Análisis multitemporal de cambios en el NDVI en una región con aprovechamiento forestal en la península de Yucatán, México

Multitemporal analysis of changes in NDVI in a region with forest harvesting

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Abstract

The forests of the Yucatán Peninsula have been periodically subjected to various natural and anthropogenic disturbance factors, among these are the occurrence of hurricanes and logging, the latter with a history of more than 300 years. The use of remote sensing has been widely employed for forest cover management and other land uses. Satellite information allows the calculation of several indexes that are useful for purposes of forest management, one of the most widely used is the Normalized Difference Vegetation Index (NDVI), which is associated with the fraction of solar radiation absorbed by plants. The objective of this study was to analyze the spatial-temporal dynamics of the NDVI changes in a region under forest harvesting in the state of Quintana Roo and determine their possible causes during the 1985-2022 period. A time series of NDVI values was generated from Landsat sensor images for the years 1985, 1993, 2000, 2010 and 2022. Differences in NDVI values were wide and appear to follow the recurrence of hurricanes in the region. Logging did not explain the upward and downward patterns in NDVI values, nor did these patterns coincide with the changes in vegetation, as they do not change the land cover characteristics. These results provide partial evidence that significant changes in vegetation characteristics occur only after major and extensive disturbances such as hurricanes.

Key words: Logging, hurricanes, satellite images, Yucatán Peninsula, disturbances, remote sensing.

Resumen

Las selvas de la Península de Yucatán han estado sujetas periódicamente a diferentes factores de perturbación natural y antropogénica, entre ellos la ocurrencia de huracanes y el aprovechamiento maderable, este último con una historia de más de 300 años. El uso de sensores remotos se ha empleado ampliamente para la gestión...
de coberturas forestales y otros usos del suelo. La información satelital permite el cálculo de diversos índices útiles para la administración forestal, uno de los más usados es el Índice de Vegetación de Diferencia Normalizada (NDVI) que se asocia a la fracción de la radiación solar absorbida por las plantas. El objetivo del presente estudio fue analizar la dinámica espacio-temporal de los cambios en el NDVI en una región con aprovechamiento maderable en el estado de Quintana Roo y determinar sus posibles causas durante el periodo 1985-2022. Se generó una serie de tiempo de valores de NDVI en imágenes de los sensores Landsat para los años 1985, 1993, 2000, 2010 y 2022. Las diferencias en los valores del NDVI fueron amplias y parecen seguir la recurrencia de huracanes en la región. La tala forestal no explicó los patrones al alza y a la baja en los valores del NDVI, ni coincidieron con las modificaciones en la vegetación, ya que no cambian las características de la cobertura del suelo. Estos resultados proporcionan evidencia parcial de que cambios significativos en las características de la vegetación solo ocurren después de perturbaciones importantes y extensas como los huracanes.

**Palabras clave:** Aprovechamiento forestal maderable, huracanes, imágenes satelitales, Península de Yucatán, perturbaciones, teledetección.

### Introduction

Setting the Amazon aside, the Mayan Rainforest of the Yucatán Peninsula is part of the largest tropical forest massif in the Americas. It extends through southern Mexico, Belize and northern Guatemala, and constitutes a unique biogeographic region covering an area of more than 14 million hectares (Rodstrom et al., 1999). Historically, it has had constant timber logging and has been the livelihood of the Mayan people for more than 300 years (Navarro-Martínez, 2011).

Commercial timber logging is important for the regional economy. Timber currently sustains a rural population grouped into approximately 150 ejidos in Campeche, Quintana Roo and Yucatán (information provided by the Secretaría de Medio Ambiente y Recursos Naturales (Ministry of Environment and Natural Resources)). In addition, these forests frequently suffer extreme weather events such as hurricanes, storms, and tropical depressions. Storms increase fuels on the ground, leading to more severe wildfires (Vester and Navarro, 2007). These phenomena impact vegetation canopies, causing damage such as defoliation, uprooting, and
breakage (Navarro and Granados, 1997; Navarro-Martínez et al., 2012). Disturbance then generates changes in forest cover.

