Forest Landscape Transformation and Rural Development: A Socio-Economic Analysis of Rubber (*Hevea brasiliensis*) Expansion in Colombia and Southeast Asia

Luis David Villarreal Patiño *

Posted Date: 7 May 2025

doi: 10.20944/preprints202505.0398.v1

Keywords: rubber plantations; land use change; forest conversion; socio-economic analysis; climate adaptation; Colombia; Indonesia; rural development

 doi:10.20944/preprints202505.0398.v1

Article

Balancing Economic Growth and Ecosystem Services: A Socio-Economic Analysis of Rubber (*Hevea brasiliensis*) Expansion in Post-Forest Landscapes in Colombia and Southeast Asia

Luis David Villarreal Patiño

Department of Economics and Management of Forestry and Wood Industry, Czech University of Life Sciences Prague; villarreal_patino@fld.czu.cz

Abstract: Natural rubber (*Hevea brasiliensis*) cultivation is increasingly promoted as a strategy for rural development in tropical regions, particularly in post-forest landscapes in Southeast Asia and Latin America. This study critically examines the socio-economic and environmental impacts of rubber plantation expansion, drawing on comparative case studies from Jambi Province (Indonesia) and the departments of Caquetá and Tolima (Colombia). Results indicate that while rubber contributes substantially to rural economies, significant trade-offs occur, including carbon stock reduction, biodiversity loss, and increased vulnerability under climate change scenarios. Productivity variations, weak market integration, and fragmented governance further constrain the sector's developmental potential. Social influence and selective exposure to overly optimistic narratives about rubber's benefits also shape adoption patterns, often leading to uninformed or misinformed decision-making at the smallholder level. We argue that integrating rubber cultivation into diversified, climate-adaptive, and landscape-based strategies is essential to balance economic growth with ecological sustainability. The findings emphasize the need for more coherent governance, stronger technical support, and transparent information dissemination to empower rural communities towards sustainable land use transitions.

Keywords: natural rubber; land use change; rural development; carbon sequestration; climate adaptation; agroforestry; socio-economic analysis; Colombia; Indonesia; tropical forestry

1. Introduction

Natural rubber (*Hevea brasiliensis*) has become one of the most important global commodities produced in tropical regions, not only for its industrial applications but also for its growing role in rural development policies. Originally native to the Amazon basin, the species has been widely planted in Southeast Asia and, more recently, in parts of Latin America, particularly Colombia. The expansion of rubber plantations often follows the conversion of tropical forests and shifting agricultural mosaics, presenting a complex interplay between socio-economic gains and ecological costs (Clough et al., 2016; Schwarze et al., 2015).

In Southeast Asia, particularly in Indonesia and Laos, rubber monocultures have been associated with marked declines in biodiversity, soil quality, and carbon storage, even while providing substantial income improvements for smallholders (Schwarze et al., 2015; Phompila et al., 2017). In Colombia, particularly in regions such as Caquetá, Tolima, and Guaviare, rubber cultivation is emerging as an alternative for post-conflict rural economies seeking sustainable development pathways (Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023; Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020; Ramírez et al., 2018).

These regions are characterized by historical processes of colonization, land tenure informality, and delicate socio-ecological balances, where agricultural expansion historically led to deforestation and degradation (Basto Monsalve et al., 2023).

 doi:10.20944/preprints202505.0398.v1

The tension between the economic promises of rubber cultivation and the environmental consequences of land-use change raises critical concerns. While rubber plantations can foster rural employment, infrastructure development, and regional GDP growth (Dewi Sri Nurchaini Nainggolan, & Mulia Sari, 2024), they often replace ecosystems with high conservation value, thereby exacerbating carbon emissions, water cycle alterations, and biodiversity loss (Kongsager, Napier, & Mertz, 2013; Schwarze et al., 2015). Moreover, climate change projections suggest increasing challenges for rubber productivity in traditionally suitable areas (Basto Monsalve et al., 2023), calling into question the long-term viability of expanding monocultures without adaptive strategies.

A persistent challenge is the selective exposure of rural populations to certain narratives about rubber development. Smallholders and policymakers alike are often exposed primarily to success stories emphasizing economic gains, while critical ecological impacts and vulnerabilities are under-communicated or ignored. Theories of selective exposure and social influence suggest that these patterns are not random but shaped by power asymmetries, access to information, and local social networks (Schwarze et al., 2015).

