Research article

Assessing Land Use Change and Causes of Deforestation in the Last 30 Years Using Satellite Images in the Municipality of Cobija, Pando Province, Bolivian Amazonia

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Abstract This study employs advanced Geographic Information System (GIS) techniques and satellite imagery to conduct a comprehensive analysis of land use and land cover changes and deforestation trends over the course of three decades within the Cobija Municipality, situated in the heart of Bolivian Amazonia. The research focused on light on the intricate relationship between human activities, environmental alterations, and socio-economic conditions, particularly emphasizing Cobija city's susceptibility to illegal logging, heavily influenced by the region's low economic income. Within this geographic expanse, characterized by rich biodiversity and vast forest cover, Cobija grapples with pivotal challenges. Dominated by agroforestry (51.04%) and Amazonian fruit cultivation (29.16%) as primary economic activities, the area faced persistent hurdles in converting pastures into agriculturally viable fields. This struggle is compounded by socio-economic disparities, with 26.04% of the population earning the Bolivia's minimum wage, and a striking 61.45% subsisting on incomes below this threshold. Notably, Cobija, despite being a significant timber supplier, stands as one of Bolivia's poorest cities. The role of timber extraction significantly contributed to deforestation trends in Cobija, exacerbating the region's socio-economic challenges. The lure of profits from the timber trade amplified the pressures on forested areas, rendering Cobija highly susceptible to deforestation practices. The outcomes of this research underscore the urgent need for nuanced policy interventions. By integrating economic incentives into conservation strategies, policymakers can address the intricate interplay between socio-economic conditions and environmental conservation in Cobija. This holistic approach is essential to foster sustainable land management practices, mitigate deforestation, reduce erosion risk and preserve the ecological integrity of the Bolivian Amazonia.

Keywords land use and land cover, deforestation, satellite imagery, socio-economic conditions, Amazonia

INTRODUCTION

Tropical deforestation is an important issue because of its possible ecological, environmental, economic, and agronomic effects (Myers, 1995). Deforestation has occurred in the tropics throughout history (Tucker and Richards, 1983; Hecht and Cockburn, 1989; Williams,1989) and has accelerated recently, particularly in areas of seasonally deciduous tropical forests (Schmink and Wood, 1984; Janzen, 1986; Fearnside, 1986, Houghton, 1991; Skole and Tucker, 1993; Maass, 1995). Accurate information on the extent of tropical forests and deforestation is essential for estimation of changes in surface energy balance and atmospheric greenhouse gas emissions (Cook et al., 1990; Gash and Shuttleworth, 1991).

An important consideration among several factors affecting agricultural sustainability of land converted from rainforest to arable or pastoral land uses is adverse changes in soil properties that influence the soil's quality and productivity. Deforestation and intensive agricultural land use can lead to land degradation, with drastic adverse changes in soil properties such an increase in bulk density, a decrease in aggregation and aggregate size distribution, a reduction available water-holding capacity, a decrease in macro porosity and infiltration capacity (Lal and Cummings, 1979; Alegre et al., 1986), and an increase in susceptibility to erosion (Lal, 2003). These effects are exacerbated by a reduction in the activity and species diversity of soil fauna, a decrease in the quantity and quality of soil organic matter content, and a possible reduction in the formation of organic mineral complexes, etc. Intensive burning can also alter aggregate size distribution (Ghuman and Lal, 1989).

The research area of Cobija Municipality is in Bolivian Amazonia, serving as the capital of the Department of Pando and the Province of Nicolás Suárez. Over the past two decades, Cobija has experienced substantial deforestation rates (Bolivian National Statistical Institute, 2015). The progress of this phenomenon was significantly shaped by the prevailing socio-economic characteristics within the area, with this region standing out as one of the most economically deprived areas throughout Bolivia.

OBJECTIVE

The study aims to comprehensively analyze and quantitatively assess the evolving patterns of land use and land cover changes and deforestation within the specified region over the past three decades, concurrently investigating and discussing the causative factors driving deforestation trends.

