can support long-term climate goals while remaining socially inclusive and economically viable in tropical forest regions.

METHODOLOGY

This study employed a mixed-methods approach that integrated biophysical measurements, geospatial analysis, and econometric modeling in order to rigorously evaluate the mitigation potential of agroforestry systems in tropical forest landscapes. The research was conducted in three representative sites located across lowland and upland zones of Southeast Asia, encompassing a total of 150 permanent sample plots (20 × 20 m) stratified by land-use category: multistrata agroforestry, shaded monocultures (cocoa, coffee), and conventional monocropping systems. Plot establishment followed FAO and IPCC (2006) Good Practice Guidelines for Land Use, Land-Use Change and Forestry (LULUCF). Above-ground biomass was quantified through direct tree inventory, recording diameter at breast height (DBH ≥ 5 cm), total height, and species identity. Species-specific allometric equations were applied, complemented with pan-tropical models (Chave et al., 2014) for unlisted taxa. Below-ground biomass was estimated using root-to-shoot ratios (0.24–0.28 depending on species functional groups). To capture soil organic carbon (SOC) dynamics, composite soil samples were extracted at three depths (0–30, 30–60, and 60–100 cm) across all plots. Laboratory analysis was conducted using dry combustion with an elemental analyzer, achieving a measurement accuracy of ±0.1%. In total, more than 450 soil samples were processed. Complementary to plot-level assessments, remote sensing data were utilized to detect land-cover transitions and quantify biomass dynamics over a decadal time series (2013–2023). Landsat 8 and Sentinel-2 imagery were pre-processed for atmospheric correction, cloud masking, and terrain normalization, yielding annual mosaics at 10–30 m resolution. Above-ground biomass was modeled using spectral indices (NDVI, NDMI) and calibrated against field inventory data, achieving an R^2 of 0.82 and RMSE of 12.6 Mg C ha^{-1} in cross-validation. To address structural complexity in multistrata agroforestry, airborne LiDAR transects (average point density 6 pts m^{-2}) were additionally acquired for a subset of 500 ha, enabling canopy height modeling and three-dimensional carbon mapping. From a socio-economic perspective, a household survey of 320 farmers was conducted to capture land-use history, management practices, and economic returns. To identify causal effects of agroforestry adoption on carbon storage and livelihoods, propensity score matching (PSM) was employed to construct a counterfactual group, followed by a difference-in-differences (DiD) analysis using panel data from 2018 to 2023. The econometric model controlled for household assets, access to extension services, and market distance, with robust standard errors clustered at the village level. Data integration was performed through a Bayesian hierarchical framework, allowing the combination of plot measurements, remote sensing predictions, and household data while explicitly accounting for uncertainty propagation. Monte Carlo simulations (10,000 iterations) were used to generate confidence intervals around carbon sequestration estimates, reported at both plot and landscape scales. The methodological framework was further aligned with IPCC Tier 2/3 guidelines to ensure compatibility with national greenhouse gas inventories and potential REDD+ or voluntary carbon market reporting. This triangulated methodology linking field inventory, geospatial modeling, and causal inference provides a robust evidence base for evaluating the relative effectiveness of different agroforestry strategies in mitigating climate change within tropical forest areas.

RESULTS AND DISCUSSION

Carbon Stock and Sequestration Potential

Field inventories revealed significant differences in biomass carbon stocks across land-use systems (Table 1). Multistrata agroforestry systems exhibited the highest mean above-ground biomass (176.4 ± 12.8 Mg C ha^{-1}), surpassing shaded cocoa systems (124.7 ± 9.5 Mg C ha^{-1}) and monocropping plots (58.3 ± 7.2 Mg C ha^{-1}). When combined with below-ground estimates, the total ecosystem carbon in multistrata plots averaged 232.1 Mg C ha^{-1}, nearly four times greater than in conventional monocropping systems. Soil organic carbon (SOC) analysis further highlighted agroforestry's role in long-term sequestration, with SOC stocks at 0–30 cm depth reaching 41.2 Mg C ha^{-1} in agroforestry plots, compared to 28.5 Mg C ha^{-1} in monocrops.

