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Research article

# 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 *NVDI* 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 *NDV*I 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 *NVDI*, 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 $\mu$m) and near-infrared (0.7 to 1.1 $\mu$m), 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).

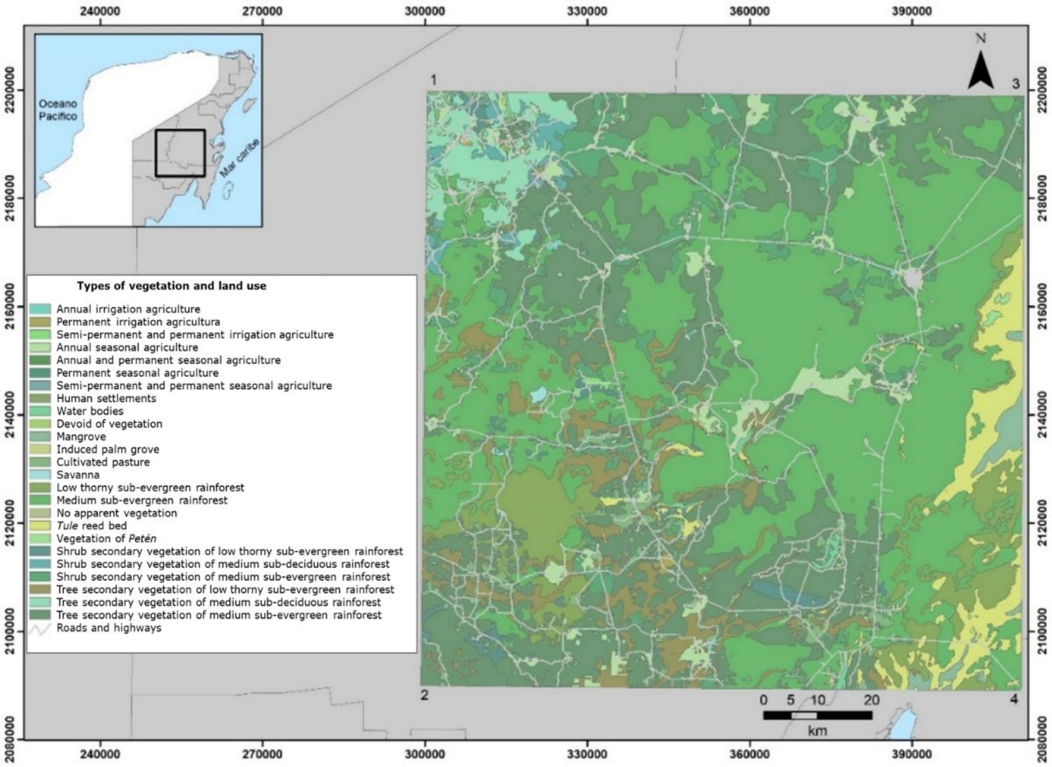
The *NDVI* is a numerical indicator that quantifies the spectral difference between the red and near-infrared ranges of the electromagnetic spectrum, *i. e.*, on a scale of -1 to 1, with values close to 1 indicating dense and healthy vegetation, and values close to -1 suggesting the presence of arid 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).



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, savannahs, 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 1 290 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.

| Date | Sensor | Path* | Row* | Date | Sensor | Path* | Row* |
|---|---|---|---|---|---|---|---|
| 14/01/1985 | Landsat 5 | 19 | 46 | 09/02/2000 | Landsat 5 | 19 | 47 |
| 14/01/1985 | Landsat 5 | 19 | 47 | 28/02/2010 | Landsat 7 | 19 | 46 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 21/02/1993 | Landsat 5 | 19 | 46 | 28/02/2010 | Landsat 7 | 19 | 47 |
| 21/02/1993 | Landsat 5 | 19 | 47 | 25/03/2022 | Landsat 8 | 19 | 46 |
| 09/02/2000 | Landsat 5 | 19 | 46 | 25/03/2022 | Landsat 8 | 19 | 47 |

* Row and column number within the scene catalog of the Landsat Worldwide Reference System that allows the image fragment to be identified, respectively.