METHODOLOGY

Site Description

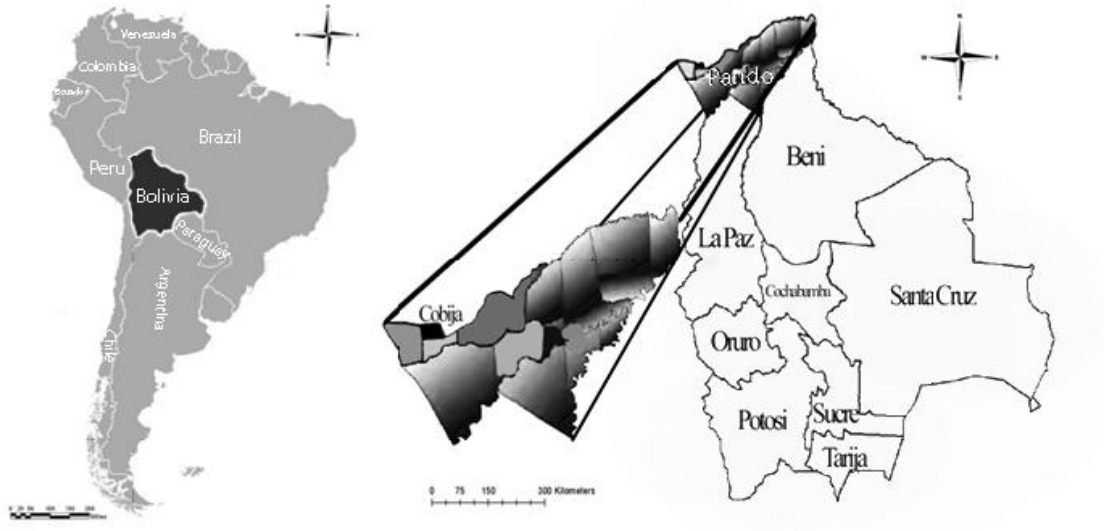

Fig. 1 Location of study area in Cobija, Bolivian Amazonia

The land uses were greatly influenced by the regional development strategy initiated by the Bolivian Government in 1989. Local farmers gradually transformed the forested landscape into other land uses. The climate in the study area is classified as equatorial, characterized by hot and humid conditions with a tropical transition. There is a distinct dry season from June to August, and the average annual precipitation is 2,016 mm (Mayoralty of Cobija, 2022). The research area spans 401

km^2, with an average annual temperature ranging from 32˚C to 24˚C. The monthly average air moisture ranges from 80 to 85 percent. The terrain is undulating, with elevations ranging from 100 to 120 meters above sea level.

Data Collection Strategy

The data was collected using Landsat satellite imagery from 1992 to 2023, strategically chosen to cover a three-decade timeline, facilitating a comprehensive analysis of temporal land use changes. Specifically sourced from Landsat 5, 7, and 8 satellites, ensured temporal consistency and access to diverse spectral bands essential for detailed land cover analysis. By meticulously curating these temporal intervals and satellite sources, this study dealt with the evolution of land use patterns within the Cobija Municipality over the last 30 years. This dataset empowered an in-depth examination of land cover dynamics.

Preprocessing Steps

Preprocessing of the Landsat imagery included radiometric and geometric corrections, using the Dark Object Subtraction (DOS) method in ArcGIS to mitigate atmospheric distortions. The annual selection of the best available image minimized cloud influence and atmospheric variability. This process standardized the dataset, harmonizing spectral responses across different sensors and acquisition dates, which facilitated a reliable analysis of land use dynamics and deforestation trends in Cobija Municipality.

Pixel-Level Analysis Preparation

Preprocessed Landsat imagery, prepared using ArcGIS, formed the basis for pixel-level analysis, including spectral analysis and classification, to assess land use and land cover changes and the causes of deforestation over the last 30 years in the Municipality of Cobija, Pando Province, Bolivian Amazonia. The preprocessing workflow in ArcGIS involved radiometric calibration, atmospheric correction, geometric alignment, and cloud masking to ensure the imagery was free from artifacts and distortions that could compromise accuracy. These steps harmonized spectral data across different acquisition dates and sensors, enabling precise pixel-by-pixel comparisons.

Land Cover Classification

Utilizing unsupervised classification techniques, this study delineated distinct clusters and patterns within the satellite imagery, facilitating the identification of varied land cover classes solely based on spectral characteristics. Not reliant on prior training data, this approach enabled a comprehensive exploration of the multifaceted land cover types prevalent in Cobija Municipality. This study used unsupervised classification algorithms like K-means and ISODATA to cover land map in Cobija using only the spectral information from satellite imagery.

These algorithms group similar pixels into clusters representing different land use and land cover types. ISODATA, specifically, refines these clusters by merging or splitting them based on statistical thresholds, effectively adjusting the number of classes to better capturing the complex spectral variations in the imagery and produce a more accurate land use and land cover map.

Socio-economic Analysis

In accordance with data sourced from the National Institute of Statistics in Bolivia (INE), the estimated population of Cobija city stands at 46,267 individuals. Of this population, 25.3% reside in rural areas, constituting a total of 11,708 rural inhabitants. Employing a confidence interval of 95% and a margin of error of 5%, the sample size utilized for the study was determined to be 96 individuals.