Due to its economic and ecological importance, the Mayan rainforest in recent years has been the subject of research studying the dynamics in forest cover (Dupuy et al., 2012; Hernández-Gómez et al., 2019, 2020), deforestation (Ellis et al., 2017; Huchin et al., 2022), and human caused deterioration (Ellis et al., 2020, 2021). The estimation and dynamics in forest biomass and carbon, among other aspects, have also been addressed (Dai et al., 2014; Hernández-Stefanoni et al., 2018, 2020, 2021; Hernández and Ellis, 2023). Albeit little consideration has been given to understanding vegetation health (Huechacona-Ruiz et al., 2020).

Several methodologies exist to assess forest health, the most common of which is the estimation of vegetation indices using remote sensing techniques (Gilabert et al., 1997). Remote sensing is a key tool in forest management, providing valuable information on the forest cover, the forest structure, and its changes over time (Moizo, 2004; Torres-Rojas et al., 2016).

**Evaluation of vegetation quality and vigor**

The Normalized Difference Vegetation Index (NDVI) is one of the most widely used indexes for measuring the amount and health of forest vegetation (Manrique, 1999, Vázquez et al., 2013); it also allows monitoring seasonal and interannual changes in both photosynthetic activity and vegetation growth. The NDVI results from the normalized quotient between spectral bands that show a clear contrast between the visible ones (0.6 to 0.7 μm) and near-infrared (0.7 to 1.1 μm), making it possible to
characterize vegetation cover (Chuvieco, 2010). This index correlates with the chlorophyll content in the foliage, photosynthetically active radiation, net plant productivity and Leaf Area Index, among others (Chuvieco, 2010).

The NDVI has multiple applications, especially when observations form time series. Analysis of these series facilitates the monitoring of the vegetation and the detection of changes in land cover and land use (Vázquez et al., 2013; Hernández-Ramos et al., 2020), characterization of vegetation phenology, and monitoring of phenomena such as drought (Manrique, 1999). NDVI helps in the study of disturbed areas (Ruiz et al., 2017; Díaz et al., 2021).

The NDVI is a numerical indicator that quantifies the spectral difference between the red and near-infrared ranges of the electromagnetic spectrum, i. e., on a scale of -1 to 1, with values close to 1 indicating dense and healthy vegetation, and values close to -1 suggesting the presence of arid areas lacking vegetation or low photosynthetic activity (Alcaraz-Segura et al., 2008; Millano-Tudare et al., 2017).

This study analyzes the spatial-temporal dynamics of changes in NDVI in a region with forest logging in the state of Quintana Roo and to determine its possible causes during the 1985-2022 period.

Materials and Methods

Study area
The study area covered an area of 1 200 000 ha from the central zone of Quintana Roo, in Felipe Carrillo Puerto, Bacalar, José María Morelos and Othón P. Blanco municipalities. Geographically, it is located between zone 16 UTM: 341172.21 W and 2176773.48 N (point 1), 341124.94 W and 2130846.12 N (point 2), 386219.6 W and 2177180.19 N (point 3), and 385929.44 W and 2131213.15 N (point 4) (Conabio, 2023) (Figure 1).

![Location of the study area](image)

Océano Pacífico = Pacific Ocean; Mar Caribe = Caribbean Sea. The numbering corresponds to each point at the corner of the study area.

Prepared by the authors based on Conabio (2023).

**Figure 1.** Location of the study area.
The main vegetation type is tropical dry forest, which forms a large matrix interspersed with patches of flood plains, savannas, and crop fields (Conabio, 2023). Under this vegetation several types of soil have developed: lithosol, vertisol, and gleysol soils (Bautista et al., 2011). The average annual precipitation is 1290 mm, and the mean temperature is 26 °C (García, 2004).

Slash-and-burn agriculture and commercial timber harvesting both are important in the local economy (Morales, 2017). Currently, 23 timber species are harvested in the study area, mahogany (Swietenia macrophylla King) the one most sought after. In addition, other timber products such as palisade, charcoal and firewood are also harvested (Navarro et al., 2000).

**Imagery retrieval and processing**

The study area was selected because it contains a particular set of collective ownerships called ejidos that decided to introduce innovations in their forest management to explicitly address the ecology and dynamics of the forest, including natural disturbance regimes. Two spectral images from Landsat 5, 7, and 8, were used for each year of study, adding up to a total of ten images (Table 1). All images were taken during the dry season.