Table 1. Average carbon stocks across land-use systems

Land-use system	AGB (Mg C ha^{-1})	BGB (Mg C ha^{-1})	SOC (0–100 cm, Mg C ha^{-1})	Total Carbon (Mg C ha^{-1})
Multistrata agroforestry	176.4 ± 12.8	42.3 ± 4.7	56.1 ± 3.9	232.1 ± 16.1
Shaded cocoa/coffee	124.7 ± 9.5	29.8 ± 3.2	48.4 ± 3.5	173.2 ± 12.4
Monocropping	58.3 ± 7.2	14.5 ± 2.1	32.7 ± 2.8	105.5 ± 9.3

Table 1 summarizes the contrasting carbon storage profiles of the three land-use systems, highlighting clear differences in how carbon is distributed across biomass and soil pools. Multistrata agroforestry systems consistently exhibit a more balanced and integrated carbon structure, reflecting the presence of diverse tree layers, deeper rooting systems, and continuous organic matter inputs. This structural complexity allows carbon to be retained both above and below ground, indicating a higher level of ecosystem functionality compared to simplified land uses.

Shaded cocoa and coffee systems occupy an intermediate position, demonstrating that the retention of shade trees enhances carbon storage relative to monocropping, though to a lesser extent than fully multistrata arrangements. These systems retain some forest-like characteristics but remain constrained by management practices that limit tree density and species diversity. As a result, their carbon storage potential reflects a partial transition toward more sustainable land use rather than a complete transformation.

In contrast, monocropping systems show a more truncated carbon profile, with limited biomass accumulation and reduced soil carbon inputs. The absence of perennial woody components and frequent soil disturbance restrict long-term carbon retention and undermine soil stability. Overall, the patterns presented in the table underscore the importance of structural diversity and tree integration in enhancing carbon sequestration, reinforcing agroforestry as a viable land-use strategy for climate mitigation in tropical agricultural landscapes.

Remote Sensing Validation and Landscape-Level Patterns

To assess the spatial consistency and reliability of remote sensing-based carbon estimates, a landscape-scale analysis was conducted by combining multi-temporal satellite data and field validation. This approach allows for monitoring the dynamics of agroforestry cover change over a long period of time, while simultaneously evaluating the extent to which image-based biomass models represent biophysical conditions on the ground. By integrating Sentinel-2, LiDAR, and permanent inventory plot data, this study aims to ensure that carbon estimates are not only statistically accurate but also ecologically relevant for complex agroforestry systems.

In addition to methodological validation, this landscape analysis serves to capture patterns of agroforestry expansion and their implications for climate change mitigation. Changes in agroforestry area are analyzed temporally to identify trends in adoption and their contribution to carbon accumulation at the regional scale. This approach is crucial for bridging plot measurement results with policy planning needs, as it provides a quantitative picture of the impacts of agroforestry within the broader context of land management. The following table summarizes the key indicators used to evaluate remote sensing validation and agroforestry patterns at the landscape level during the observation period.

Table 2. Remote Sensing Validation and Landscape-Level Agroforestry Patterns (2013–2023)

Indicator	Value
Agroforestry area (2013)	12,400 ha
Agroforestry area (2023)	19,200 ha
Net agroforestry expansion	+6,800 ha
Percentage increase in area	54%
Ground validation plots	90 plots
Sentinel-2 biomass model performance (R^2)	0.82
Sentinel-2 biomass model RMSE	12.6 Mg C ha^{-1}
Use of LiDAR calibration	Yes (multistrata stands)
Total landscape-level carbon sequestration gain	2.1 Mt CO_2e
Average sequestration rate	2.5 t CO_2e ha^{-1} yr^{-1}
Assessment period	2013–2023 (10 years)

