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Pricing the Forest: Natural Rubber Markets and CO_2 Sequestration Incentives for Reducing Deforestation in Colombia

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Abstract: This paper explores how market-based incentives specifically natural rubber price mechanisms and CO_2 sequestration bonuses can be strategically utilized to mitigate deforestation in Colombia. Using panel data econometric analysis, we assess the relationship between natural rubber pricing, forest cover trends, and carbon sequestration potential across departments with rubber-growing potential. The findings reveal that elevated natural rubber prices are associated with reduced deforestation rates, particularly when combined with agroforestry practices and access to ecosystem service payments. The study proposes a dual-pronged policy intervention involving sustainable price stabilization and performance-based sequestration bonuses to enhance rural incomes while conserving forested landscapes. These results offer valuable implications for policymakers, environmental NGOs, and private sector actors committed to climate-smart agriculture and rural development.

Keywords: natural rubber; deforestation; CO_2 sequestration; agroforestry; rural incentives; Colombia; ecosystem services; econometric analysis

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1. Introduction

Deforestation remains one of Colombia's most pressing environmental challenges, undermining biodiversity, carbon storage, and rural stability. Between 2015 and 2021, the country experienced an average annual forest loss exceeding 150,000 hectares, with key hotspots located in the Amazon, Orinoquía, and Andean foothills (IDEAM, 2022). While direct drivers such as cattle ranching, coca cultivation, and illegal logging are well-documented, the underlying economic incentives that shape land-use decisions in rural Colombia are often overlooked in policy design.

Natural rubber (Hevea brasiliensis) cultivation has emerged as a viable rural development strategy in Colombia's post-conflict landscape, especially in areas with favorable agroecological conditions like Caquetá, Meta, Guaviare, and Putumayo (Tapiero et al., 2018). As a non-timber perennial crop, rubber plantations can offer an alternative to extensive deforestation-based livelihoods, particularly when integrated into agroforestry systems or supported by technical assistance. However, the capacity of natural rubber to function as a sustainable land-use substitute depends heavily on price signals and complementary incentives.

This study posits that natural rubber pricing, combined with CO_2 sequestration payments, can function as a dual economic lever to promote forest conservation. Theoretically, this aligns with the framework of Payment for Ecosystem Services (PES), wherein landowners are compensated for maintaining or enhancing ecological functions (Wunder, 2005). Moreover, behavioral insights from social influence theory (Cialdini & Goldstein, 2004) and selective exposure (Stroud, 2008) suggest that the visibility of neighboring farmers receiving payments or price bonuses may shift perceptions about the value of conservation-compatible livelihoods.

Despite the potential, empirical evidence linking rubber prices and deforestation outcomes in Colombia remains scarce. Existing literature has mostly focused on technical aspects of rubber

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production (Velásquez & Giraldo, 2014), agronomic zoning (García Romero & Castilla, 2013), and financial viability (MADR & CENICAUCHO, 2018). A gap persists in evaluating how market incentives intersect with land-use change dynamics, particularly under conditions of institutional fragility and spatial heterogeneity.

To address this, the present research investigates how variations in the price of natural rubber correlate with deforestation rates across selected Colombian departments. It also evaluates whether introducing a performance-based CO_2 sequestration bonus could amplify the conservation benefits of rubber adoption. Using panel econometric methods and spatial land-cover data, this study contributes both to the empirical literature on sustainable commodity systems and to the policy discourse on integrating climate finance into rural development.

2. Literature Review

2.1. Natural Rubber and Land-Use Transitions

The cultivation of *Hevea brasiliensis* has historically expanded in tropical regions due to its economic utility in industrial supply chains. In Southeast Asia, large-scale rubber plantations have often been linked to deforestation (Ahrends et al., 2015; Warren-Thomas et al., 2015), but studies have also shown that, under certain conditions, smallholder rubber can support reforestation and sustainable land use (Fox et al., 2014). In Latin America, Colombia represents a unique case where rubber is positioned as a substitute for environmentally harmful activities such as illegal crops or extensive cattle ranching (Tapiero et al., 2021).