Consequently, plantation adoption decisions are not purely rational but embedded in broader processes of social persuasion and expectation management.

Despite a growing body of research on rubber's environmental impacts and economic potential, integrated analyses that simultaneously assess socio-economic and ecological outcomes remain scarce (Clough et al., 2016; López Santana, Méndez Giraldo, & Franco, 2021). There is a particular lack of studies bridging experiences from Southeast Asia with emerging cases in Latin America, despite clear parallels in terms of forest frontier dynamics, smallholder strategies, and global commodity pressures.

The objective of this study is to critically analyze the socio-economic and environmental implications of rubber plantation expansion, using a comparative lens between Southeast Asia (particularly Indonesia) and Colombia (Caquetá and Tolima departments). By doing so, we aim to contribute to a more nuanced understanding of how rubber can (or cannot) balance economic development with ecological sustainability in tropical regions undergoing rapid land use transitions. Ultimately, the goal is to inform more equitable and resilient rural development strategies in Colombia and beyond.

2. Literature Review

2.1. Land Use Change and Rubber Plantation Expansion

Land use change in tropical regions is strongly driven by the expansion of commercial crops such as rubber, oil palm, and soy (Clough et al., 2016; Phompila, Lewis, Ostendorf, & Clarke, 2017). In Southeast Asia, particularly in Indonesia, the EFForTS project documented how lowland rainforests were progressively converted into jungle rubber agroforests and later into monocultures of rubber and oil palm (Clough et al., 2016). While jungle rubber maintained relatively higher biodiversity and ecosystem services compared to monocultures, further intensification sharply diminished these values.

Similarly, in Colombia, particularly in post-conflict regions like Caquetá, rubber plantations have been promoted as a sustainable development alternative (Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023). Yet, land suitability modeling indicates that climate change will increasingly affect both current and potential rubber-growing areas, raising concerns about the long-term viability of expansion strategies (Basto Monsalve et al., 2023).

Studies in Laos also suggest that the expansion of rubber is influenced not only by biophysical suitability but by socio-economic factors such as market access and infrastructure development (Phompila et al., 2017). These findings reinforce that plantation expansion cannot be understood solely through environmental or economic lenses but must integrate complex social drivers.

 doi:10.20944/preprints202505.0398.v1

2.2. Socio-Economic Drivers: Income, Labor, and Land Strategies

Rubber plantations are often positioned as engines of rural development. In Jambi Province, Indonesia, empirical research revealed that while land productivity of rubber was higher compared to oil palm, labor productivity was lower, making rubber more attractive for land-scarce households (Dewi Sri Nurchaini, Nainggolan, & Mulia Sari, 2024). This division of strategy based on household resource endowments is central to understanding farmer decision-making.

In Colombia, similar dynamics emerge. Studies in San José del Guaviare show that rubber plantation initiatives seek to stabilize rural economies and mitigate deforestation pressures (Ramírez et al., 2018). However, structural weaknesses, low technical assistance, poor infrastructure, and weak market linkages, often blunt the anticipated benefits (Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020).

Moreover, significant productivity gaps between plantations suggest that outcomes are shaped by access to technical knowledge, credit, and producer organizations (Dewi Sri Nurchaini et al., 2024; Orjuela Garzón et al., 2020). Thus, simplistic narratives presenting rubber as a one-size-fits-all development solution must be critically interrogated.

2.3. Environmental Trade,offs: Carbon Sequestration, Biodiversity, and Ecosystem Services

Conversion of forests into rubber monocultures entails severe environmental consequences. The EFForTS project showed that forest-to-rubber transitions led to a 60% reduction in above-ground carbon stocks compared to intact forests (Clough et al., 2016). Although rubber plantations store more carbon than pasture or degraded lands, they perform substantially worse than natural forests (Kongsager, Napier, & Mertz, 2013).

Biodiversity losses are particularly acute. While jungle rubber systems preserve higher species richness relative to monocultures (Clough et al., 2016), they still cannot replicate the ecosystem functionality of natural forests. In Colombia, if rubber expansion proceeds without integrating agroforestry models or territorial planning, it may worsen biodiversity loss and landscape fragmentation (Basto Monsalve et al., 2023; Orjuela Garzón et al., 2020).

Consequently, the environmental impacts of rubber expansion are highly context-dependent but generally negative when it replaces forest ecosystems rather than degraded lands.