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 $m^2$) 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):

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \quad (1)$$

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):

$$Sample\ size = \frac{\frac{z^2\ X\ \ p(1-p)}{e^2}}{1+\left(\frac{z^2\ X\ P(1-p)}{e^2 N}\right)} \qquad (2)$$

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):

$$R = 0.0007e^{0.01156p0} \qquad (3)$$

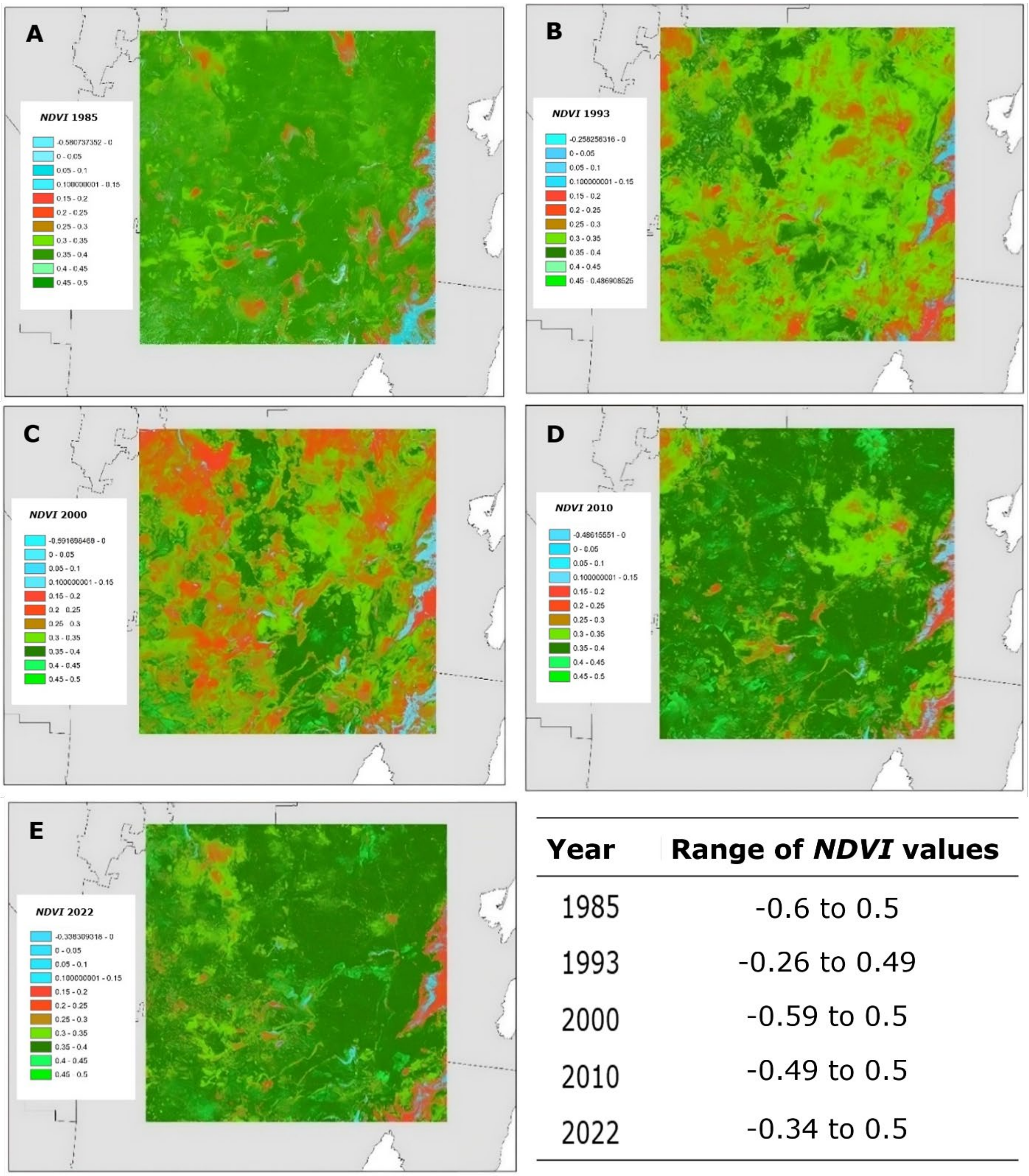
Where:

$p0$ = 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.



| Year | Range of *NDVI* values |
|---|---|
| 1985 | -0.6 to 0.5 |
| 1993 | -0.26 to 0.49 |
| 2000 | -0.59 to 0.5 |
| 2010 | -0.49 to 0.5 |
| 2022 | -0.34 to 0.5 |

A = 1985; B = 1993; C = 2000; D = 2010; E = 2022.