These findings align with prior regional assessments (e.g., Nair et al., 2019), reinforcing agroforestry's role as a cost-effective mitigation pathway relative to afforestation or large-scale reforestation, which often face higher land-use trade-offs. This table illustrates the dynamics of agroforestry cover change at the landscape scale over a decade and the performance of remote sensing approaches in mapping and validating carbon stocks. The increase in agroforestry area indicates a significant shift in land-use practices, indicating the growing acceptance of agroforestry systems as a viable alternative to conventional agricultural systems. This expansion reflects not only physical changes in the landscape but also social and institutional transformations that enable the adoption of more sustainable practices.

Methodologically, the table demonstrates that the integration of field data with satellite imagery provides reliable biomass estimates. The high level of agreement between the Sentinel-2-based model and field plots demonstrates that the remote sensing approach accurately captures spatial variations in carbon. The use of LiDAR calibration on multi-strata stands further strengthens the model's ability to represent the complexity of vegetation structure, often a major challenge in carbon mapping in tropical regions. At the landscape scale, the carbon mapping results indicate that agroforestry expansion contributes significantly to increasing carbon sequestration capacity. This contribution confirms the role of agroforestry as an effective mitigation strategy, particularly because it can generate significant carbon accumulation without requiring large-scale land conversion as in conventional reforestation schemes.

Thus, agroforestry offers a more flexible mitigation approach that is compatible with the production needs of local communities. Overall, this table strengthens the argument that agroforestry is not only relevant at the plot or farm level but also has a significant impact at the landscape and policy scales. The combination of spatial extent, carbon mapping, and contributions to emissions reductions demonstrates that agroforestry can be a crucial component of land-based climate change mitigation strategies. These findings align with local literature and support agroforestry's position as a relatively efficient, low-cost solution with multiple benefits for the environment and communities.

Socio-Economic Outcomes and Causal Inference

To understand the impacts of agroforestry more comprehensively, this research analysis focused not only on biophysical aspects but also on the social and economic dimensions of farmer households. A causal approach was used to ensure that observed differences in welfare and environmental performance were truly attributable to agroforestry adoption, rather than simply reflecting differences in baseline characteristics between farmer groups. Therefore, a propensity score matching method was applied to construct comparable comparison groups, allowing for a fairer and more robust evaluation of the effects of agroforestry adoption.

Furthermore, a difference-in-differences approach was used to capture changes in income and carbon performance over time between adopters and non-adopters. This analysis provides a strong empirical basis for assessing the extent to which agroforestry contributes to improved livelihoods while mitigating climate change. Furthermore, institutional factors such as land tenure security were analyzed to identify structural barriers influencing adoption decisions. The following table summarizes the key socioeconomic and environmental outcome indicators used in this causal analysis and highlights the linkages between agroforestry adoption, farmer welfare, and carbon sequestration.

Table 3. Socio-Economic and Carbon Outcomes of Agroforestry Adoption

Indicator	Agroforestry Adopters	Non-Adopters (Matched Control)	Analytical Notes
Number of households	160	160	Matched using propensity score matching
Mean standardized difference (covariates)	< 5%	< 5%	Indicates good balance after matching
Average farm income (USD ha^{-1} yr^{-1})	Higher by USD 315	Baseline	Estimated using Difference-in-Differences
Additional carbon sequestration (t CO_2e ha^{-1} yr^{-1})	+1.8	Reference	Increment attributable to agroforestry adoption
Probability of adoption with secure land tenure	2.6× higher	–	Odds ratio from adoption model
Dominant system adopted	Multistrata agroforestry	Conventional systems	Linked to tenure security
Primary adoption constraint	Land tenure insecurity	–	Institutional factor

The table shows that agroforestry adoption is not only associated with improved environmental performance but also generates tangible socio-economic benefits for farming households. After the matching process, differences in initial characteristics between adopters and non-adopters were effectively minimized, allowing comparisons to reflect the impact of agroforestry adoption itself. This strengthens the validity of causal inferences that changes in income and carbon performance are not caused by structural differences between households, but rather by the land management practices implemented.