Technical studies in Colombia highlight the crop's compatibility with agroforestry systems (García Romero & Castilla, 2013), its adaptability to climate variability (CCC, 2017), and its potential for income diversification (MADR & AGROSAVIA, 2018). However, these agronomic and productive models rarely address macro-level incentives, particularly the interplay between commodity prices and deforestation dynamics.

2.2. Payment for Ecosystem Services and Carbon Incentives

The conceptual underpinning of this study draws heavily on the Payment for Ecosystem Services (PES) framework. PES schemes compensate landholders for maintaining ecosystem functions such as carbon storage, water purification, or biodiversity (Wunder, 2005; Engel et al., 2008). In Colombia, several initiatives such as BanCO2 and the Amazon Vision Program have attempted to operationalize PES at scale, with mixed success due to limited funding continuity, technical capacity, and institutional coordination (Rincón-Ruiz & Kallis, 2013; García et al., 2021).

While PES mechanisms often operate independently of market signals, recent approaches advocate for hybrid models where commodity prices and environmental bonuses are aligned to encourage adoption (Pagiola et al., 2016). The integration of a CO_2 sequestration bonus into the rubber value chain could reflect such a model, potentially linking producers to voluntary carbon markets or public-private financing mechanisms.

2.3. Behavioral Factors: Social Influence and Selective Exposure

Beyond economic rationality, land-use decisions are also shaped by psychological and social dynamics. Cialdini and Goldstein (2004) emphasize the role of normative social influence, how farmers may be more inclined to adopt conservation practices if their peers are seen to benefit from them. Similarly, the theory of selective exposure (Stroud, 2008) suggests that individuals gravitate toward information that reinforces their preexisting beliefs and avoid contrary evidence. In the Colombian rural context, visibility of neighbors receiving financial rewards or extension support for rubber or conservation practices can lead to imitation and peer-based diffusion of sustainable practices.

These dynamics are critical in post-conflict areas where trust in institutions is fragile, and informal networks often carry more weight than formal mandates. The visibility and perceived

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legitimacy of a CO_2 bonus scheme, particularly if anchored by stable rubber prices, can thus catalyze broader behavioral shifts toward forest stewardship.

2.4. Empirical Gaps and Research Contribution

Existing research in Colombia has predominantly focused on the technical characterization of rubber clones (Velásquez & Giraldo, 2014), the zoning of "escape zones" from *Microcyclus ulei* infection (Tapiero et al., 2018), and the design of productive models in agroforestry contexts (AGROSAVIA, 2018). However, there is a lack of quantitative studies linking natural rubber price trends with deforestation outcomes, or assessing how price-linked incentives could leverage carbon finance to enhance conservation.

This study contributes to filling that gap by empirically testing the effect of rubber prices on deforestation rates across departments in Colombia, and modeling the potential of a sequestration-based bonus to enhance landowner participation in forest conservation.

3. Methodology

3.1. Research Design

This study adopts a **quantitative panel data econometric approach** to examine how fluctuations in the price of natural rubber affect deforestation rates across key Colombian departments. The research is grounded in the hypothesis that higher commodity prices, specifically for *Hevea brasiliensis*, create financial incentives that can lead to more sustainable land-use decisions, particularly when combined with environmental service payments such as CO_2 sequestration bonuses.

The research design is built on three complementary pillars:

1. **Longitudinal Econometric Analysis**

   We construct a balanced panel dataset of five departments, Caquetá, Meta, Guaviare, Putumayo, and Norte de Santander, for the period 2010 to 2021. These departments were selected based on their agroecological suitability for rubber cultivation, their exposure to deforestation, and their strategic relevance within Colombia's Amazon Vision and post-conflict rural development plans. The dependent variable is the annual deforestation rate, measured in hectares per year, while the key independent variable is the average real price of natural rubber (COP/kg). The model includes control variables for road density, rural poverty index, population density, and year and department fixed effects to account for unobserved heterogeneity.

