Agroind. sci. 14(3): 217-223 (2024)

Agroindustrial Science

Website: http://revistas.unitru.edu.pe/index.php/agroindscience

Escuela de Ingeniería Agroindustrial

Universidad Nacional de Trujillo

Assessing the spatio-temporal impacts of land-use change in a primary forest of Ecuador

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ABSTRACT

This investigation focused on identifying deforested areas, tracking land use changes, and performing temporal analysis through thematic mapping in La Concordia canton, located in northwestern Ecuador. Utilizing NDVI analysis of Sentinel-2 L2A images from 2019, 2022, and 2023, the study assessed vegetation health and cover. NDVI values were categorized into land cover classes to calculate deforestation rates. The analysis reveals significant changes in La Concordia's vegetation, characterized by a decline in healthy vegetation and an increase in bare soil areas from 2019 to 2023, alongside a concerning deforestation rate of -3.89% over the same period. These findings underscore the urgent need for sustainable land management practices to address the impacts of agricultural expansion and intensification on the region's ecosystem.

Keywords: Deforestation; NDVI analysis; land use change; vegetation dynamics.

1. Introduction

Vegetation plays a critical role in maintaining the stability of terrestrial ecosystems, impacting everything from soil health and climate regulation to biodiversity and human well-being (Xu et al., 2022; Li et al., 2021). Changes in vegetation can significantly affect these factors, influencing global warming and the abundance of life (Huang et al., 2021). Sustainable forest management is crucial to achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda, particularly those related to food security, biodiversity conservation, and climate change (UN, 2015). However, global forest cover has declined from 31.6% to 30.6% between 1990 and 2015 (Giljum et al., 2022; Franco-Solís & Montanía, 2021). South America exemplifies this critical issue. While the region gained around 2 million hectares of agricultural land annually during this period, it lost over 3 million hectares of forest. The ABP region (Argentina, Brazil, and Paraguay) bore the brunt of this loss, with FAOSTAT data revealing an annual loss of over 5.5 million hectares of forest compared to a gain of 3 million hectares in agricultural land (López-Carr, 2021; Franco-Solís & Montanía, 2021).

Ecuador, once boasting remarkable tree diversity, lost a staggering 12% of its natural forest cover between 1990 and 2018, primarily due to land-use changes driven by urbanization, mining, oil extraction, livestock grazing, and agricultural expansion (Rivas et al., 2024; Kleemann et al., 2022). This deforestation, the worst in South America during the 1990s and 2000s, reached rates as high as -1.8% annually, fragmenting 30% of natural landscapes and impacting 47 ecosystems (López, 2022; Fischer et al., 2021; Ojeda, et al., 2020). The coastal region suffered the most, losing an alarming 678 square kilometers of forest per year between 1990 and 2008 (Rivas et al., 2021). Among these, the Chocó lowland evergreen forests faced the most exten-

Recibido 21 agosto 2024
Aceptado 8 octubre 2024

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DOI: http://doi.org/10.17268/agroind.sci.2024.03.04

sive deforestation, with an annual loss of 1.72% (Rivas et al., 2024).

La Concordia canton in Santo Domingo de Los Tsáchilas, Ecuador, is a haven of biodiversity, teeming with life at the convergence of two critically endangered hotspots: Tumbes Chocó Magdalena and Tropical Andes. This region boasts a staggering 2,000 plant species, 450 bird species, 44 mammals, 61 reptiles, and 38 amphibians. Despite the tireless efforts of wildlife rescue centers like "Sussan Shepard" and "James Brown" to rehabilitate fauna and restore fragmented forests, La Concordia faces a grave threat. Since 1990, the canton has lost 4,294 hectares of forest due to expanding agriculture for national and international markets. This deforestation disrupts the region's water balance, highlighting the urgent need for sustainable practices to conserve this irreplaceable ecosystem.