**Table 1.** Main characteristics of the satellite images used for the NDVI analysis.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Path*</th>
<th>Row*</th>
<th>Date</th>
<th>Sensor</th>
<th>Path*</th>
<th>Row*</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/01/1985</td>
<td>Landsat 5</td>
<td>19</td>
<td>46</td>
<td>09/02/2000</td>
<td>Landsat 5</td>
<td>19</td>
<td>47</td>
</tr>
<tr>
<td>14/01/1985</td>
<td>Landsat 5</td>
<td>19</td>
<td>47</td>
<td>28/02/2010</td>
<td>Landsat 7</td>
<td>19</td>
<td>46</td>
</tr>
</tbody>
</table>
The images were downloaded from The Copernicus Open Access Hub platform (https://scihub.copernicus.eu/). These images reach a resolution of 30×30 m (900 m²) per pixel. They contain less than 5 % cloudiness. Early processing included radiometric and atmospheric corrections. Visible and near-infrared spectrum bands were used (Vega *et al.*, 2008).

Images were analyzed with ArcGIS™ v.10.4 software (ESRI, 2015), using different scales that fit the resolution of the Landsat sensor (Lemma *et al.*, 2021).

**Normalized Difference Vegetation Index (NDVI)**

The *NDVI* was estimated using the near infrared and visible red spectral bands of the Landsat satellite sensors, using the following equation (Tecuapetla-Gómez *et al.*, 2022):

\[
NDVI = \frac{(\text{NIR} - \text{RED})}{(\text{NIR} + \text{RED})}
\]  

(1)
Where:

\( NDVI \) = Normalized Difference Vegetation Index

\( NIR \) = Near-infrared

\( RED \) = Visible red

Images shown in Table 1 allowed full coverage of the entire study area. Images were joined by pairs and by date to cover 1,200,000 ha and then generate \( NDVI \) for 1985, 1993, 2000, 2010 and 2022. Those time spans were chosen because they registered effects of known hurricanes and similar phenomena in the area. The \( NDVI \) was standardized considering 11 classes for a clearer depiction of index changes. A classification was obtained by dividing the total \( NDVI \) value into values every 0.05 steps.

The study area was divided into 1,200,000 one-hectare plots. \( NDVI \) values were collected from 385 random plots. The sample size was determined expecting a confidence interval of 95%, based on the following formula (Daniel, 1991):

\[
\text{Sample size} = \frac{z^2 \cdot p(1-p)}{e^2} \cdot \frac{1}{N} \\
(2)
\]

Where:

\( z \) = Punctuation

\( p = 0.5 \)

\( e \) = Margin of error
Analysis of the causes of changes in NDVI

A bibliographic review was carried out to explore possible causes of NDVI changes, including those derived from natural phenomena and anthropogenic activities such as silviculture, hurricanes, droughts, and fires in the study area and in the Yucatan Peninsula (Hammond, 1982; Suárez et al., 1994; Boose et al., 2003; Snook, 2005; Vester and Navarro, 2007; Navarro-Martínez, 2011; Navarro-Martínez et al., 2012; Márdero et al., 2012; Estrada-Medina et al., 2016; Rivera-Monroy et al., 2020; Sánchez-Rivera and Gómez-Mendoza, 2022). Forest plans from ejidos Chan Santa Cruz and Betania (Felipe Carrillo Puerto municipality), were additionally reviewed, along a previous regional land use cover study.

All factors considered, only hurricanes have shown an impact on the loss of vegetation cover at the largest scale of analysis as captured in its reflectance, hence in the NDVI.

Analysis of hurricanes relied on their trajectories. In order to do so, their paths were downloaded from the official NOAA web page (https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r00/access/shapefile/), as well as from a file with the extension (.shp) showing all hurricane paths in the region from 1972 to the present. These were trimmed to display only the study area. Subsequently, the radii of the segments of the hurricane trajectories were calculated using the formula published in the basic guide for the preparation of state hazard and risk atlases (SSPC-Cenapred, 2021).

The R-value of the maximum wind radius was estimated (in km) using the following equation (SSPC-Cenapred, 2021):
Where:

\( p_0 \) = Central pressure
\( e \) = Base of the natural logarithm (\( e = 2.71828 \))

**Results**

NDVI values varied between -0.59 and 0.5 depending on category and year of evaluation (Figure 2); thus, for the years 1985, 1993, 2000, 2010 and 2022, the lowest values (first category) were -0.58, -0.26, -0.59, -0.49, and -0.34, respectively. Negative values represent sites with sparse vegetation or less vigorous vegetation than sites with positive NDVI values. The closer to 1, the healthier the vegetation condition.
Figure 2. Normalized Difference Vegetation Index per year for 1 200 000 ha in the Mayan Forest of Quintana Roo.