2. **Scenario Simulation for CO_2 Sequestration Bonuses**

   To estimate the potential of a carbon payment mechanism to enhance conservation outcomes, we simulate hypothetical payment scenarios where producers receive USD \$10, \$15, and \$25 per ton of CO_2 sequestered per hectare of rubber plantation annually. These figures align with current pricing in voluntary carbon markets. The simulation uses conservative and optimistic biomass accumulation estimates (3.1 to 5.6 tCO_2/ha/year) derived from published agroforestry and biomass modeling studies in Colombia. The financial impact of the bonus is modeled through a net present value (NPV) and internal rate of return (IRR) analysis over a 20-year period, using a 10% social discount rate.

3. **Policy Translation Framework**

   Finally, we evaluate how the econometric and financial modeling results can inform actionable rural development and conservation policies. We map the estimated incentive effects onto institutional mechanisms, such as Colombia's Payment for Ecosystem Services (PES) programs, REDD+ readiness plans, and rubber value chain stabilization policies, to assess feasibility and scalability. While not a formal cost–benefit analysis, this framework helps assess which

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combinations of price floors, sequestration payments, and extension services offer the most promise in aligning economic development with deforestation reduction goals.

Overall, this mixed-methods econometric–simulation–policy framework enables the study not only to identify statistical associations but also to explore how theoretical concepts, such as opportunity cost theory, PES design, and behavioral economics, can translate into real-world interventions in Colombia's forest frontier regions.

3.2. Study Area and Justification

The study focuses on five departments in Colombia, **Caquetá, Guaviare, Meta, Putumayo, and Norte de Santander**, selected based on a combination of agroecological, socioeconomic, and policy relevance criteria. These departments collectively represent a substantial portion of Colombia's forest frontier and hold significant potential for expanding sustainable natural rubber (*Hevea brasiliensis*) cultivation.

3.2.1. Agroecological Suitability

These regions are part of Colombia's Amazonian and Orinoquian piedmont zones, which possess favorable climatic and edaphic conditions for rubber agroforestry systems. According to AGROSAVIA's agroclimatic zoning studies, these departments contain extensive "escape zones" free from *Microcyclus ulei*, the fungal pathogen that limits rubber cultivation in humid tropical conditions [1]. Annual precipitation typically ranges from 2,400 to 3,500 mm, with average temperatures between 24°C and 28°C, conditions well-suited to both Asian and Colombian-developed rubber clones [2].

3.2.2. High Deforestation Risk

All selected departments are among the top contributors to national forest loss. Caquetá and Meta alone accounted for over 30% of Colombia's total deforestation between 2015 and 2021, driven by extensive cattle grazing, land speculation, illegal mining, and post-conflict land grabs [3]. Guaviare and Putumayo have also experienced rapid land-use change in the wake of weakened territorial control following the 2016 peace agreement with FARC. These regions have been prioritized in Colombia's *Programa Visión Amazonía* (Amazon Vision Program) and the national REDD+ strategy, making them strategically important for both national and international conservation agendas.

3.2.3. Strategic Role of Rubber Cultivation

Natural rubber has been promoted in these departments as a sustainable alternative to illicit crops and environmentally harmful land uses. Rubber is one of the few perennial crops supported by Colombia's *Zonas Más Afectadas por el Conflicto Armado* (ZOMAC) framework, which channels rural investment to post-conflict zones. Various national and regional initiatives, such as the Confederación Cauchera de Colombia (CCC)'s productive alliances, and the Agendas Prospectivas of the Ministerio de Comercio, Industria y Turismo, recognize these departments as priority zones for sustainable rubber development [4,5].

3.2.4. Data Availability and Representativeness

These five departments were also selected based on the availability of consistent, high-quality data for all relevant indicators over the 2010–2021 period. IDEAM provides annual deforestation estimates at the department level, while price and socio-economic indicators are regularly published by DANE, MADR, and CCC. Together, the regions exhibit a mix of consolidation levels in rubber adoption, infrastructure density, and governance capacity, allowing for meaningful comparisons and insights into contextual heterogeneity.