Advancements in remote sensing have revolutionized the acquisition of vegetation data, making it more accessible and comprehensive. A pivotal tool in this area is the Normalized Difference Vegetation Index (NDVI), which was developed in 1969 and has become instrumental in monitoring vegetation health due to its extensive historical data, ease of use, and compatibility with various satellite sensors (Jiang et al., 2021). In the context of conserving biodiversity in La Concordia canton, this study leverages NDVI and satellite imagery from Landsat 8 and 9 to address the challenge of deforestation. By analyzing data from 2019, 2022, and 2023, the study aims to identify areas that have experienced deforestation, monitor changes in land use, and perform a temporal analysis through thematic mapping. These maps will provide detailed insights into the current forest conditions in the canton, forming a critical foundation for updating Spatial Development Plans and designing effective conservation programs to protect these vital natural areas.

2. Materials and methods

Description of the study area

La Concordia canton, situated in northwestern Ecuador (Figure 1), experiences a humid tropical climate (Calderón et al., 2020). This 324.46 km² region, approximately 40 km distant from the provincial capital Santo Domingo, exhibits average tempe-ratures between 23-25.5 °C. The elevation ranges from 240 meters above sea level (masl) to a maximum of 315 masl. Precipitation is a defining characteristic, with historical records indicating a substantial 2,000 to 3,000 mm annually. Additionally, the relative humidity remains consistently high at 88% (Anzules-Toala et al., 2022).

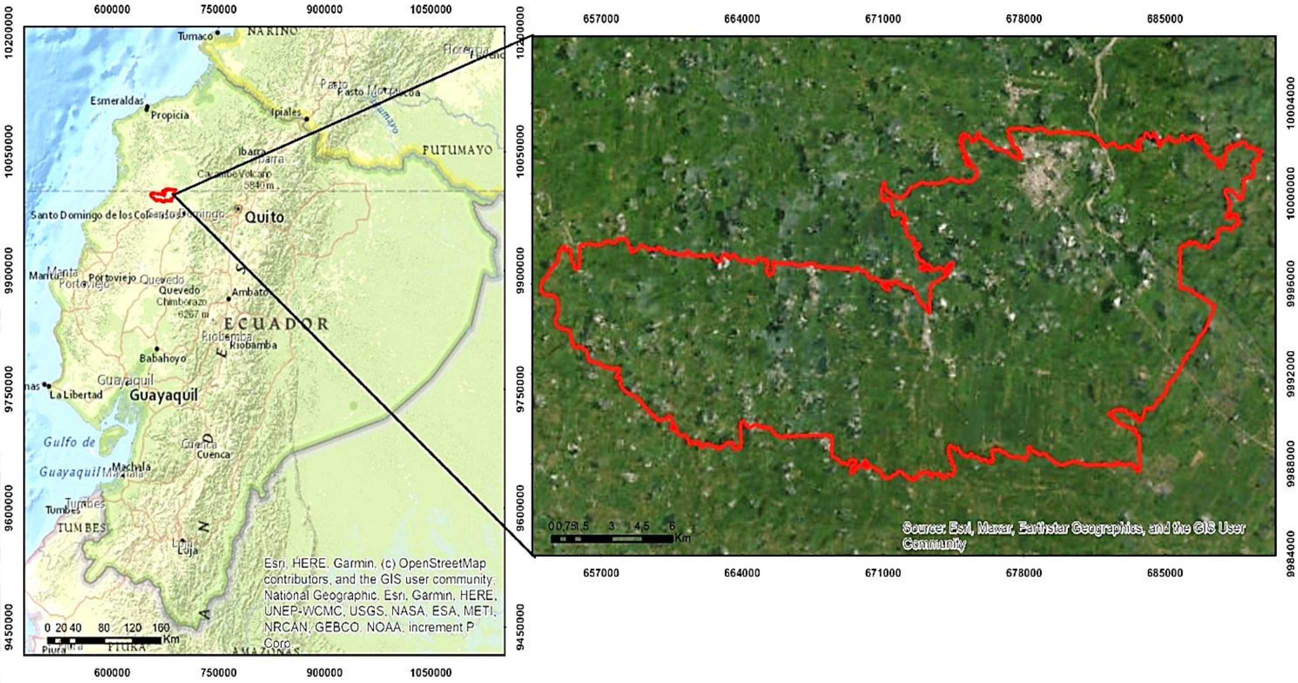

Figure 1. La Concordia canton, situated in northwestern Ecuador, spans 324.46 km² and features a humid tropical climate renowned for its substantial precipitation and high relative humidity.