To those 96 individuals, socio-economic survey was conducted focusing on age, gender, farming experience, education, occupation, land size area, annual income, household size, agricultural activity, type of farming, in addition to deforestation reason.

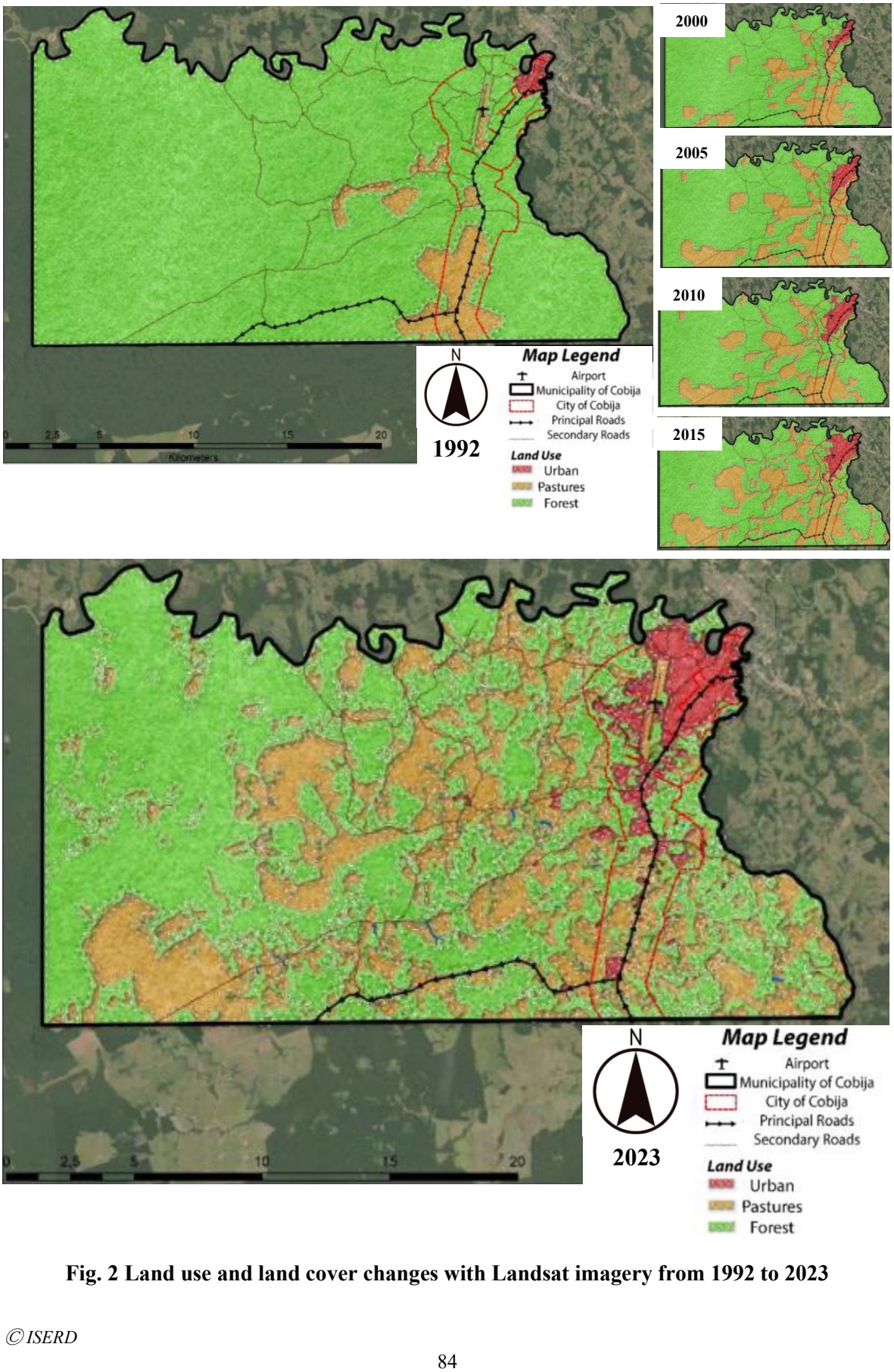

Fig. 2 Land use and land cover changes with Landsat imagery from 1992 to 2023

RESULTS AND DISCUSSION

Temporal Analysis of Land Use Changes

The analysis of Landsat imagery from 1992 to 2023 revealed distinct temporal trends in land use and land cover within the Cobija Municipality (Fig. 2, Tables 1 and 2). Over this three-decade period, noticeable shifts in land cover dynamics were observed, notably in forested areas. Initial assessments indicated a gradual decrease in forest cover, particularly between 2005 and 2015, followed by a potentially accelerated rate of deforestation by 2023. These findings suggest a concerning trend of land transformation.