A = 1985; B = 1993; C = 2000; D = 2010; E = 2022.
For all years, the highest value registered was 0.5, meaning there were major differences, particularly in the years 1985 to 1993 (Figure 3A), and from 1993 to 2000 (Figure 3B). The trend is consistent throughout periods. For instance, between 1985 and 1993 a decrease of 79.1 % was found. From 1993 to 2000 NDVI values dropped by 57.1 %, while in the 2000 to 2010 period, the NDVI rose by 83.7 %, suggesting vegetation recovery and improved vegetation quality (Table 2; Figure 4).

**Figure 3.** Average NDVI by period and date of occurrence of cyclonic phenomena in the Mayan Forest of Quintana Roo.
Table 2. Change in forest cover lost and recovered by period in the study area in hectares and percentage.

<table>
<thead>
<tr>
<th>Period</th>
<th>Lost surface area (ha)</th>
<th>%</th>
<th>Recovered surface area (ha)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985-1993</td>
<td>960 468</td>
<td>79.1</td>
<td>253 045</td>
<td>20.9</td>
</tr>
<tr>
<td>1993-2000</td>
<td>693 509</td>
<td>57.1</td>
<td>520 005</td>
<td>42.9</td>
</tr>
<tr>
<td>2000-2010</td>
<td>197 882</td>
<td>16.3</td>
<td>1 015 632</td>
<td>83.7</td>
</tr>
<tr>
<td>2010-2022</td>
<td>619 896</td>
<td>51.1</td>
<td>593 617</td>
<td>48.9</td>
</tr>
</tbody>
</table>

Figure 4. Annual changes in the average NDVI values for the central zone of the Mayan Rainforest of Quintana Roo during 1985 and 2020.

Regarding the occurrence of cyclonic phenomena in the study area, during 1988 and 2017, a total of ten events touched land in Quintana Roo, particularly in the south-central zone (Figure 5A): five hurricanes, two of Category 3 (Roxana and Dean), two of Category 1, and Gilberto of Category 5. Two storms and three tropical depressions also occurred (Table 3). Prior to these meteorological phenomena, seven additional events happened between 1972 and 1986 (Figure 5B). As can be seen in figures 5C and 5D, all these events impacted a wide swath that includes the
study area, therefore, it is reasonable to think that such phenomena might have driven large differences in NDVI values.


**Figure 5.** Trajectory and amplitude of meteorological phenomena in the study area.

**Table 3.** Occurrence of cyclonic events in the study area during the 1988–2017 period.

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Km h⁻¹</td>
</tr>
</tbody>
</table>

173
<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Category</th>
<th>Max NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilberto</td>
<td>1988</td>
<td>H5</td>
<td>259</td>
</tr>
<tr>
<td>Diana</td>
<td>1990</td>
<td>H1</td>
<td>140</td>
</tr>
<tr>
<td>Opal</td>
<td>1995</td>
<td>TD</td>
<td>55</td>
</tr>
<tr>
<td>Roxanne</td>
<td>1995</td>
<td>H3</td>
<td>185</td>
</tr>
<tr>
<td>Dolly</td>
<td>1996</td>
<td>H1</td>
<td>120</td>
</tr>
<tr>
<td>Cindy</td>
<td>2005</td>
<td>TD</td>
<td>55</td>
</tr>
<tr>
<td>Stan</td>
<td>2005</td>
<td>TS</td>
<td>74</td>
</tr>
<tr>
<td>Dean</td>
<td>2007</td>
<td>H3</td>
<td>203</td>
</tr>
<tr>
<td>Harvey</td>
<td>2017</td>
<td>TD</td>
<td>46</td>
</tr>
<tr>
<td>Franklin</td>
<td>2017</td>
<td>TS</td>
<td>95</td>
</tr>
</tbody>
</table>

H = Hurricane Category; TS = Tropical Storm; TD = Tropical Depression.

It is worth mentioning that, as is well known, the effects of such phenomena on the dynamics of forest cover loss and recovery are both immediate and long-term, as well as broad spatially. Thus, a sound analysis should consider the entire study period.