Satellite image acquisition and processing

To analyze changes in the study area, three cloud-optimized Sentinel-2 Level-2A (L2A) images were acquired from the Copernicus Open Access Hub for the years 2019, 2022, and 2023. Cloud cover, a critical factor for satellite imagery in humid regions, was strictly limited to less than 20% in all images to ensure optimal data quality for further processing (Ochoa-Brito et al., 2023< Heredia et al., 2021).

Normalized Difference Vegetation Index (NDVI)

To estimate the vegetation health and cover within the study area, the Normalized Difference Vegetation Index (NDVI) was calculated for each Sentinel-2 L2A image (2019, 2022, 2023). NDVI leverages the spectral reflectance properties of vegetation. Plants absorb visible red light for photosynthesis but reflect near-infrared radiation (NIR). This phenomenon allows NDVI to be calculated using the equation [1] applied within the QGIS software's raster calculator tool:

$$NDVI = ((R_{IRC} - R_{R,vis}) \,/\, (R_{IRC} + R_{R,vis})) \qquad (1)$$

NDVI values typically range from -1 to +1. Dense and healthy vegetation with high chlorophyll content absorbs a significant portion of visible red light for photosynthesis while reflecting near-infrared radiation. This phenomenon results in high positive NDVI values (closer to +1). Conversely, sparse vegetation or areas with low plant cover reflect more visible light and less NIR, leading to lower NDVI values (closer to 0 or negative values in extreme cases).

In the study conducted by Hernández & Cima (2023), NDVI values were interpreted through a comprehensive analysis involving quantitative, colorimetric, and qualitative correlations to assess variations in vegetation conditions, as summarized in Table 1.

After generating NDVI raster for each year, a supervised classification was performed. This classification used the NDVI values defined in Table 1 to categorize the land cover within the study area. The resulting polygons representing different land cover types were then used to calculate the area (in hectares) of each class within the software.

Annual deforestation rate calculation

The average annual deforestation was calculated using the equation proposed by the Ministry of the Environment. This method involves calculating the change in forest area between two points in time in equation [2]. The annual deforestation rate was determined using the methodology proposed by FAO in 1995 (Puyravaud, 2002) [3].

$$R = \frac{A_1 - A_2}{t_2 - t_1} \qquad (2)$$

Where R: Average annual total deforestation for a given period; A_1: Initial Forest area (ha); A_2: Final Forest area (ha); t_1: Initial year; t_2: Final.

$$q = \left(\frac{1}{t_2 - t_1}\right) * Ln\left(\frac{A_2}{A_1}\right) * 100 \qquad (3)$$

Where q: Deforestation rate in continental Ecuador; A_1: Initial Forest area (ha); A_2: Final Forest area (ha); t_1= Initial year; t_2= Final year.

3. Results and discussion

Changes in vegetation health, soil coverage, and nutrient levels were assessed according to the criteria outlined in table 1. Over the three-year study period, variations in these classifications reveal significant trends. Healthy vegetation exhibited a pattern where its prevalence was highest in 2019 (28.06%), followed by a decrease in 2023 (24.02%), and the lowest in 2022 (17.58%). Vegetation experiencing a moderate nutrient shortage increased from 41.35% in 2019 to 48.97% in 2022, subsequently decreasing to 24.02% by 2023. Severe nutrient deficiencies affected 16.21% of vegetation in 2019, reduced to 14.62% in 2023, and further declined to 11.24% by 2024. Diseased or plagued vegetation accounted for 5.24% in 2019, rose to 8.73% in 2022, and then decreased to 6.12% in 2023. Sparse vegetation (bare soil) showed a consistent increasing trend over the years: 3.27% in 2019, 4.25% in 2022, and 4.44% in 2023, as depicted in Figure 2.

