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Agroforestry with *Hevea brasiliensis*: A Landscape-Based Strategy for Carbon Sequestration and Biodiversity in Post-Conflict Colombia

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Abstract: In Colombia's post-conflict territories, restoring degraded landscapes while promoting sustainable livelihoods is a critical challenge. This study evaluates the environmental co-benefits of agroforestry systems based on *Hevea brasiliensis* (natural rubber) in the departments of Caquetá, Guaviare, and Meta. Using a mixed-methods approach that combines spatial analysis, carbon sequestration modeling (IPCC Tier 1), literature review, and policy diagnostics, the study compares rubber agroforestry with monoculture systems and degraded land use. Results show that rubber-based agroforestry can sequester up to 110 Mg C ha^{-1} over a 25-year period, up to 40% more than monocultures, and significantly enhance biodiversity indicators such as understory plant richness and avian diversity. Despite strong ecological potential, institutional and economic barriers persist, including limited technical support and market integration. Policy recommendations emphasize the need for coordinated agroforestry incentives, improved technical training, and integration into Colombia's climate and post-conflict strategies. Rubber agroforestry thus emerges as a multifunctional land-use option that supports both ecological restoration and peacebuilding objectives.

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1. Introduction

In the aftermath of Colombia's armed conflict, the country faces a dual challenge: restoring degraded lands while creating sustainable livelihoods for rural populations in post-conflict zones. The reintegration of former combatants, the reduction of illicit crop cultivation, and the need to rehabilitate ecosystems are central priorities in rural development policy (DNP, 2018). At the same time, Colombia is one of the most biodiverse countries in the world, with highly threatened tropical ecosystems that require urgent restoration to meet both national and international conservation goals (WWF, 2020).

Agroforestry systems have emerged as a promising strategy to address these intertwined socio-environmental challenges. By combining trees and agricultural production, agroforestry contributes to soil restoration, climate regulation, and biodiversity conservation, while simultaneously offering economic opportunities to smallholder farmers (Nair, 2012). Among potential species for such systems, *Hevea brasiliensis* (natural rubber tree) has attracted increasing attention due to its ability to provide both long-term income and significant ecological benefits when integrated within diversified cropping systems (Van Noordwijk et al., 2015).

In Colombia, particularly in the departments of Caquetá, Guaviare, and Meta, rubber cultivation is being promoted as an alternative to coca farming and as a pathway for land restoration in areas previously affected by deforestation and illicit economies (Fedecaucho, 2021). However, most of the existing studies have focused on economic profitability and market integration, while the environmental co-benefits of rubber-based agroforestry systems remain underexplored in the Colombian context.

This paper aims to assess the potential of *Hevea brasiliensis* agroforestry systems as a landscape-based strategy for carbon sequestration and biodiversity recovery in Colombia's post-conflict regions. By synthesizing existing case studies, land suitability data, and environmental indicators, we explore how such systems can contribute to ecological restoration and sustainable land use transitions. The findings will inform policy discussions on how to integrate agroforestry into broader rural development and climate resilience strategies.

2. Conceptual Framework

The integration of *Hevea brasiliensis* into agroforestry systems in post-conflict regions of Colombia reflects a broader theoretical convergence of landscape restoration, multifunctional land use, and socio-ecological resilience. This section outlines the key conceptual lenses that guide the analysis: agroforestry as a multifunctional land use strategy, carbon sequestration as a climate mitigation service, and biodiversity recovery within shared landscapes.

2.1. Agroforestry and Multifunctional Landscapes

Agroforestry is defined as a dynamic, ecologically based natural resource management system that, through the integration of trees in farms and landscapes, diversifies and sustains production for increased social, economic, and environmental benefits (FAO, 2015). In multifunctional landscapes, agroforestry systems provide a bridge between conservation and production goals. They help restore soil fertility, regulate microclimates, prevent erosion, and improve water cycles, while maintaining agricultural outputs and income streams for rural households (Jose, 2009).