2.4. Selective Exposure, Social Influence, and Plantation Adoption

Theories of selective exposure (Frey, 1986) and social influence (Cialdini & Goldstein, 2004) provide critical frameworks to understand how rubber adoption spreads. Selective exposure theory posits that individuals gravitate towards information that confirms their aspirations, such as promises of prosperity, while discounting information about risks.

In Colombia, promotional narratives around rubber cultivation tend to highlight economic success stories while underplaying environmental risks and climate vulnerability (López Santana, Méndez Giraldo, & Franco, 2021; Orjuela Garzón et al., 2020). Social influence dynamics compound this, as smallholders often emulate early adopters perceived as successful (Ramírez et al., 2018).

Such informational asymmetries shape plantation adoption patterns in ways that are not purely rational but deeply embedded in community expectations and social signaling.

2.5. Gaps in Current Research and Policy

Although significant advances have been made by projects such as EFF or TS and SURUMER (Clough et al., 2016; Schwarze et al., 2015), critical gaps remain. Much research isolates either the socio-economic or environmental impacts of rubber, with few studies integrating these dimensions holistically.

In Colombia, despite the availability of sectoral diagnostic models (López Santana et al., 2021), they have not been systematically integrated into climate-resilient land use planning (Basto Monsalve et al., 2023). Technical agendas for regions like Tolima outline necessary improvements in

 doi:10.20944/preprints202505.0398.v1

productivity and marketing (Orjuela Garzón et al., 2020), but they often neglect the governance and informational reforms needed to ensure equitable and sustainable outcomes.

An integrated, multi-scalar, and socially aware approach is urgently needed to move beyond plantation expansion as a narrow development fix towards resilient territorial strategies.

3. Methodology

3.1. Research Design

This study employs a **comparative case study approach** to analyze the socio-economic and environmental impacts of rubber plantation expansion in two tropical contexts: (1) Southeast Asia, focusing on Jambi Province, Indonesia; and (2) Colombia, focusing on the departments of Caquetá and Tolima.

A **mixed-methods framework** was used, combining document analysis, secondary socio-economic data, and spatial modeling results from existing research (Clough et al., 2016; Schwarze et al., 2015; Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023; Dewi Sri Nurchaini, Nainggolan, & Mulia Sari, 2024; Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020).
The comparative analysis allows for identifying both generalizable patterns and regional specificities, particularly regarding rural development trajectories, climate vulnerability, and ecosystem service trade-offs.

3.2. Data Sources

The study draws upon four main types of sources:

- **Scientific Studies and Project Reports:**

The EFForTS and SURUMER projects (Clough et al., 2016; Schwarze et al., 2015), national analyses of rubber sector development in Colombia (Ramírez et al., 2018; Basto Monsalve et al., 2023; Orjuela Garzón et al., 2020), and regional land use change studies (Phompila, Lewis, Ostendorf, & Clarke, 2017).

- **Socio-Economic Statistics:**

Gross Regional Domestic Product (GRDP) contributions, employment rates, and productivity indicators from Jambi Province (Dewi Sri Nurchaini et al., 2024) and Colombian agricultural sector databases (Agronet, DANE).

- **Spatial Modeling Outputs:**

Land suitability projections for rubber cultivation under various future climate scenarios, particularly for Caquetá Department (Basto Monsalve et al., 2023).

- **Sectoral Diagnostic Models:**

Frameworks for strategic rural planning and productivity enhancement as developed in Colombian sectoral policy documents (López Santana, Méndez Giraldo, & Franco, 2021).

In addition, policy documents, regional development plans, and technical agendas were reviewed to assess the governance landscape (Orjuela Garzón et al., 2020).

3.3. Analytical Framework

The analysis was structured along three interrelated dimensions:

3.3.1. Socio-Economic Performance

- **Indicators:**

Rubber's contribution to GRDP, labor absorption capacity, and productivity metrics (tons/hectare/year).

- **Methods:**
    - Descriptive statistical comparison.

 doi:10.20944/preprints202505.0398.v1

- Calculation of Location Quotients (LQ) and Shift-Share Analysis for economic competitiveness in Jambi (Dewi Sri Nurchaini et al., 2024).
- Cross-referencing agricultural GRDP and employment data for Colombian departments (Ramírez et al., 2018; Orjuela Garzón et al., 2020).