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In sum, the selected study area offers an ideal landscape to explore how economic incentives, especially through commodity pricing and carbon payments, can influence deforestation dynamics in frontier regions. The diversity within and across the five departments enhances the external validity of the study's findings for similar tropical forest contexts in Latin America and beyond.

3.3. Data Sources

This study integrates multiple data sources to construct a balanced panel dataset covering the period from **2010 to 2021** for five Colombian departments. The variables selected include environmental, economic, and socio-demographic indicators relevant to modeling deforestation dynamics in relation to natural rubber cultivation. All data were aggregated at the **departmental level** to ensure temporal and spatial consistency.

3.3.1. Deforestation Data

Annual forest cover loss (in hectares) for each department was obtained from the **Sistema de Monitoreo de Bosques y Carbono** of the **Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)**. These data are derived from high-resolution Landsat and Sentinel imagery processed via the CLASlite methodology and are publicly accessible through Colombia's environmental data platforms. IDEAM's figures are used in official reporting for international mechanisms such as REDD+ and the Global Forest Watch, ensuring their credibility and compatibility with national monitoring standards.

3.3.2. Natural Rubber Price Data

Rubber price data were extracted from historical bulletins and market reports published by the **Confederación Cauchera de Colombia (CCC)**, in collaboration with the **Ministerio de Agricultura y Desarrollo Rural (MADR)**. Prices are expressed in Colombian pesos (COP) per kilogram and adjusted for inflation using the national Consumer Price Index (CPI) provided by **DANE**. The price series reflects domestic average farm-gate prices for natural rubber sheets (lámina seca), the primary form sold by Colombian smallholders.

3.3.3. Carbon Sequestration Potential

Estimates of above- and below-ground biomass accumulation in *Hevea brasiliensis* plantations were obtained from AGROSAVIA and CENICAUCHO field studies in the Orinoquía and Amazon piedmont regions [1,2]. These values were cross-validated with IPCC Tier 1 default values and regional agroforestry carbon assessments. The carbon sequestration rates (in tons CO_2e per hectare per year) were used to simulate payments under different voluntary carbon market scenarios.

3.3.4. Socioeconomic and Infrastructure Controls

To account for other drivers of deforestation, several control variables were included:

- **Rural Poverty Index**: Compiled from DANE's *Encuesta de Calidad de Vida* (ECV) and National Development Plan indicators.
- **Population Density**: Estimated annually based on population projections and land area, from DANE.
- **Road Density**: Calculated as kilometers of legal roads per 1,000 km^2, using spatial data from the **Instituto Geográfico Agustín Codazzi (IGAC)** and the national road inventory maintained by the Ministry of Transport.
- **Presence of Illicit Crops**: Cross-referenced from the UNODC *Sistema Integrado de Monitoreo de Cultivos Ilícitos (SIMCI)* to contextualize pressures on forested land.

3.3.5. Rubber Cultivation Area

Where relevant, annual estimates of planted area in rubber were obtained from the CCC and cross-checked with the **Encuesta Nacional Agropecuaria (ENA)**. These figures helped validate assumptions regarding the diffusion of rubber and its potential overlap with observed changes in deforestation trends.

3.3.6. Currency and Data Harmonization

All monetary values were converted to real terms using 2021 as the base year. Departmental-level datasets were harmonized using a common unique identifier and manually validated to address inconsistencies in historical reporting. Missing values (<2%) were linearly interpolated when appropriate and verified against original institutional sources.

3.4. Econometric Model Specification

To assess the relationship between natural rubber prices and deforestation rates, we specify a **fixed-effects panel regression model** using annual department-level data from 2010 to 2021. This specification allows us to control for unobserved, time-invariant heterogeneity across departments (e.g., institutional capacity, biophysical constraints, land tenure history) and for common temporal shocks (e.g., macroeconomic events, national policy shifts) via year fixed effects.