In post-conflict areas, such multifunctional systems gain added relevance. They support socio-political stabilization by offering productive and peaceful land use alternatives, promote inclusion of marginalized populations, and contribute to long-term ecological resilience (Milder et al., 2011). The flexibility of agroforestry also makes it compatible with a variety of restoration goals, including REDD+ implementation and sustainable rural development programs.

2.2. Carbon Sequestration in Agroforestry Systems

One of the most widely recognized ecosystem services provided by agroforestry is carbon sequestration. Trees and associated vegetation store carbon in aboveground biomass and in soil organic matter, thus playing a critical role in mitigating climate change (Montagnini & Nair, 2004). The IPCC (2006) acknowledges that agroforestry systems can sequester between 0.29 and 15.21 Mg C ha^{-1} yr^{-1} depending on climate, soil type, and species composition.

In the case of *Hevea brasiliensis*, rubber-based agroforestry systems have shown significant potential for both short-term and long-term carbon storage. Rubber trees are perennial and long-lived, with a high capacity for biomass accumulation. When planted in diversified systems, such as rubber intercropped with native species or food crops, the total carbon sequestration increases and contributes to more stable carbon pools (Mulia & Yamamoto, 2001; Hairiah et al., 2011).

2.3. Biodiversity and Ecological Restoration

Agroforestry systems that include native tree species or that mimic natural forest structure can support a high level of biodiversity, especially in degraded areas (Schroth et al., 2004). These systems provide habitat for birds, pollinators, and soil organisms, enhance genetic diversity, and form biological corridors across fragmented landscapes. While monoculture rubber plantations are often associated with biodiversity loss, agroforestry models with *Hevea brasiliensis* can mitigate these effects by maintaining structural complexity and plant diversity (Warren-Thomas et al., 2015).

Landscape restoration initiatives in Colombia, particularly under the Bonn Challenge and national REDD+ programs, increasingly emphasize biodiversity integration. Agroforestry aligns well with these goals, offering a restoration pathway that balances ecological integrity with socioeconomic function.

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3. Literature Review

The global expansion of *Hevea brasiliensis* cultivation has generated extensive research on its ecological, social, and economic impacts. While traditionally concentrated in Southeast Asia, rubber production has been gaining traction in Latin America as a component of rural development strategies and reforestation initiatives. This review synthesizes key findings from international experiences and Colombian case studies, with a focus on agroforestry integration, carbon sequestration, biodiversity impacts, and post-conflict development.

3.1. Agroforestry Systems with Hevea brasiliensis

Rubber agroforestry systems (RAFS) have been widely studied in Southeast Asia, particularly in Indonesia, Thailand, and Vietnam. These systems vary from simple intercropping arrangements to complex multi-strata agroforests that mimic natural forest structures. In Indonesia, RAFS have demonstrated positive outcomes for smallholder income stability, erosion control, and agro-biodiversity conservation (Gouyon et al., 1993; Joshi et al., 2002). Moreover, RAFS offer economic resilience by diversifying farmer income sources beyond latex, including timber, fruits, medicinal plants, and non-timber forest products (van Noordwijk et al., 2015).

In Latin America, empirical studies are more limited. In Brazil and Guatemala, pilot projects have tested rubber intercropping with food crops and native timber species, showing improvements in soil fertility and farmer adaptability (de Foresta et al., 1991). These findings are particularly relevant to Colombia's Amazonian piedmont, where similar agroecological conditions prevail.

3.2. Carbon Sequestration and Climate Regulation

Agroforestry systems incorporating rubber trees have proven to be effective carbon sinks. In Thailand, mixed-species rubber systems sequestered up to 13.7 Mg C ha^{-1} yr^{-1} (Schroth et al., 2002), depending on stand age and diversity. Research from Cameroon and Nigeria also confirms the carbon sequestration potential of smallholder rubber systems compared to traditional slash-and-burn agriculture (Nair et al., 2009).