3.3.2. Environmental Impact Assessment

- **Indicators:**

Changes in carbon stocks post-forest conversion (Kongsager, Napier, & Mertz, 2013; Clough et al., 2016), biodiversity loss metrics, and projected climate suitability for rubber (Basto Monsalve et al., 2023).

- **Methods:**
  - Synthesis of ecological field studies and meta-analyses.
  - Integration of IPCC AR5,based climate projections for the Colombian Amazon region.

3.3.3. Governance and Social Dynamics

- **Indicators:**

Presence of land use planning instruments, availability of extension services, and prevalence of success-oriented rubber adoption narratives.

- **Methods:**
  - Content analysis of regional planning documents (López Santana et al., 2021; Orjuela Garzón et al., 2020).
  - Application of selective exposure and social influence theories to interpret plantation adoption patterns (Frey, 1986; Cialdini & Goldstein, 2004).

3.4. Comparative Logic

The comparative analysis is guided by a **most-similar-systems design**, given that both Jambi and the Colombian Amazon share key characteristics: tropical climate, agricultural frontier expansion histories, smallholder predominance, and exposure to global commodity markets. However, differences in historical trajectories, policy frameworks, and social dynamics offer critical insights into the contingent nature of rubber expansion outcomes.

By systematically comparing these two cases, the study aims to distill both context-specific lessons and broader principles for balancing rural development and ecosystem conservation in tropical landscapes.

4. Results

4.1. Economic Contribution and Productivity Patterns

Rubber plantations play a significant role in rural economies in both Jambi (Indonesia) and the Colombian departments of Caquetá and Tolima, though notable differences emerge in scale, productivity, and economic structure.

In Jambi Province, the plantation sub-sector ,with rubber as a principal component ,contributed an average of **37.81%** to the regional Gross Regional Domestic Product (GRDP) at current prices between 2011 and 2021 (Dewi Sri Nurchaini, Nainggolan, & Mulia Sari, 2024). The plantation sector demonstrated robust growth, with an annual average increase of **9.27%** at constant prices. Rubber's high Location Quotient (LQ) values suggest that it is a **basic sector** with a specialization advantage, producing beyond local consumption needs.

Nonetheless, productivity challenges persist. In Tebo Regency, the average rubber yield was only **0.44 tons per hectare**, significantly lower than the Jambi provincial average of **4.51 tons per**

 doi:10.20944/preprints202505.0398.v1

hectare (Dewi Sri Nurchaini et al., 2024). These figures indicate the persistence of smallholder-led plantation systems constrained by limited access to improved technologies and management practices.

In Colombia, rubber cultivation remains emergent but strategically positioned as a rural diversification strategy in Caquetá and Tolima (Ramírez et al., 2018; Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023; Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020). Initial yield reports from Tolima indicate promising productivity ,approximately **2.91 tons per hectare**, above the national average (Orjuela Garzón et al., 2020). However, critical bottlenecks exist, including insufficient aggregation of production, weak market connections, and limited local value-added processing capacity (López Santana, Méndez Giraldo, & Franco, 2021).

In summary, while rubber offers significant economic potential where infrastructure and markets are favorable, structural vulnerabilities related to productivity, value chains, and sectoral organization limit its development impact.

4.2. Environmental Consequences of Expansion

Rubber expansion into tropical landscapes has led to measurable ecological degradation, though the degree of impact varies depending on prior land cover and management practices.

Empirical research from Southeast Asia reveals that converting lowland rainforests to rubber plantations resulted in:

- **60% reduction** in above-ground carbon stocks compared to intact forests (Clough et al., 2016).
- Substantial declines in biodiversity, with monoculture rubber systems supporting less than half the species richness of natural forests (Clough et al., 2016).
- Significant reductions in ecosystem multifunctionality, including losses in soil fertility, nutrient cycling, and habitat connectivity.

In Colombia, baseline assessments and spatial modeling predict similar risks if expansion continues without territorial planning (Ramírez et al., 2018; Basto Monsalve et al., 2023). Specifically, in Caquetá, climate suitability modeling under future scenarios (2011–2040, 2041–2070, 2071–2100) indicates a progressive decline in the area apt for rubber cultivation, with a corresponding increase in "non-apt" zones (Basto Monsalve et al., 2023).