Table 1 Land use and land cover changes in hectares from 1992 to 2023

	Year					
Land use	1992	2000	2005	2010	2015	2023
Forest	37546.63	31801.28	28354.71	27681.03	26121.14	24043.96
Pasture	1964.90	6544.32	9092.70	9283.15	10201.44	11737.27
Urban area	244.61	609.52	1034.58	1500.74	1924.80	2177.43
Agriculture	344.86	1154.88	1608.1	1636.08	1852.62	2141.34

Table 2 Land use and land cover changes in percentages from 1992 to 2023

	Year					
Land use	1992	2000	2005	2010	2015	2023
Forest	93.63%	79.28%	70.71%	69.03%	65.14%	59.96%
Pasture	4.90%	16.32%	22.70%	23.15%	25.44%	29.27%
Urban area	0.61%	1.52%	2.58%	3.74%	4.80%	5.43%
Agriculture	0.86%	2.88%	4.01%	4.08%	4.62%	5.34%

Analysis of land use and land cover changes between 1992 and 2023 revealed a significant shift in land cover within the study area. Forest cover experienced a substantial decline, decreasing from 93.63% (37,546.63 ha) in 1992 to 59.96% (24,043.96 ha) by 2023, representing a loss of over 13,500 ha. This loss is primarily attributed to the expansion of pastureland, which increased from 4.90% (1,964.90 ha) to 29.27% (11,737.27 ha) over the same period, indicating a strong trend of forest conversion for livestock grazing. While urban and agricultural areas also expanded, growing from 0.61% to 5.43% and 0.86% to 5.34%, respectively, their growth in terms of area was considerably less pronounced than the expansion of pastures. This analysis underscored the dominant role of pasture expansion as the primary driver of deforestation within the study area during the examined time frame.

Spatial Distribution of Deforestation

The spatial analysis of deforestation hotspots across the municipality exhibited spatial clustering primarily along the eastern and southern fringes, coinciding with increased expansion of pasture and urban areas. Notably, these areas exhibited consistent patterns of forest degradation and conversion to other land uses, highlighting specific regions that demanded immediate conservation attention.

Socio-economic Impact on Deforestation

In Bolivia, the department of Pando stands out as one of the most economically challenged regions, grappling with pronounced levels of extreme poverty, as identified by the FAO. Table 3 revealed a population primarily engaged in small-scale, subsistence or socio-communitarian agriculture, focused on agroforestry and Amazonian fruit production, characterized by low incomes, small landholdings (under 1 ha for 88.54% of respondents), and limited formal education. The primary driver of deforestation is economic necessity, with low income (46.87%) and low profitability of agriculture (19.80%).

Also, Fig. 3 illustrated a significant increase in timber price over the past three decades. Prices surged from USD 281 per 1,000 board feet in 1992 to USD 369 in 1996 and USD 430 in 2004. This upward trend intensified after 2015, with prices reaching USD 593 in 2018 and peaking at USD 1,500 in 2021. This trend on rising timber price directly incentivized logging activities, often leading to increased rates of deforestation, particularly in regions where governance and enforcement are weak (FAO and UNEP, 2020; Global Forest Watch, 2021). This escalating profitability has become a key driver of deforestation, particularly in regions with weak governance, such as Cobija, one of Bolivia's poorest cities. Cobija has a remote location, limited state oversight, and proximity to international borders facilitate illegal logging and timber trafficking. As a results, Bolivia's forest cover has declined significantly, from 93.63% in 1992 to 59.96% in 2023. This demonstrates the critical link between rising timber prices and accelerated deforestation in regions with high economic dependence on natural resources and limited regulatory capacity.

Table 3 Socio-economic profiles of farmers in the rural area of municipality of Cobija