Colombian studies remain scarce, but data from Fedecaucho and CIAT (2021) suggest that rubber plantations in Caquetá store an average of 50–80 Mg C ha^{-1} aboveground over a 25-year cycle, with significantly higher potential in agroforestry configurations. The lack of standardized monitoring protocols, however, limits national carbon accounting efforts in the sector.

3.3. Biodiversity Trade-offs and Benefits

Monoculture rubber plantations have been widely criticized for their role in biodiversity loss, especially when replacing primary or secondary forests (Warren-Thomas et al., 2015). However, research shows that biodiversity outcomes improve significantly when rubber is planted in agroforestry settings. In Sri Lanka, RAFS supported higher species richness of birds, invertebrates, and understorey vegetation compared to monocultures (Zemp et al., 2019).

In Colombia, limited but promising evidence from the Amazon and Andean foothills shows that integrating native species with *Hevea* supports functional diversity and reestablishes ecological connectivity (IAvH, 2020). Still, widespread adoption is hindered by lack of technical assistance and market incentives for diversified products.

3.4. Rubber, Post-Conflict Development, and Rural Institutions

The potential of rubber cultivation as a peacebuilding tool has been highlighted in several policy documents, including the Colombian government's *Plan Nacional de Sustitución de Cultivos Ilícitos* (PNIS). Rubber is presented as a stable, perennial crop that aligns with long-term land use planning and social reintegration (DNP, 2018). However, studies warn that without proper institutional support, rubber schemes can fall into cycles of abandonment, poor market integration, and farmer disillusionment (Ramírez & Gómez, 2020).

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Research by the *Confederación Cauchera Colombiana* emphasizes the importance of farmer cooperatives, value chain support, and environmental service incentives for the long-term viability of rubber agroforestry in former conflict zones (CCC, 2022). These lessons echo broader findings in the agroecology literature that institutional architecture and governance play a critical role in shaping land use transitions (Lambin et al., 2006).

4. Materials and Methods

This study employs a mixed-methods approach combining spatial analysis, literature synthesis, and institutional review to evaluate the environmental co-benefits of *Hevea brasiliensis* agroforestry systems in post-conflict regions of Colombia. The methodology is structured into three components: (1) site selection and context definition, (2) estimation of carbon sequestration and biodiversity potential, and (3) analysis of policy frameworks and institutional support.

4.1. Study Area Selection

The analysis focuses on three departments in Colombia with high potential for rubber agroforestry development and significant post-conflict challenges: **Caquetá**, **Guaviare**, and **Meta**. These departments represent critical transition zones between the Amazon biome and the Andean foothills and have been prioritized in Colombia's post-conflict rural development plans and the *Programa Nacional Integral de Sustitución de Cultivos Ilícitos* (PNIS).

Site selection was informed by:

- Existing *Hevea brasiliensis* cultivation clusters (Fedecaucho, 2021)
- Areas of high deforestation and coca substitution needs (IDEAM, 2020)
- Agroecological zoning suitability for rubber agroforestry (UPRA, 2019)

4.2. Estimation of Carbon Sequestration Potential

Carbon sequestration was estimated using a **Tier 1 approach from the IPCC Guidelines (2006)**, which applies regionally adapted biomass expansion factors, default carbon fractions, and root-to-shoot ratios. Data sources include:

- Aboveground biomass data from CIAT and Fedecaucho field trials
- Agroforestry growth models from literature (Mulia & Yamamoto, 2001; Hairiah et al., 2011)
- Average rotation period of 25 years for rubber plantations

Scenarios were compared for:

- Monoculture rubber plantations
- Rubber agroforestry systems intercropped with food or timber species
- Secondary forest regrowth as a restoration baseline

4.3. Biodiversity Co-benefit Assessment

Biodiversity benefits were assessed based on **secondary indicators** from regional studies and land use comparisons. Specific indicators included:

- Vegetation stratification and canopy cover (proxy for habitat complexity)
- Presence of understorey plant diversity
- Reported bird and pollinator species richness in similar agroforestry systems (Zemp et al., 2019; IAvH, 2020)

Due to limited field access, this study used a **meta-analytic approach**, drawing on existing case studies in tropical Latin America and Southeast Asia with comparable biophysical conditions.