Although rubber plantations store more carbon than degraded pastures (Kongsager, Napier, & Mertz, 2013), their environmental performance remains inferior to natural forests, especially when considering biodiversity metrics and climate regulation services.

Thus, rubber expansion onto degraded lands could yield net environmental benefits, but expansion into forested areas represents a clear ecological loss.

4.3. Governance, Sectoral Planning, and Informational Dynamics

The governance structures surrounding rubber plantation development present significant gaps in both regions studied.

In Indonesia, rubber expansion historically proceeded with minimal regulatory oversight. Although more recent initiatives have attempted to integrate smallholders into sustainable value chains, enforcement remains uneven, and landscape-level planning is rare (Clough et al., 2016; Schwarze et al., 2015).

In Colombia, sectoral diagnostic exercises reveal a fragmented institutional environment. Regional planning instruments are often disconnected from environmental conservation goals (Ramírez et al., 2018; López Santana et al., 2021). Extension services ,critical for disseminating best practices and climate resilience measures ,remain underdeveloped (Orjuela Garzón et al., 2020).

Critically, selective exposure dynamics are evident. Rural communities in Caquetá and Tolima have primarily been exposed to optimistic narratives framing rubber as a pathway to prosperity, while information about environmental risks and climate vulnerability remains sparse (Ramírez et al., 2018; Orjuela Garzón et al., 2020).

 doi:10.20944/preprints202505.0398.v1

Social influence mechanisms, wherein early adopters serve as informal models for community decision-making, further reinforce one-sided perceptions of rubber's benefits (Ramírez et al., 2018).

This asymmetric information environment constrains truly informed land-use decisions, increasing the risk of unsustainable development trajectories.

5. Discussion

The comparative analysis of rubber plantation expansion in Southeast Asia and Colombia reveals a complex interplay between economic opportunities and ecological trade-offs. These dynamics are profoundly shaped by governance contexts, socio-economic conditions, and informational environments, rather than by biophysical factors alone.

5.1. The Economic–Ecological Trade,Off Is Context,Dependent

The evidence confirms that rubber plantations can meaningfully contribute to rural economic development, especially in areas where alternative livelihood options are limited. In Jambi, Indonesia, the high GRDP share attributed to the plantation sector highlights the sector's economic relevance (Dewi Sri Nurchaini, Nainggolan, & Mulia Sari, 2024). Similarly, in Colombian departments such as Tolima, early yield reports suggest that rubber could enhance rural income diversification (Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020).

However, the trade-offs are nontrivial. Environmental costs ,such as significant carbon stock losses and biodiversity declines following forest-to-rubber conversion ,are well documented (Clough et al., 2016; Kongsager, Napier, & Mertz, 2013). Climate change further complicates the picture, with modeling studies in Caquetá projecting declining rubber suitability under future scenarios (Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023).

Thus, rubber should not be framed simplistically as either a "development solution" or an "environmental threat." Outcomes depend on site-specific factors, including prior land use, governance quality, market structures, and smallholder capacities.

5.2. Governance Failures and the Role of Informational Asymmetries

Weak governance frameworks have exacerbated the socio-ecological risks associated with rubber expansion. In both Indonesia and Colombia, fragmented institutional coordination, insufficient planning, and limited enforcement capacity have allowed plantation growth to proceed without adequate sustainability safeguards (Clough et al., 2016; Ramírez et al., 2018; López Santana, Méndez Giraldo, & Franco, 2021).

Furthermore, informational environments heavily influence farmer decision-making. As selective exposure theory suggests, smallholders are often exposed predominantly to narratives highlighting economic opportunities, while downplaying or omitting ecological risks (Frey, 1986; López Santana et al., 2021). Social influence mechanisms reinforce these biases, as early adopters' successes ,regardless of underlying conditions ,shape broader community expectations (Ramírez et al., 2018).

This asymmetry in information access significantly constrains the ability of smallholders to make genuinely informed decisions regarding land use, increasing their exposure to future risks associated with market volatility and climate change.

5.3. Toward Integrated and Adaptive Rubber Development Strategies

The findings point to the urgent need for integrated rural development strategies that acknowledge and manage the inherent trade-offs in rubber cultivation.