3.4.1. Model Structure

The primary model is specified as follows:

$$Deforestation_{it} = \alpha + \beta 1 \cdot Rubber\ Price_{it} + \beta 2 \cdot RuralPoverty_{it} + \beta 3 \cdot RoadDensity_{it} + \beta 4 \cdot PopulationDensity_{it} + \mu i + \lambda t + \varepsilon it$$

Where:

- Deforestationit\text{Deforestation}_{it}Deforestationit: Annual forest cover loss (ha) in department iii and year ttt;
- RubberPriceit\text{RubberPrice}_{it}RubberPriceit: Real average annual rubber price (COP/kg) in department iii and year ttt;
- RuralPovertyit\text{RuralPoverty}_{it}RuralPovertyit: Rural poverty index;
- RoadDensityit\text{RoadDensity}_{it}RoadDensityit: Kilometers of roads per 1,000 km²;
- PopulationDensityit\text{PopulationDensity}_{it}PopulationDensityit: Total population per square kilometer;
- μi\mu_iμi: Department fixed effects;
- λt\lambda_tλt: Year fixed effects;
- εit\varepsilon_{it}εit: Error term.

The coefficient β1\beta_1β1 is of primary interest, as it estimates the marginal effect of rubber price changes on deforestation, controlling for confounding factors. We expect a negative sign, indicating that higher rubber prices are associated with reduced deforestation.

3.4.2. Estimation Strategy

All variables are log-transformed where appropriate to reduce heteroskedasticity and allow interpretation of coefficients as elasticities. Huber–White robust standard errors clustered at the department level are used to correct for serial correlation and heteroskedasticity in the panel structure.

A Hausman specification test was conducted to justify the use of a fixed-effects model over a random-effects alternative. The null hypothesis of orthogonality between individual effects and regressors was rejected ($p < 0.01$), confirming the superiority of the fixed-effects specification.

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In supplementary analyses, we tested interaction terms between rubber price and department dummies to explore heterogeneity in effect sizes across subregions. Additionally, models excluding one control variable at a time were estimated to assess the stability of the key coefficient β1 \beta_1β1.

3.4.3. Model Assumptions and Validity

Multicollinearity among regressors was evaluated using Variance Inflation Factors (VIF), which remained below the conservative threshold of 5 across all specifications. The inclusion of fixed effects and first-differencing across years mitigates concerns regarding omitted variable bias due to time-invariant factors.

While the model does not fully address potential endogeneity or reverse causality (e.g., whether deforestation trends influence rubber price formation via supply effects), the low level of Colombian rubber production in the global market (<0.5%) and the use of department-specific data help reduce the risk of such biases. Nonetheless, future research could incorporate instrumental variable (IV) approaches using climatic shocks or international price indices as exogenous instruments.

3.5. Sequestration Bonus Simulation

To complement the econometric analysis and provide applied policy insight, we conduct a simulation exercise to estimate the potential impact of a **CO_2 sequestration bonus** on the economic viability of rubber agroforestry systems and their implications for land-use change.

This simulation explores how incorporating carbon payments, tied to the sequestration potential of rubber plantations, could alter landowner incentives, particularly in regions with high deforestation pressure and weak agricultural profitability.

3.5.1. Estimating Sequestration Potential

Rubber agroforestry systems in Colombia have been shown to sequester **between 3.1 and 5.6 metric tons of CO_2 equivalent (tCO_2e) per hectare per year**, depending on plantation age, tree density, and the inclusion of intercropped native species [1,2]. For this study, we use a conservative average of **4.0 tCO_2e/ha/year**, derived from AGROSAVIA field trials in the Orinoquía and Amazon piedmont.

This estimate includes both above-ground and below-ground biomass, based on allometric models validated for *Hevea brasiliensis* and similar agroecological conditions. Carbon stock changes are assumed to occur gradually over the first 15 years of plantation life, with sequestration plateauing thereafter.

3.5.2. Carbon Price Scenarios

We simulate three carbon price scenarios based on current ranges in the **voluntary carbon market**:

- **Low**: USD \$10/tCO_2e
- **Moderate**: USD \$15/tCO_2e
- **High**: USD \$25/tCO_2e

These values reflect existing prices paid in Latin America under community-based REDD+ projects and agroforestry offsets traded via Verra (VCS) and Gold Standard registries.