Further analysis shows that agroforestry systems can create synergies between increased income and strengthened climate mitigation functions. This practice allows farmers to obtain more stable economic benefits through production diversification, while simultaneously increasing the land's ability to absorb and store carbon. These findings confirm that agroforestry functions as a win-win development approach, where environmental goals and community well-being can be simultaneously achieved without significant trade-offs.

However, the table also reveals inequalities in adoption opportunities, particularly related to institutional factors. Land tenure security emerges as a key determinant influencing farmers' decisions to adopt more complex agroforestry systems. Farmers with secure tenure tend to be more willing to invest in long-term systems like multi-strata agroforestry, while land tenure uncertainty is a major deterrent for other groups.

Overall, the patterns shown in the table underscore the importance of policy interventions that go beyond purely technical aspects. Efforts to expand agroforestry adoption need to be accompanied by institutional strengthening, particularly in terms of tenure reform and access to institutional support. Without a supportive policy framework, the potential of agroforestry as an inclusive and sustainable climate mitigation strategy will be difficult to realize broadly.

Uncertainty and Robustness

Uncertainty is an integral aspect of carbon stock estimation, especially when the analysis integrates various biophysical components such as aboveground biomass, belowground biomass, and soil organic carbon. To ensure that the results of this study are not only accurate but also reliable, uncertainty analysis and robustness tests were conducted on the resulting carbon stock estimates. This approach is crucial for assessing the extent to which variations in input parameters and methodological assumptions can influence the magnitude of the estimated carbon.

In this study, Monte Carlo simulations were used to propagate uncertainty from various sources and generate a range of estimates that reflect a level of statistical confidence. Furthermore, sensitivity analyses were conducted to test the stability of the results to changes in key parameters, such as the root-to-shoot ratio, a frequently debated source in carbon studies. Evaluation of the main sources of uncertainty also allows identification of which components contribute most to variation in the results, thus providing guidance for future methodological improvements. The following table summarizes the results of the uncertainty analysis and robustness tests for carbon stock estimates, while also demonstrating the consistency of land-use system rankings under various simulation scenarios.

Table 4. Uncertainty and Robustness Analysis of Carbon Stock Estimates

Component / Analysis Aspect	Metric / Scenario	Estimated Value	Interpretation
Total Carbon Stock (plot-level)	Mean estimate	215.0 Mg C ha^{-1}	Average total carbon estimate from the integration of AGB, BGB, and SOC
Uncertainty Range (Monte Carlo)	95% Confidence Interval	±14.3 Mg C ha^{-1}	Uncertainty range of total carbon from 10,000 simulations
Dominant Source of Uncertainty	Allometric equations	58% of total variance	Allometric variability as a major contributor to uncertainty
Secondary Source of Uncertainty	SOC measurement error	34% of total variance	Soil carbon measurement error
Minor Source of Uncertainty	Biomass sampling error	8% of total variance	Biomass sampling variation
Sensitivity Test (Root-to-shoot ratio)	–10% adjustment	–4.1% change in total C	Change in total carbon estimate
Sensitivity Test (Root-to-shoot ratio)	+10% adjustment	+4.6% change in total C	Change in total carbon estimate
Land-use System Ranking	Across simulations	Stable	Land system sequence unchanged

This table comprehensively illustrates the uncertainty and robustness of carbon stock estimates obtained through modeling and simulation approaches. The results indicate that although plot-level carbon estimates are not completely free from variation, the identified uncertainty ranges are still within acceptable limits for ecological and climate mitigation studies. This confirms that an integrative approach combining aboveground and belowground biomass and soil organic carbon is capable of producing scientifically reliable estimates.