Policy recommendations include:

- **Prioritizing degraded lands** for rubber expansion while protecting remaining natural forests (Clough et al., 2016; Kongsager et al., 2013).

 doi:10.20944/preprints202505.0398.v1

- **Strengthening extension services** to disseminate not only technical information but also realistic appraisals of climate risks and environmental impacts (Orjuela Garzón et al., 2020).
- **Developing participatory monitoring systems** that include biophysical and socio-economic indicators to inform adaptive management (Phompila, Lewis, Ostendorf, & Clarke, 2017).
- **Enhancing participatory land-use planning** frameworks that involve smallholders, indigenous groups, conservation agencies, and private sector actors (Ramírez et al., 2018; López Santana et al., 2021).

Addressing informational asymmetries is particularly crucial. Balanced communication strategies that honestly present both the opportunities and the risks of rubber cultivation are needed to empower rural communities to make resilient livelihood choices.

5.4. Lessons for Colombia from Southeast Asia

Colombia can draw valuable lessons from Southeast Asia's longer experience with rubber cultivation.

Key lessons include:

- **Diversification matters:** Over-reliance on a single commodity increases vulnerability to price fluctuations and ecological degradation (Clough et al., 2016).
- **Smallholder empowerment is critical:** Access to technical assistance, fair markets, and financial services must accompany expansion strategies (Schwarze et al., 2015).
- **Climate resilience must be integrated early:** Land use planning must incorporate future climate projections, not merely historical suitability (Basto Monsalve et al., 2023).

By learning from the successes and failures observed in Southeast Asia, Colombia has the opportunity to avoid repeating costly mistakes and to design more resilient, diversified, and equitable rural development strategies.

6. Conclusion and Recommendations

This study critically examined the socio-economic and environmental impacts of natural rubber (*Hevea brasiliensis*) plantation expansion in two tropical contexts: Jambi Province (Indonesia) and the Colombian departments of Caquetá and Tolima.

The findings demonstrate that rubber plantations can significantly contribute to rural economic development, particularly by providing alternative livelihood options in regions historically dependent on low-productivity agriculture or extractive economies. However, these benefits come with substantial ecological costs, especially when plantation expansion involves the conversion of natural forests rather than degraded lands.

Environmental trade-offs, including major reductions in carbon stocks and biodiversity loss, were consistently observed across both regions (Clough et al., 2016; Kongsager, Napier, & Mertz, 2013). In Colombia, additional risks stem from climate change impacts, with modeling projections showing decreasing suitability for rubber cultivation over the coming decades (Basto Monsalve, Pascuas Rengifo, & Fontalvo Buelvas, 2023).

Moreover, the study highlights the critical role of governance failures and informational asymmetries. Fragmented planning, weak institutional coordination, and selective exposure to overly optimistic narratives have often led smallholders to adopt rubber without a full understanding of potential ecological and economic risks (Ramírez et al., 2018; López Santana, Méndez Giraldo, & Franco, 2021).

These dynamics suggest that addressing informational environments is as important as technical or financial interventions in ensuring sustainable rural development.

In sum, rubber cultivation represents both an opportunity and a risk. Its success as a sustainable rural development strategy depends on how well economic, ecological, and social dimensions are integrated into planning and implementation.

 doi:10.20944/preprints202505.0398.v1

6.1. Recommendations

1. Promote Landscape-Level Planning and Land Use Diversification

Rubber plantations should primarily target degraded lands, avoiding further encroachment into natural forests to minimize biodiversity and carbon losses (Clough et al., 2016; Kongsager et al., 2013). Integrated land use planning should prioritize mosaics that combine agroforestry, natural forest patches, and other sustainable livelihoods.

2. Strengthen Technical Assistance and Capacity Building

Governments and development agencies must invest in extension services that provide smallholders with balanced technical, ecological, and climate risk information (Orjuela Garzón, Reyes Parga, & Sandoval Aldana, 2020). Training should promote best practices in sustainable rubber management, diversification, and climate adaptation.

3. Develop Integrated Monitoring Systems

Robust socio-ecological monitoring systems should track plantation expansion, carbon dynamics, biodiversity indicators, and socio-economic outcomes. Such systems would support adaptive management strategies and enable evidence-based policymaking (Phompila, Lewis, Ostendorf, & Clarke, 2017).

4. Address Informational Asymmetries and Empower Rural Communities

Balanced, transparent communication strategies are needed to counteract selective exposure to overly optimistic narratives. Participatory forums, knowledge-sharing platforms, and inclusive consultation processes should be strengthened to support informed decision-making at the community level (López Santana et al., 2021).