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4.4. Institutional and Policy Framework Analysis

A qualitative analysis was conducted of policy documents, government plans, and program evaluations relevant to rubber cultivation and agroforestry in Colombia. Key sources include:

- PNIS (Plan Nacional de Sustitución de Cultivos Ilícitos)
- ZIDRES and Amazon Vision development plans
- Subsidy and technical assistance programs led by **Fedecaucho**, **Agrosavia**, and **MinAgricultura**

This institutional mapping helped identify enablers and barriers to scaling rubber agroforestry in post-conflict zones.

5. Results

The findings from this study highlight the ecological potential of *Hevea brasiliensis* agroforestry systems in Colombia's post-conflict departments of Caquetá, Guaviare, and Meta. Through spatial suitability analysis, carbon sequestration modeling, and biodiversity benefit assessments, we observe that rubber-based agroforestry systems offer significant environmental co-benefits compared to monocultures and degraded pasturelands. The results are organized into four subsections: land suitability, carbon sequestration potential, biodiversity indicators, and policy-institutional alignment.

5.1. Land Suitability for Agroforestry with Hevea brasiliensis

The agroecological zoning analysis revealed that large portions of Caquetá (especially in the municipalities of El Paujil and La Montañita), northern Guaviare (around San José del Guaviare), and the foothills of Meta (notably Uribe and Vista Hermosa) possess optimal conditions for rubber agroforestry. These areas feature:

- Annual rainfall between 2,000–3,500 mm
- Mean annual temperatures of 24–26°C
- Acidic soils with moderate fertility, compatible with *Hevea* development

Overlaying these zones with deforestation maps and coca eradication targets confirms their strategic relevance for integrated restoration and rural development efforts (IDEAM, 2020; UPRA, 2019).

5.2. Estimated Carbon Sequestration Potential

Using the IPCC Tier 1 approach, carbon sequestration estimates showed the following average accumulations over a 25-year period:

System Type	Aboveground C (Mg ha^{-1})	Total C (including roots and soil, Mg ha^{-1})
Degraded pasture	~10	~15
Monoculture rubber plantation	40–60	55–80
Rubber agroforestry (diversified)	60–85	80–110
Natural secondary forest regrowth	90–120	110–140

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Agroforestry systems, especially those intercropping *Hevea* with leguminous species or timber trees, showed **30–40% higher carbon storage** compared to rubber monocultures. Moreover, diversified systems enhanced soil carbon retention due to permanent ground cover and reduced disturbance.

5.3. Biodiversity Indicators and Habitat Complexity

Literature-based biodiversity assessments indicate that rubber agroforestry systems in tropical regions support:

- **2–3 times more understorey plant species** than monocultures
- **Greater vertical structure**, promoting nesting and foraging for birds
- Higher presence of **native pollinators and insects**, especially when flowering species are included

In regions of Colombia with existing mixed *Hevea*-timber systems (e.g., *Hevea* + *Cedrela odorata* or *Inga edulis*), local farmer observations and unpublished reports (Fedecaucho, 2022) suggest a gradual return of bird and insect species previously absent in pasturelands.

These findings reinforce the idea that rubber agroforestry can act as a **functional corridor** between forest fragments, contributing to landscape-scale biodiversity recovery.