Further analysis revealed that the primary source of uncertainty stems from methodological aspects, specifically the use of allometric equations and soil carbon measurements. This finding indicates that biological variation between species and soil heterogeneity play a significant role in influencing absolute carbon estimates. However, the contribution of uncertainty from the biomass sampling process was relatively small, indicating that the sampling design and field measurement procedures were carried out consistently and under control.

Sensitivity tests conducted on variations in the root-shoot ratio strengthened the robustness of the study results. Changes in key parameter assumptions resulted in only small shifts in total carbon estimates, thus concluding that the study results are not overly dependent on a single parameter value. This increases confidence in the model's stability and reduces the risk of bias due to structural parameter uncertainty.

Most importantly, the table shows that despite absolute uncertainty, the relative patterns between land-use systems remain consistent across simulations. This ranking stability has important implications for decision-making, as it confirms the robustness of comparative conclusions regarding land system performance in storing carbon. Therefore, the research results can be used reliably as a basis for policy formulation and planning of agroforestry-based climate change mitigation strategies.

Implications for Climate Mitigation and Policy

To assess the significance of this research's findings in the broader context of climate policy, it is necessary to map the empirical results into relevant indicators for decision-making. This type of evaluation allows agroforestry to be understood not only as a site-level land management practice but also as a strategic instrument within national and international climate change mitigation frameworks. Therefore, comparison with established conservation schemes, such as REDD+, is crucial for positioning agroforestry's performance relative to the spectrum of existing climate policies.

In addition to carbon mitigation performance, non-carbon aspects such as livelihood benefits, carbon leakage risks, and compatibility with market-based and non-market incentive mechanisms are also considered. This approach reflects the growing global policy push to integrate mitigation objectives with sustainable development and social equity agendas. At the same time, the identification of adoption barriers and monitoring challenges provides a realistic picture of the institutional and technical prerequisites that must be met for agroforestry to be effectively mainstreamed.

The following table summarizes key indicators relevant to climate mitigation and policy, positioning agroforestry systems in a conceptual comparison with REDD+-based conservation approaches. This presentation aims to highlight the relative advantages, limitations, and policy implications that need to be considered when integrating agroforestry into climate change mitigation strategies and nationally determined contribution targets (NDCs).

Table 5. Climate Mitigation and Policy-Relevant Indicators of Agroforestry Systems

Indicator	Agroforestry Systems	REDD+ Conservation (Reference Range)	Policy Relevance
Average carbon sequestration rate (t CO_2e ha^{-1} yr^{-1})	2.5	1.5–2.3	Competitive mitigation performance
Carbon leakage risk	Low	Moderate–High	Stronger permanence of benefits
Livelihood co-benefits (income change)	Positive	Neutral to limited	Supports pro-poor climate action

Eligibility for carbon credit schemes	High	High	Market-based mitigation potential
Suitability for PES programs	High	Moderate	Incentive-based adoption
Adoption constraint: insecure land tenure (%)	38	42	Key institutional barrier
Adoption constraint: limited credit access (%)	46	39	Financial access limitation
Data loss due to sensor biofouling (%)	12	8	Monitoring and MRV challenge
Scalability under national climate policy	High	Moderate	Alignment with NDC targets

The table shows that agroforestry holds a strategic position as a climate change mitigation instrument that is not only environmentally effective but also policy-relevant. Compared to purely protection-based conservation approaches, agroforestry offers competitive mitigation performance with a relatively lower risk of carbon leakage. This is primarily due to its integration into production systems, resulting in stable and sustainable land-use changes over the long term.

In addition to contributing to emissions mitigation, the table also highlights the strong socio-economic dimension of agroforestry. This system is consistently associated with improved household welfare, making it more inclusive than mitigation schemes that do not directly address community livelihoods. This characteristic strengthens the argument that agroforestry aligns with low-carbon development approaches oriented toward social equity and poverty reduction.

From a policy perspective, agroforestry demonstrates a high degree of compatibility with various climate incentive instruments, including carbon markets and payment for environmental services schemes. This flexibility allows agroforestry to be integrated into national and international policy frameworks without requiring major structural changes. Thus, agroforestry has the potential to serve as a bridge between climate mitigation policies and sustainable agricultural development policies.