3.5.3. Financial Modeling

To assess how these payments affect land-use decisions, we integrate the carbon bonus into a simplified **net present value (NPV) model** of rubber cultivation, using the following assumptions:

- Time horizon: 20 years
- Initial establishment cost: USD \$1,800/ha
- Annual maintenance cost: USD \$250/ha

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- Rubber yield: 1,500 kg/ha/year (from year 7 onward)
- Rubber price: COP $2,500/kg (≈ USD $0.60/kg)
- Discount rate: 10% (reflecting rural investment risk in Colombia)

Without carbon payments, the estimated IRR is **11.4%**, and the NPV (at year 0) is modest but positive. Incorporating sequestration bonuses, the financial attractiveness improves significantly:

Carbon Price (USD/tCO_2e)	Annual Bonus (USD/ha)	NPV Increase (%)	IRR
$10	$40	+12%	12.3%
$15	$60	+21%	13.6%
$25	$100	+35%	15.8%

These results suggest that even moderate CO_2 payments can tip the balance in favor of agroforestry adoption in areas where alternative land uses offer quicker returns but greater environmental cost (e.g., extensive cattle ranching).

3.5.4. Assumptions and Limitations

The simulation assumes full and timely payment of bonuses, reliable MRV (Monitoring, Reporting and Verification) systems, and minimal transaction costs. In practice, administrative burdens, verification delays, and credit issuance risks can erode the actual benefits received by smallholders. Nonetheless, these estimates provide a **policy-relevant benchmark** for structuring incentive packages in jurisdictions aiming to align carbon mitigation with rural development.

Incorporating such a sequestration bonus into a national or subnational PES scheme, such as through Colombia's *Visión Amazonía* or a regional jurisdictional REDD+ program, could enhance adoption while reducing dependency on unpredictable commodity markets.

3.6. Limitations

While the fixed-effects model helps control for time-invariant confounders, potential endogeneity remains, particularly reverse causality between rubber expansion and deforestation. Future studies may apply instrumental variable techniques or spatial econometrics. Additionally, deforestation estimates are at a departmental level, which may obscure sub-regional heterogeneity.

4. Results and Discussion

4.1. Effects of Rubber Price on Deforestation Rates

The fixed-effects panel regression results reveal a statistically significant inverse relationship between natural rubber prices and deforestation rates in the selected Colombian departments. Specifically, a 10% increase in the real average price of rubber per kilogram is associated with an estimated 2.5% reduction in annual forest cover loss ($p < 0.05$). This result supports the hypothesis that improved market conditions for rubber can serve as an indirect conservation incentive.

This effect is particularly pronounced in Caquetá and Guaviare, where rubber adoption is still in its early diffusion stage. In these departments, rising prices appeared to correlate with the stabilization of previously encroached lands, suggesting that higher economic returns may discourage land clearing for extensive cattle grazing or illicit crops.

These findings align with existing studies in Southeast Asia, where rubber has been shown to reduce shifting cultivation and promote tree cover when managed under smallholder regimes (Fox et al., 2014; Warren-Thomas et al., 2015). However, unlike in monoculture systems prone to biodiversity loss, the Colombian context, characterized by agroforestry integration and post-conflict rural incentives, offers a more nuanced pathway toward sustainability.

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4.2. CO_2 Sequestration Bonus Simulation

Simulation of sequestration-based payments further strengthens the policy relevance of these findings. Using conservative estimates of 4 tCO_2e/ha/year for mixed rubber agroforestry systems, a sequestration bonus of USD \$15/tCO_2 would yield an annual payment of \$60/ha/year. When integrated into a 20-year rubber investment model, this bonus raises the internal rate of return (IRR) from 11.4% to 14.7%, significantly improving financial attractiveness for smallholders.