Table 1

Colorimetric correlation of NDVI values with biological components

Color	NDVI	Biological component
Red	⋜ 0.1 – 0.3	Sparse vegetation, bare soil, water stress or low planting density
Orange	0.3 – 0.4	Diseased and/or plagued vegetation
Yellow	0.4 – 0.5	Vegetation with strong nutrient deficiency
Light green	0.5 – 0.6	Vegetation with mild nutrient deficiency
Dark green	0.6 - 1	Healthy vegetation, very healthy plants

Source: Hernández et al. (2024).

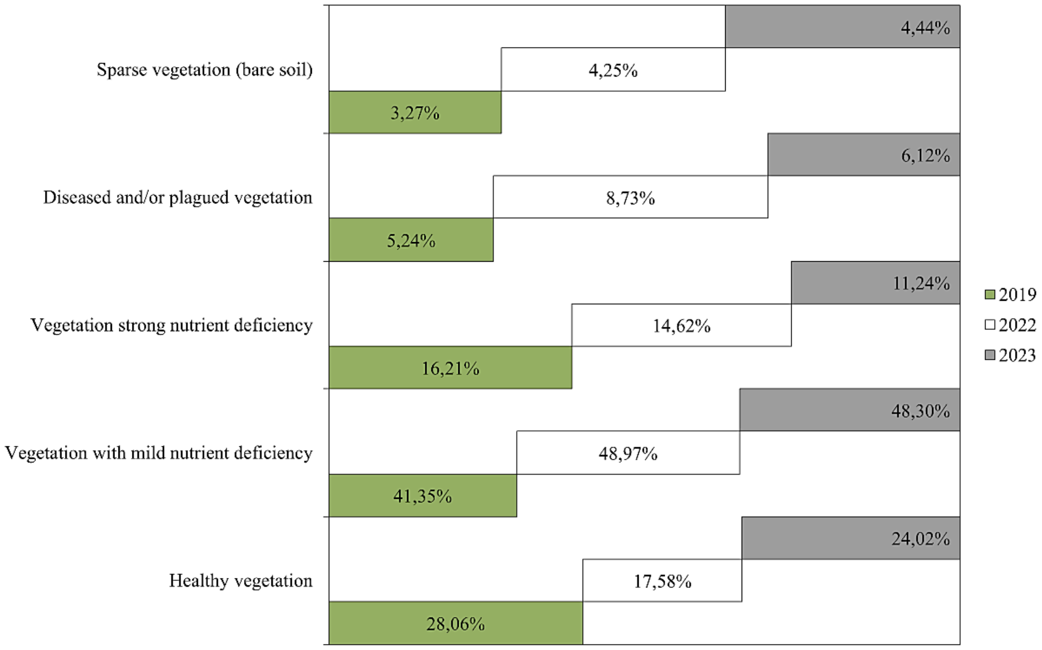

Figure 2. Percentage of the distribution of the types of vegetation analyzed during three different years.

NDVI analysis of La Concordia revealed significant vegetation changes between 2019, 2022 and 2023. A marked decline in vegetation cover, particularly in the western region, was evident in 2022, as indicated by the prevalence of lower NDVI values. While a partial recovery was observed in 2023, bare soil patches persisted, suggesting ongoing environmental pressures (Figure 3). Potential drivers of these changes include deforestation, land-use alterations, and the impacts of climate change. To comprehensively understand these dynamics, further analysis is essential. This includes change detection analysis, land cover classification, and correlation studies with environmental factors. Such in-depth analysis can inform targeted conservation strategies and sustainable land management practices for La Concordia.