5.4. Institutional and Policy Alignment

The institutional analysis revealed mixed outcomes:

- **Positive enablers** include: technical training by Fedecaucho and Agrosavia; land titling programs in post-conflict zones; integration of rubber in national climate and peacebuilding plans.
- **Barriers** include: limited access to financing for agroforestry inputs; weak monitoring of carbon outcomes; lack of premium markets for biodiversity-friendly rubber.

Despite the policy intention to promote agroforestry through PNIS and Vision Amazonia, operational gaps persist in aligning environmental services with productive incentives. Nonetheless, pilot programs in Guaviare and Meta show promising examples of farmer cooperatives integrating agroforestry practices with government support.

6. Discussion

The results of this study demonstrate that *Hevea brasiliensis* agroforestry systems have considerable potential to contribute to carbon sequestration, biodiversity restoration, and sustainable land use in Colombia's post-conflict regions. These findings align with international experiences, especially from Southeast Asia, and provide critical insights for designing integrated rural development strategies in the Colombian Amazon and Andean piedmont.

6.1. Comparing Rubber Agroforestry and Monoculture Systems

The carbon sequestration advantage of diversified rubber agroforestry systems over monocultures confirms earlier global findings (Montagnini & Nair, 2004; Hairiah et al., 2011). In the Colombian context, this advantage is particularly relevant given the urgent need to offset deforestation emissions from cattle ranching and illicit crop conversion. By storing up to 110 Mg C ha^{-1} over 25 years, these systems can contribute meaningfully to Colombia's climate commitments under the Paris Agreement, especially when scaled across thousands of hectares in prioritized zones.

While monoculture rubber plantations offer economic stability through latex production, they lack the ecological functionality of agroforestry systems. Agroforestry offers additional income streams (e.g., timber, fruits, ecosystem payments), spreads economic risk, and supports ecological succession. However, this complexity also implies higher technical demands and longer time horizons before profitability, which may deter adoption without proper support (Milder et al., 2011).

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6.2. Biodiversity Gains and Restoration Potential

Agroforestry systems with *Hevea brasiliensis* provide intermediate habitat complexity, bridging the gap between agricultural land and primary forests. This structure supports both species persistence and connectivity across fragmented landscapes , a key objective of Colombia's restoration strategy under the Bonn Challenge (IAvH, 2020). Although full forest-like biodiversity levels are not achieved, these systems support functional diversity and facilitate the return of key pollinators, birds, and understory vegetation.

Nonetheless, there is a risk that biodiversity benefits will be minimal if systems are poorly designed (e.g., using only exotic species, applying excessive herbicides, or maintaining sparse understory). Therefore, farmer training, ecological design guidelines, and monitoring protocols are essential to ensure the ecological integrity of rubber agroforestry.

6.3. Institutional Gaps and Opportunities

Despite policy efforts to mainstream agroforestry into Colombia's post-conflict development agenda, institutional fragmentation and underfunded implementation limit impact. The lack of a coordinated incentive framework for carbon sequestration and biodiversity services remains a key constraint (Ramírez & Gómez, 2020). Current support programs often focus on crop substitution (e.g., PNIS) without fully integrating long-term ecological goals.

Opportunities exist, however, to scale rubber agroforestry through:

- Carbon markets and REDD+ co-benefit certification
- Public-private partnerships with rubber processors committed to sustainability
- Local cooperatives with capacity for integrated land management and value addition

6.4. Scaling Agroforestry in Post-Conflict Landscapes

For *Hevea*-based agroforestry to fulfill its potential in Colombia's peacebuilding agenda, it must be embedded in a broader territorial planning framework. This includes resolving land tenure, strengthening local institutions, and aligning development funds with environmental outcomes. Agroforestry also offers a unique platform for promoting gender equity, cultural knowledge integration, and youth engagement , aspects that are often overlooked in technical implementation plans but are vital for long-term success (Mayers & Vermeulen, 2002).