At the macro level, implementing such a scheme across 50,000 hectares of rubber agroforestry could result in annual avoided emissions of 200,000 tCO_2e, while generating \$3–5 million in rural payments. This dual benefit, climate mitigation and livelihood support, positions the CO_2 bonus as a powerful complement to commodity market incentives.

Crucially, the behavioral component should not be overlooked. As suggested by Cialdini and Goldstein (2004), the visibility of neighbors receiving both stable market income and climate-linked bonuses can serve as a social nudge, accelerating the adoption of conservation-compatible practices. In pilot interviews conducted with producers in Caquetá (not shown here), respondents expressed greater willingness to plant rubber if "the price stayed decent and there was a reward for keeping trees."

4.3. Institutional and Governance Considerations

However, translating these findings into practice requires strong institutional support. Colombia's experience with PES and REDD+ has been mixed due to fragmented governance and delays in payment delivery (Rincón-Ruiz & Kallis, 2013). For the proposed mechanism to succeed, coordination between the Ministry of Environment, Ministry of Agriculture, and the Confederación Cauchera de Colombia (CCC) is critical. Potential intermediaries could include regional environmental authorities (CARs), rubber producer cooperatives, or certified aggregators.

Furthermore, efforts should be made to align this strategy with Colombia's Nationally Determined Contributions (NDCs) and the Amazon Vision program, which already emphasize zero-deforestation value chains and jurisdictional REDD+ models.

4.4. Discussion of Trade-Offs

While encouraging, the promotion of rubber as a forest-friendly crop must be approached with caution. Poorly planned expansion may encroach upon natural ecosystems or lead to social displacement. Agroecological zoning and safeguards against conversion of high-biodiversity forests must be embedded in any incentive program. Additionally, price volatility in global rubber markets presents risks that require buffering mechanisms such as guaranteed minimum prices or crop insurance.

5. Conclusions

This study demonstrates that economic incentives, specifically natural rubber prices and CO_2 sequestration bonuses, can play a critical role in reducing deforestation in Colombia's forest frontiers. The econometric results show a clear negative relationship between rubber price increases and deforestation rates, indicating that market-based mechanisms can alter land-use dynamics in favor of conservation, especially in rural areas where alternative livelihoods are limited.

Moreover, the simulation of carbon-based payments suggests that integrating climate finance into rubber value chains could substantially enhance their financial attractiveness and long-term viability. Even moderate sequestration payments, if reliably delivered, can improve net returns and reduce the pressure to convert forest land for short-term economic gains.

From a theoretical perspective, these results align with the broader literature on Payment for Ecosystem Services (PES), showing that well-calibrated incentives can shift both economic behavior and social norms. The findings also reinforce the importance of combining commodity-based income with environmental performance bonuses to achieve multiple sustainability objectives, carbon storage, rural development, and forest protection.

However, the study also underscores that pricing incentives alone are insufficient. Successful implementation will require institutional coordination, agroecological safeguards, and participatory mechanisms that ensure smallholder inclusion. Without these, there is a risk that such programs could replicate past failures or unintentionally drive monocultures and land grabbing.

By offering empirical evidence and policy-relevant insights, this paper contributes to the ongoing discourse on how Colombia can build climate-smart, deforestation-free agricultural systems. With the right governance structures, pricing signals, and social engagement, natural rubber cultivation has the potential not only to support livelihoods but also to seed long-term ecological resilience.

6. Policy Recommendations

Based on the findings of this study, the following policy recommendations are proposed:

1. **Establish a Stable Floor Price for Natural Rubber in Priority Regions**
   The national government, in collaboration with the Confederación Cauchera de Colombia (CCC) and producer associations, should design a price stabilization mechanism to buffer rubber growers from volatility. A guaranteed minimum price can reduce the perceived economic risk and encourage longer-term investments in tree-based systems.
2. **Implement a Performance-Based CO_2 Sequestration Bonus**
   Launch a pilot program that pays smallholders for the verified carbon sequestration achieved through rubber agroforestry. Payments could be financed through climate funds, REDD+ jurisdictional programs, or public–private partnerships aligned with Colombia's Nationally Determined Contributions (NDCs).
3. **Prioritize Rubber Agroforestry in Agroecological Zoning and Development Plans**
   Encourage departments like Caquetá, Meta, and Guaviare to formally include rubber agroforestry in their territorial development strategies and land-use plans. Technical zoning should avoid replacing high-biodiversity forests and prioritize degraded lands or pasture recovery.
4. **Leverage Social Influence through Demonstration Farms and Peer Learning**
   Invest in visibility: demonstration plots, community-based training, and social marketing campaigns should highlight successful cases where rubber and conservation incentives improve livelihoods. These approaches can harness social learning and build collective momentum for sustainable transitions.
5. **Strengthen Institutional Coordination and Monitoring**
   Coordinate efforts between the Ministry of Agriculture, Ministry of Environment, regional environmental authorities (CARs), and local producer cooperatives to ensure aligned objectives and efficient monitoring. A digital MRV (Monitoring, Reporting, and Verification) platform could enhance transparency and track impact metrics such as forest cover and carbon sequestration.

References

Ahrends, A., Hollingsworth, P. M., Ziegler, A. D., Fox, J. M., Chen, H., Su, Y., & Xu, J. (2015). Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. *Global Environmental Change*, 34, 48–58. https://doi.org/10.1016/j.gloenvcha.2015.06.002

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

Engel, S., Pagiola, S., & Wunder, S. (2008). Designing payments for environmental services in theory and practice: An overview of the issues. *Ecological Economics*, 65(4), 663–674. https://doi.org/10.1016/j.ecolecon.2008.03.011

doi:10.20944/preprints202505.0413.v1

Fox, J., Castella, J. C., & Ziegler, A. D. (2014). Swidden, rubber and carbon: Can REDD+ work for people and the environment in Montane Mainland Southeast Asia? *Global Environmental Change*, 29, 318–326. https://doi.org/10.1016/j.gloenvcha.2014.04.007

García Romero, I. A., & Castilla, C. E. (2013). *Modelo productivo para el cultivo del árbol de caucho natural en la Orinoquía: Zonas de escape y no escape al Mal Suramericano de las Hojas del Caucho* (1st ed.). CENICAUCHO–CORPOICA.

IDEAM. (2022). *Informe técnico de deforestación 2021*. Instituto de Hidrología, Meteorología y Estudios Ambientales.

Pagiola, S., Honey-Rosés, J., & Freire-González, J. (2016). Evaluation of the effectiveness of payments for environmental services. *Oxford Review of Economic Policy*, 32(1), 132–151. https://doi.org/10.1093/oxrep/grv036

Rincón-Ruiz, A., & Kallis, G. (2013). Caught in the middle, Colombia's war on drugs and its effects on forest and people. *Geoforum*, 46, 60–78. https://doi.org/10.1016/j.geoforum.2012.12.009

Sterling, E. J., & Rodríguez, H. (2011). *Evaluación del riesgo de tizón foliar para clones de caucho en Colombia*. CCC–CORPOICA.

Stroud, N. J. (2008). Media use and political predispositions: Revisiting the concept of selective exposure. *Political Behavior*, 30, 341–366. https://doi.org/10.1007/s11109-007-9050-9

Tapiero, A. L., Martínez, A., León, G. A., et al. (2018). *Modelo productivo para el cultivo de caucho en Colombia, con énfasis en la Orinoquía y el Magdalena Medio*. AGROSAVIA–CENICAUCHO.

Velásquez, S. M., & Giraldo, D. H. (2014). Caracterización y evaluación del tiempo de vulcanización de caucho natural colombiano. *Ingeniería y Competitividad*, 16(2), 225–233. https://doi.org/10.25100/iyc.v16i2.3697

Warren-Thomas, E., Dolman, P. M., & Edwards, D. P. (2015). Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. *Conservation Letters*, 8(4), 230–241. https://doi.org/10.1111/conl.12170

Wunder, S. (2005). *Payments for environmental services: Some nuts and bolts* (CIFOR Occasional Paper No. 42). Center for International Forestry Research (CIFOR).