However, the table also highlights implementation challenges that require serious attention. Institutional constraints such as tenure uncertainty and limited access to financing remain major barriers to adoption by smallholder farmers. Meanwhile, technical challenges in monitoring and reporting highlight the need to strengthen MRV systems that adapt to field conditions. Overcoming these barriers is a crucial prerequisite for ensuring that the potential of agroforestry can be optimally utilized on a broader scale.

Discussion

The results of this study consistently confirm that the complexity of vegetation structure is a key factor in determining the carbon storage and sequestration capacity of tropical land-use systems. The superiority of multi-strata agroforestry in storing carbon, both in biomass and soil, suggests that the integration of layered trees with agricultural crops can replicate some of the functions of natural forest ecosystems. These findings strengthen the theoretical argument that the presence of long-lived woody trees, deep root systems, and continuous organic matter flow creates a more stable carbon sequestration mechanism than extractive and short-term monoculture systems.

At the landscape scale, the consistency between remote sensing-based estimates and field data provides scientific legitimacy for the use of spatial approaches in agroforestry carbon assessments. This validation is important because it demonstrates that the complexity of agroforestry structure, often a challenge in tropical biomass modeling, can be adequately represented through the integration of satellite imagery and LiDAR. Thus, these results not only strengthen the reliability of the empirical findings but also open up opportunities for continuous agroforestry monitoring in the context of evidence-based climate policy planning.

The socio-economic discussion shows that the benefits of agroforestry are not limited to the environmental dimension but also have a significant impact on the welfare of farming households

(Gao et al., 2014). Causal findings indicate a synergy between increased income and strengthened climate mitigation functions, positioning agroforestry as an inclusive low-carbon development strategy. However, the central role of tenure security in driving adoption emphasizes that the success of agroforestry is highly dependent on the institutional context, so that purely technical policy interventions will be insufficient without institutional reforms that support long-term farmer investments.

From a climate policy and mitigation perspective, this study demonstrates agroforestry's strategic position as a competitive and adaptive land-based mitigation instrument. The robustness of the findings across various uncertainty scenarios reinforces the belief that comparative conclusions across land-use systems can inform decision-making (Müller-Hansen et al., 2017). By combining mitigation performance, livelihood benefits, and policy flexibility, agroforestry emerges as a bridging approach to climate and sustainable development goals, although its success at scale still requires institutional strengthening, access to financing, and reliable monitoring systems.

CONCLUSION

This study demonstrates that agroforestry systems represent a scientifically robust and socially viable strategy for mitigating climate change in tropical forest areas. Field inventories, geospatial analysis, and econometric modeling consistently revealed that multistrata agroforestry outperforms both shaded monocultures and conventional monocropping in terms of carbon sequestration capacity. On average, multistrata systems stored more than 230 Mg C ha^{-1}, nearly four times greater than monocropping plots, and contributed to a landscape-level mitigation gain of 2.1 Mt CO_2e between 2013 and 2023. Beyond biophysical benefits, socio-economic analysis confirmed that agroforestry adoption simultaneously enhances farmer livelihoods, with adopters earning an additional USD 315 ha^{-1} yr^{-1} while sequestering more carbon than their counterparts. This dual functionality positions agroforestry as a cornerstone of climate-smart development, aligning local livelihood imperatives with global climate targets. However, adoption is mediated by structural barriers, including tenure insecurity, limited credit access, and extension gaps, which constrain widespread implementation. The integration of Bayesian uncertainty analysis and validation with remote sensing further strengthens the robustness of these findings, ensuring that results are not only locally relevant but also scalable for policy frameworks such as REDD+ and voluntary carbon markets. By coupling ecological resilience with socio-economic co-benefits, agroforestry systems emerge as a low-cost, high-impact mitigation pathway that can complement forest conservation and restoration initiatives.

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