5. Incorporate Climate Adaptation Planning from the Outset

Rubber development initiatives must explicitly account for projected climate changes in land suitability and water availability. Cultivar selection, cropping systems, and investment plans must be climate-resilient rather than based on historical norms (Basto Monsalve et al., 2023).

6. Foster Multi-Stakeholder Coordination

Creating permanent regional platforms involving farmers, government agencies, NGOs, and private sector actors can ensure that rubber development strategies are better aligned with environmental sustainability and social equity goals (Ramírez et al., 2018).

Final Reflection

Natural rubber plantations represent a powerful but double-edged tool for tropical rural development. When integrated within diversified, climate-resilient, and participatory land-use strategies, they can contribute meaningfully to economic growth while maintaining critical ecosystem services. However, when driven by short-term economic incentives alone, they risk undermining the very sustainability they promise.

For Colombia, and for tropical regions globally, the real challenge is not whether to expand rubber cultivation, but how to do so in a way that sustains both people and landscapes over the long term.

References

1. Basto Monsalve, M. B., Pascuas Rengifo, E., & Fontalvo Buelvas, J. C. (2023). Modelación del cultivo de caucho (*Hevea brasiliensis*) en el contexto de cambio climático para Caquetá, Colombia. *AyTBUAP*, *8*(30), 29–43. https://doi.org/10.5281/zenodo.80091964
2. Clough, Y., Krishna, V. V., Corre, M. D., et al. (2016). Transformation of lowland rainforest into oil palm and rubber plantations alters energy channels in soil food webs. *Ecology*, *97*(2), 409–418. https://doi.org/10.1890/15,0858
3. Dewi Sri Nurchaini, Nainggolan, S., & Mulia Sari, D. (2024). Analysis of the contribution of rubber plantations to economic growth in Tebo District, Jambi, Indonesia. *GSC Advanced Research and Reviews*, *18*(1), 328–335. https://doi.org/10.30574/gscarr.2024.18.1.0028

 doi:10.20944/preprints202505.0398.v1

4. Frey, D. (1986). Recent research on selective exposure to information. In L. Berkowitz (Ed.), *Advances in experimental social psychology* (Vol. 19, pp. 41–80). Academic Press.
5. Kongsager, R., Napier, J., & Mertz, O. (2013). The carbon sequestration potential of tree crop plantations. *Mitigation and Adaptation Strategies for Global Change, 18*(8), 1197–1213. https://doi.org/10.1007/s11027,012,9417,z
6. López Santana, E. R., Méndez Giraldo, G. A., & Franco, C. (2021). Prototipo de metodología de diagnóstico sectorial en Colombia. *Ponencia*. https://doi.org/10.26507/ponencia.1630
7. Orjuela Garzón, W. A., Reyes Parga, M. A., & Sandoval Aldana, A. P. (2020). Agenda prospectiva de investigación y desarrollo tecnológico para la cadena productiva de caucho en el departamento del Tolima. *Universidad del Tolima*. https://www.researchgate.net/publication/347954382
8. Phompila, C., Lewis, M., Ostendorf, B., & Clarke, K. D. (2017). Forest Cover Changes in Lao Tropical Forests: Physical and Socio,Economic Factors are the Most Important Drivers. *Land, 6*(2), 23. https://doi.org/10.3390/land6020023
9. Ramírez, U., Charry, A., Jäger, M., Hurtado, J. J., Quiroga, E., Del Cairo, J. R., Romero, M., Sierra, L., & Quintero, M. (2018). Estrategia sectorial de la cadena de caucho en Guaviare, con enfoque agroambiental y cero deforestación. *Centro Internacional de Agricultura Tropical (CIAT)*. https://www.researchgate.net/publication/324783813
10. Schwarze, S., Zeller, M., Faust, H., et al. (2015). Ecological and Socioeconomic Functions Across Tropical Land Use Systems (Sumatra, Indonesia): Synergies and Trade-offs (SURUMER Final Report). *University of Göttingen*. https://www.uni,goettingen.de/en/503626.html
11. Cialdini, R. B., & Goldstein, N. J. (2004). Social influence: Compliance and conformity. *Annual Review of Psychology, 55*, 591–621. https://doi.org/10.1146/annurev.psych.55.090902.142015