**Figure 2.** Normalized Difference Vegetation Index per year for 1 200 000 ha in the Mayan Forest of *Quintana Roo.*

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).

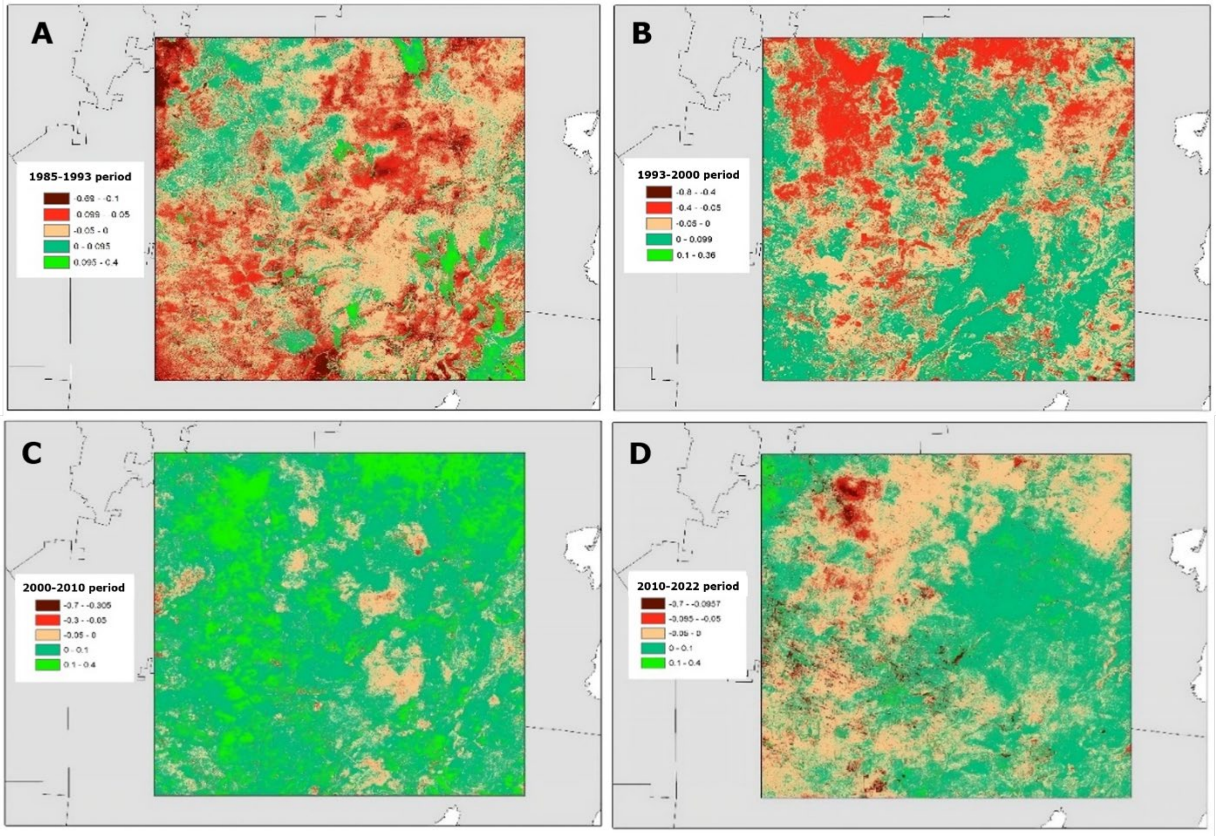


**Figure 3.** Average *NDVI* by period and date of occurrence of cyclonic phenomena in the Mayan Forest of *Quintana Roo.*