NDVI time series analysis for La Concordia from 2019 to 2023 reveals significant changes in vegetation cover. A notable decline in vegetation, particularly in the western region, was observed in 2022, as indicated by lower NDVI values. Although there was partial recovery in 2023, persistent bare soil patches highlight ongoing environmental challenges. These trends align with regional patterns, as seen in Guayas province, where cropping intensity increased by 60% from 2001 to 2020 (Recuero et al., 2023), suggesting that agricultural expansion and intensification may be affecting La Concordia's vegetation.

In the Galapagos Islands, NDVI analysis showed a statistically significant annual increase of 1% over 19 years, potentially linked to anthropogenic climate change. However, a decline in NDVI between 2003 and 2010, attributed to ENSO events and volcanic eruptions, underscores the impact of natural disturbances on vegetation dynamics (Herrera et al., 2021). Conversely, mainland Ecuador experienced net biomass loss from 2000 to 2010 due to widespread deforestation, with the Amazon exhibiting higher vegetation vigor compared to the Andes and coastal areas (Llerena et al., 2019).

Villarreal-Veloz et al. (2023) identified complex relationships between NDVI and climatic factors in Ecuador. Vegetation showed positive correlations with precipitation and negative correlations with temperature, with interactions between these variables having a more pronounced effect on NDVI. Discharge flows also significantly influenced vegetation dynamics, revealing regional variations in response to climatic factors, with distinct patterns in coastal and western Andean areas compared to the Amazon and eastern Andes (Haro-Carrión et al., 2021).

Agricultural intensification in Argentina's Mesopotamian Pampa has driven significant land use changes, as evidenced by MODIS NDVI data (Baeza & Paruelo, 2020). This trend mirrors broader South American patterns where vegetation growth is strongly influenced by soil moisture dynamics. For instance, Álvarez & Poveda (2022) linked peak NDVI values in the Amazon to transitions between wet and dry periods, underscoring the critical role of water availability. Furthermore, Reyna et al. (2023) demonstrated a robust negative correlation between Sentinel-2 derived NDVI and soil C/N ratios in Polish forests, confirming NDVI as a valuable proxy for soil biological properties.

Between 2019 and 2023, La Concordia faced a deforestation rate of -3.89%, resulting in a total forest loss of approximately 347,875 hectares.