**Discussion**

**Changes in the NDVI values**

The NDVI values in 960 468 ha (79.1 % of the study area) were much higher in 1985 than their 1993 values. After that, in 2000 a total of 693 509 ha (57.1 %)
exhibited smaller NDVI values than in 1993. The NDVI of 2000 dropped in 2010 for 197,882 ha (6.3 %), while at the same time increased in 1,015,632 ha (83.7 %), which overall meant an important recovery of forest cover. Finally, from 2010 to 2022, the NDVI was down for 619,896 ha (51.1 %), canceling those index values that surged for 593,617 ha (48.9 %). These changes in NDVI values coincide with the findings of Sánchez-Rivera and Gómez-Mendoza (2022), who recorded that 67 % of the tropical cyclones that occurred in the Yucatán Peninsula negatively impacted the vegetation of the region, causing a decrease in NDVI values in the 2010 to 2022 time period.

The NDVI decreased in the study area from 57 % up to 79 % of cases out of a total of 1,200,000 plots in the 1985 to 2022 time period. Negative values correspond to natural water bodies or waterlogged areas, while positive values close to zero identify areas with scarce vegetation, and positive NDVI values closer to 0.5 correspond to dense jungle vegetation, as suggested by Inegi (2022).

**Analysis of the possible causes of changes in the NDVI**

Regarding the possible causes of changes in NDVI in the area and during the study period (1993-2022), several studies have shown that in the state of Quintana Roo forests with commercial logging are in better condition (Navarro-Martínez, 2011; Navarro, 2015; Rivera-Monroy et al., 2020). Although timber has been harvested for more than three centuries, the cutting intensity is so low (1-2 %) (Flachsenberg and Galletti, 1999), that the impact on the forest cover is practically imperceptible and canopy recovery is swift, therefore, this aspect has no apparent influence on NDVI values. In fact, Bray et al. (2004) and Durán-Medina et al. (2007) suggest that one
of the reasons for the maintenance of the forest cover in the Quintana Roo Mayan area is the community silviculture practiced since the early 1980s. Results presented here agree with the findings of other authors, who conclude that the impact and amplitude of hurricanes is generally increased by subsequent occurrence of forest fires, as in the cases of Gilberto, Opal, Roxanne and Dean (Navarro and Granados, 1997; Navarro-Martínez et al., 2012). For the Yucatán Peninsula, Snook (1993), and Vester and Navarro (2007) conclude that hurricanes create favorable conditions for forest regeneration and foster highly resilient forests. Moreover, these factors determine the dynamics of these ecosystems (Vester and Navarro, 2007).

In the study area, the NDVI may have been affected by the impacts on trees and vegetation with canopy loss due to the felling, topping, defoliation and death of trees damaged by extreme weather events. A reason for this stems from the fact that this index is related to the chlorophyll content in the foliage and photosynthetically active radiation (Pettorelli et al., 2005; Chuvieco, 2010). Wind damage can defoliate tree crowns by up to 100 % (Navarro-Martínez et al., 2012; Pat-Aké et al., 2018), which negatively affects NDVI values making them very low (Parenti, 2015).

**Conclusions**

The differences in NDVI values are wide and seem to follow the recurrence of hurricanes in the region. Forest harvesting does not explain the upward and downward patterns in NDVI values, nor do they coincide with changes in vegetation,
as silvicultural treatments do not change land cover characteristics. These results provide partial evidence that significant changes in vegetation characteristics can only occur after major and extensive disturbances such as hurricanes.

Acknowledgments

The authors are grateful to the Consejo Nacional de Humanidades, Ciencia y Tecnología (National Council for the Humanities, Science, and Technology) for the scholarship granted for the completion of the first author’s doctoral research.

Conflict of interest

The authors declare that they have no conflict of interest or any relationship with the institutions that supported the research.

Contributions by author

Alejandro Antonio Vela-Pelaez: he generated the idea, performed the data analysis, prepared the figures and tables for the manuscript, and wrote the first draft of the manuscript; María Angélica Navarro-Martínez: she contributed to the conceptualization and review of the manuscript and to the drafting of the final version; Martín Alfonso Mendoza Briseño: he contributed to the conceptualization, discussion and drafting of the various versions of the document; Joan Alberto Sánchez-Sánchez: he contributed to the preparation of the figures and to the analysis of the information; Ligia Guadalupe Esparza-Olguín: she participated in the conceptualization, discussion of ideas and revision of the overall document.
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