**Table 2.** Change in forest cover lost and recovered by period in the study area in hectares and percentage.

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

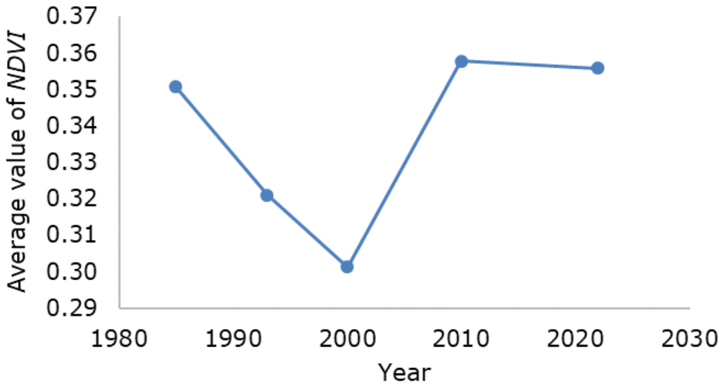
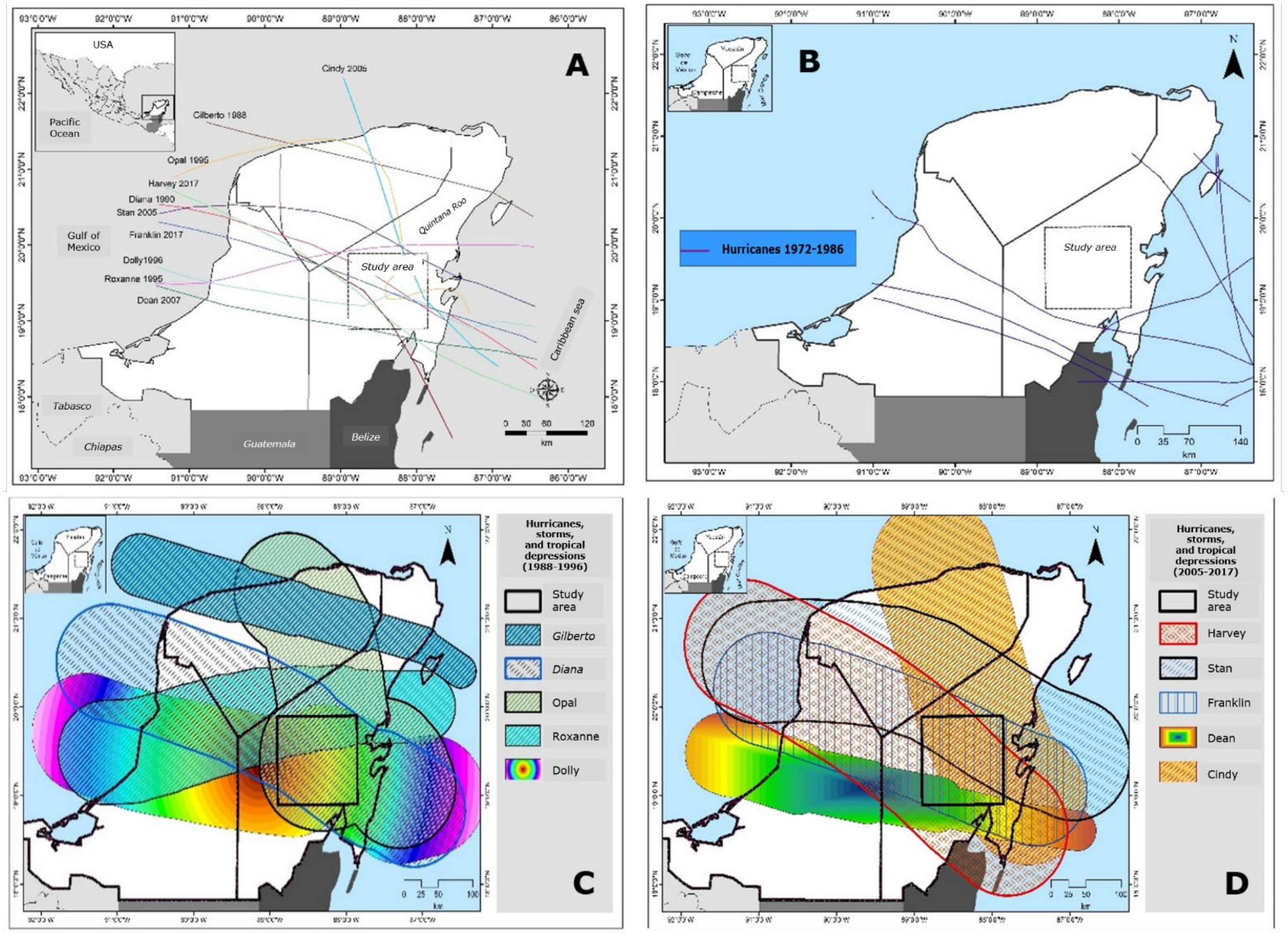