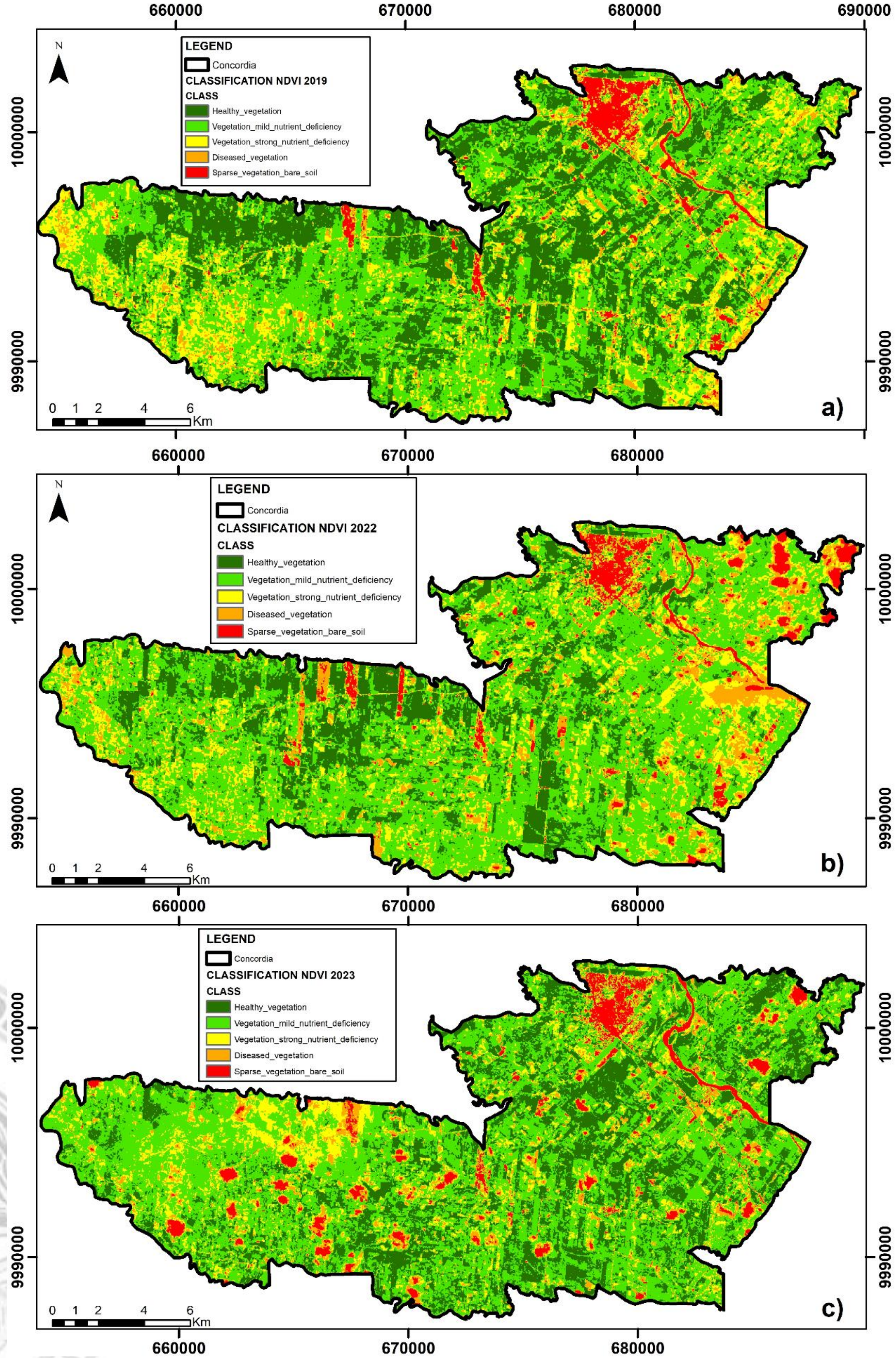

Figure 3. NDVI maps of La Concordia: Spatial distribution of vegetation indices in 2019 (a), 2022 (b), and 2023 (c).

This rapid deforestation, driven by agricultural expansion, illegal logging, and urban development, has led to biodiversity loss, soil erosion, climate change contributions, and socioeconomic impacts. Nationally, between 2000 and 2010, deforestation affected around 2,872 km² of forest, comparable to the size of Ecuador's Santa Elena or Carchi provinces (Calvas et al., 2024). In 2018, Ecuador had a deforestation rate of -0.50, with the Chocó-Darién region at -0.49, largely due to crop production (Ojeda et al., 2020). Leon et al. (2022) identified a causal relationship linking agriculture to deforestation, compounded by livestock and climate change.

In the Americas, 2020 saw the sixth highest peak in deforestation since 2004, with 5,430 hectares lost (Céspedes et al., 2023). From 2000 to 2020, forest loss was estimated at 20% in Argentina, 18% in Paraguay, and 13% in Brazil, with protected areas experiencing lower rates of deforestation (Mohebalian et al., 2022). Understanding the complex interplay between natural and anthropogenic factors influencing vegetation dynamics is crucial for effective land management and conservation strategies.

4. Conclusions

In conclusion, NDVI time series analysis reveals the complex interplay between natural and anthropogenic factors influencing vegetation dynamics, as exemplified by the case of La Concordia. The observed declines in vegetation cover and the deforestation rate of -3.89% due to agricultural expansion and intensification highlight the urgent need for sustainable land management practices. While this study provides valuable insights, further research is essential to fully comprehend the long-term implications of these changes. By combining remote sensing data with ground-truth observations and advanced modelling techniques, scientists can develop more accurate predictions and inform policy decisions aimed at mitigating the negative impacts of land-use change and climate variability on ecosystems.

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