Socio-economic characteristics	Frequency	Percentage	Socio-Economic characteristics	Frequency	Percentage
Age			Annual income		
Less than 40	43	44.79	More than 6,000 $	4	4.16
41-50	26	27.08	Between 4,000-6,000 $	8	8.33
54-60	13	13.54	Between 3,900-4,000 $	25	26.04
61-70	8	8.33	Between 740-3,900 $	38	39.58
Above 70	6	6.25	Less than 740$	21	21.88
Gender			Household size		
Male	52	52	1-5	30	31.25
Female	44	44	6-10	40	41.66
Others	4	4	11 persons or more	26	27.08
Farming experience			Agricultural activity		
1-5	8	8.33	Agroforestry	49	51.04
6-10	11	11.45	Rice production	5	5.20
11-15	35	36.45	Tuber production	6	6.25
16-20	26	27.08	Horticulture	8	8.33
More than 21	16	16.66	Fruits production	28	29.16
Education			Type of Farming		
Undergraduate	10	10.41	Extensive	9	9.37
High school	39	40.62	Commercial	20	20.83
Middle school	29	30.20	Subsistence	33	34.37
Basic school	18	18.75	Socio-communitarian	34	35.41
Occupation			Deforestation reason		
Employed	15	15.62	Low income	45	46.87
Self-Employed	75	78.13	Absence of landowner	11	11.45
Pensioner	6	6.25	Low productivity	12	12.50
Land size area			Low profitability	19	19.80
Less than 1 ha	85	88.54	No other income	9	9.37
Between 1 and 2 ha	6	6.25			
More than 2 ha	5	5.20			

Source: Field survey conducted in September 2018

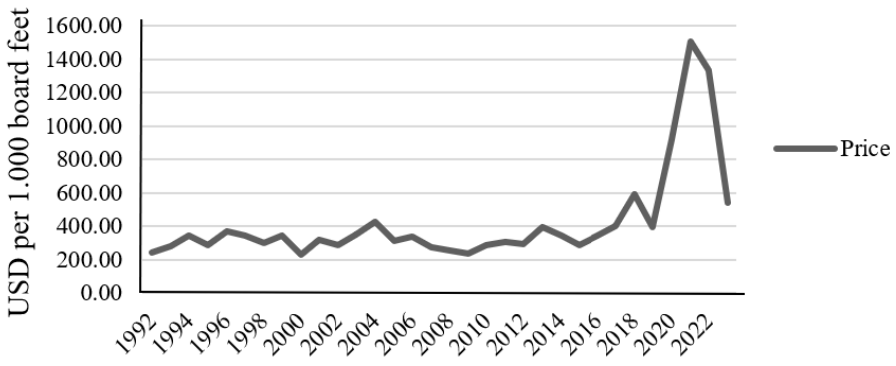

Fig. 3 Changes in timber price in USD for the last 30 years

Identification of Deforestation Drivers

Between 1992 and 2023, forest cover in Bolivia's Pando department declined sharply from 93.63% (37,546.63 ha) to 59.96% (24,043.96 ha), losing over 13,500 ha. Pasture expansion was the primary driver, growing from 4.90% (1,964.90 ha) to 29.27% (11,737.27 ha), fueled by economic necessity in one of Bolivia's poorest regions. In Pando, 88.54% of landholders operate under 1 ha, with low incomes and limited education. Economic pressures, including low income (46.87%) and unprofitable agriculture (19.80%), force land conversion. Rising timber prices, from USD 281 in 1992 to USD 1,500 in 2021, have further incentivized deforestation, particularly in regions like Cobija, where weak governance enables illegal logging. Combined these factors emphasize the urgent need for sustainable agriculture and stricter resource management to mitigate forest loss and support local livelihoods.

CONCLUSION

The land use and land cover analysis spanning from 1992 to 2023 revealed the decline of forest areas and transformation to other land uses. Especially concerning the forest areas, the data indicated a consistent decline over the three-decade period. Although forest area was 93.63% in 1992, it gradually reduced to 59.96% in 2023. This steady decline meant a substantial loss of the region's forested areas over time. Also, this study highlighted a significant land transformation from forest areas into alternative land uses, such as primarily for pastures, urban areas, and agricultural lands as shown in Fig. 2 and Tables 1 and 2. These changes have been progressed consistently over the past three decades in the study area. Among these transformations, the growth of pastures was remarkable. In 1992, pastures covered only 4.90% of the area, but it had risen to 29.27% in 2023. This steady increase suggested a deliberate shift driven by the economic challenges faced by local communities. The conversion to pastureland is particularly significant in regions like Pando, where subsistence agriculture dominates, and limited income opportunities accelerate deforestation.

It was considered that socio-economic conditions were directly related with deforestation. The cohesive analysis underscored the intricate interplay between economic activities, land ownership patterns, and environmental drivers, enriching our understanding of socio-economics influences on land use decisions and the multifaceted causes behind deforestation. Moreover, recognizing the pivotal role of wood prices in shaping land use, policymakers are urged to devise comprehensive strategies intertwining economic incentives with conservation efforts, imperative for fostering sustainable land management practices and mitigating deforestation's adverse impacts on local ecosystems and biodiversity.

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