**Figure 4.** Annual changes in the average *NDVI* values for the central zone of the Mayan Rainforest of *Quintana Roo* during 1985 and 2020.

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.



A = 1988-2017; B = 1972-1986; C = Area of affectation between 1988 and 1996; D = Period 2005-2017.

**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.

| Name | Year | Intensity | Km h$^{-1}$ |
|---|---|---|---|

| | | | |
|---|---|---|---|
| *Gilberto* | 1988 | H5 | 259 |
| *Diana* | 1990 | H1 | 140 |
| Opal | 1995 | TD | 55 |
| Roxanne | 1995 | H3 | 185 |
| Dolly | 1996 | H1 | 120 |
| Cindy | 2005 | TD | 55 |
| Stan | 2005 | TS | 74 |
| Dean | 2007 | H3 | 203 |
| Harvey | 2017 | TD | 46 |
| Franklin | 2017 | TS | 95 |

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 *NVDI* 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.

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## 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.

# References

Alcaraz-Segura, D., G. Baldi, P. Durante y M. F. Garbulsky. 2008. Análisis de la dinámica temporal del NDVI en áreas protegidas: tres casos de estudio a distintas escalas espaciales, temporales y de gestión. Ecosistemas 17(3):108-117. https://www.revistaecosistemas.net/index.php/ecosistemas/article/view/82. (20 de mayo de 2023).

Bautista, F., G. Palacio-Aponte, P. Quintana and J. A. Zinck. 2011. Spatial distribution and development of soils in tropical karst areas from the Peninsula of Yucatan, Mexico. Geomorphology 135(3-4):308-321. Doi: 10.1016/j.geomorph.2011.02.014.

Boose, E. R., D. R. Foster, A. B. Plotkin and B. Hall. 2003. Geographical and historical variation in hurricanes across the Yucatán Peninsula. In: Gómez-Pompa, A., M. F. Allen, S. L. Fedick and J. J. Jiménez-Osornio (Edits.). The lowland Maya area: Three millennia at the human-wildland interface. Food Products Press. Binghamton, NY, United States of America. pp. 495-516.

Bray, D. B., E. A. Ellis, N. Armijo-Canto and C. T. Beck. 2004. The institutional drivers of sustainable landscapes: a case study of the “Mayan Zone” in Quintana Roo, Mexico. Land Use Policy 21(4):333-346. Doi: 10.1016/j.landusepol.2003.11.001.

Chuvieco S., E. 2010. Teledetección ambiental: la observación de la Tierra desde el espacio. Ariel. Barcelona, CT, España. 590 p.

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio). 2023. Mapa de uso de suelo y vegetación Serie VII. Portal de Geoinformación 2023. Sistema Nacional de Información sobre Biodiversidad (SNIB). http://www.conabio.gob.mx/informacion/gis/. (7 de enero de 2024).

Dai, Z., R. A. Birdsey, K. D. Johnson, J. M. Dupuy, J. L. Hernandez-Stefanoni and K. Richardson. 2014. Modeling carbon stocks in a secondary tropical dry forest in the Yucatan Peninsula, Mexico. Water, Air, & Soil Pollution 225:1-15. Doi: 10.1007/s11270-014-1925-x.

Daniel, W. W. 1991. Bioestadística. Base para el análisis de las ciencias de la salud. Limusa-Waley. Cuauhtémoc, México D. F., México. 667 p.