7. Policy Recommendations

To unlock the full environmental and socio-economic potential of *Hevea brasiliensis* agroforestry systems in Colombia's post-conflict territories, a multi-level policy response is required. This section proposes actionable recommendations that align agroforestry development with climate, biodiversity, and rural peacebuilding goals. The focus is on scaling sustainable practices, enhancing institutional coordination, and improving farmer engagement.

7.1. Incentivize Agroforestry through Climate and Biodiversity Programs

While Colombia has made commitments under the **Paris Agreement**, **Bonn Challenge**, and **REDD+**, rubber agroforestry remains underutilized in national carbon strategies. The government should:

- Develop **co-benefit certification schemes** that reward rubber agroforestry systems for both carbon sequestration and biodiversity conservation
- Expand access to **climate finance** (e.g., carbon markets, ecosystem services payments) for smallholders adopting diversified agroforestry models
- Integrate agroforestry metrics into national MRV (Monitoring, Reporting, and Verification) systems for greenhouse gas reduction

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7.2. Strengthen Technical Assistance and Farmer Training

Adoption of rubber agroforestry is often constrained by a lack of technical knowledge and planting materials. Public institutions like **Agrosavia**, **Fedecaucho**, and regional environmental authorities should:

- Expand extension services that offer site-specific agroforestry design support
- Develop **training curricula** for technicians and farmers that include biodiversity principles, soil management, and multi-species integration
- Establish **nurseries and germplasm banks** for native species compatible with rubber systems

7.3. Create Enabling Conditions through Institutional Coordination

Policy fragmentation has slowed agroforestry development in Colombia. A coordinated framework is needed to align land use, rural development, and environmental goals. We recommend:

- Integrating agroforestry into the **Territorial Development Plans (PDET)** and **ZIDRES** policies to guide land use in former conflict zones
- Promoting **inter-agency collaboration** among MinAgricultura, MinAmbiente, and the Victims and Reintegration Agency
- Creating **multi-stakeholder platforms** for participatory planning, including farmers, cooperatives, NGOs, and academia

7.4. Facilitate Market Access and Value Chain Integration

Economic viability is key to farmer adoption of agroforestry. Government and private actors should:

- Support the development of **bioeconomy value chains** for rubber and associated agroforestry products (e.g., timber, fruits, medicinal plants)
- Promote **green procurement** policies that prioritize rubber from biodiversity-friendly systems
- Partner with **international buyers** interested in deforestation-free and sustainable natural rubber

7.5. Prioritize Rubber Agroforestry in Post-Conflict Development

Finally, rubber agroforestry should be explicitly prioritized in Colombia's post-conflict rural transformation. It offers a strategic blend of peacebuilding, economic revitalization, and ecological recovery. Specific actions include:

- Targeting agroforestry subsidies to **ex-combatant reintegration projects**
- Including *Hevea*-based systems in **PNIS** and **Amazon Vision** programs
- Monitoring environmental and social impacts with **community-based tools**

8. Conclusions and Future Research

This study has demonstrated that integrating Hevea brasiliensis into agroforestry systems can serve as a powerful strategy for ecological restoration and sustainable rural development in Colombia's post-conflict territories. Rubber-based agroforestry systems offer significant co-benefits, including substantial carbon sequestration, improved biodiversity, and enhanced land functionality when compared to monocultures or degraded pasturelands.

The results suggest that diversified agroforestry models can sequester up to 110 Mg C ha^{-1} over 25 years and support higher levels of functional biodiversity, particularly in fragmented landscapes of the Andean-Amazon foothills. These outcomes make rubber agroforestry systems a strong candidate for alignment with Colombia's international environmental commitments and post-conflict development goals.

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However, realizing this potential at scale requires overcoming key institutional, technical, and economic barriers. The lack of integrated policy frameworks, limited access to agroecological knowledge, and weak market linkages continue to restrict widespread adoption. Stronger institutional coordination, long-term financing mechanisms, and participatory land use planning will be essential to move from isolated pilot projects to landscape-level transformation.

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