Díaz, A., L. Sáenz-Zúñiga y B. Zutta. 2021. Formación de un humedal en la costa norte del Perú: estabilidad biofísica y diversidad biológica. Revista Peruana de Biología 28(3):1-10. Doi: 10.15381/rpb.v28i3.21132.

Dupuy R., J. M., J. L. Hernández S., R. Hernández J., F. Tun D. y F. May P. 2012. Efectos del cambio de uso del suelo en la biomasa y diversidad de plantas leñosas en un paisaje de bosque tropical seco en Yucatán. Investigación Ambiental 4(1):130-140. https://cicy.repositorioinstitucional.mx/jspui/bitstream/1003/1242/1/id26022_Dupuy_Juan.pdf. (30 de octubre de 2023).

Durán-Medina, E., J. F. Mas y A. Velázquez. 2007. Cambios en las coberturas de vegetación y usos del suelo en regiones con manejo forestal comunitario y áreas naturales protegidas de México. In: Bray, D. B., L. Merino P. y D. Barry (Edits.). Los bosques comunitarios de México. Manejo sustentable de paisajes forestales. Instituto Nacional de Ecología (INE-Semarnat) y Consejo Civil Mexicano para la Silvicultura Sostenible (CCMSS). Coyoacán, México D. F., México. pp. 267-299.

Ellis, E. A., A. Navarro M., M. García O., I. U. Hernández G. and D. Chacón C. 2020. Forest cover dynamics in the Selva Maya of Central and Southern Quintana Roo, Mexico: deforestation or degradation? Journal of Land Use Science 15(1):25-51. Doi: 10.1080/1747423X.2020.1732489.

Ellis, E. A., A. Navarro-Martínez and M. García-Ortega. 2021. Drivers of forest cover transitions in the *Selva Maya*, Mexico: Integrating regional and community scales for landscape assessment. Land Degradation & Development 32(10):3122-3141. Doi: 10.1002/ldr.3972.

Ellis, E. A., I. U. Hernández-Gómez y J. A. Romero-Montero. 2017. Los procesos y causas del cambio en la cobertura forestal de la Península Yucatán, México. Ecosistemas 26(1):101-111. Doi: 10.7818/ECOS.2017.26-1.16.

Environmental System Research Institute (ESRI). 2015. ArcGIS version 10.4. Redlands, CA, United States of America. ESRI.

Estrada-Medina, H., V. Cobos-Gasca, J. L. Acosta-Rodríguez, S. Peña F., ... y R. L. Zapata-Luna. 2016. La sequía de la península de Yucatán. Tecnología y Ciencias del Agua 7(5):151-165. https://www.scielo.org.mx/pdf/tca/v7n5/2007-2422-tca-7-05-00151.pdf. (15 de abril de 2023).

Flachsenberg, H. y H. A. Galletti. 1999. El manejo forestal de la selva en Quintana Roo, México. In: Primack, R. B., D. Bray, H. A. Galletti e I. Ponciano (Edits.). La Selva Maya: conservación y desarrollo. Siglo XXI Editores. Coyoacán, México D. F., México. pp. 74-97.

García, E. 2004. Modificaciones al sistema de clasificación climática de Köppen. Instituto de Geografía de la Universidad Nacional Autónoma de México. Coyoacán, México D. F., México. 90 p.

Gilabert, M. A., J. González-Piqueras y J. García-Haro. 1997. Acerca de los índices de vegetación. Revista de Teledetección 8:1-10. https://www.researchgate.net/publication/39195330_Acerca_de_los_indices_de_vegetacion. (28 de julio de 2023).

Hammond, N. 1982. Ancient Maya civilization. Rutgers University Press. New Piscataway, NJ, United States of America. 348 p.

Hernández G., I. U. and E. A. Ellis. 2023. Selective logging and shifting agriculture may help maintain forest biomass on the Yucatan peninsula. Land Degradation & Development 34(14):4456-4471. Doi: 10.1002/ldr.4789.

Hernández-Gómez, I. U., C. R. Cerdán-Cabrera, A. Navarro-Martínez, D. Vázquez-Luna, S. Armenta-Montero and E. A. Ellis. 2019. Assessment of the CLASlite forest monitoring system in detecting disturbance from selective logging in the Selva Maya, Mexico. Silva Fennica 53(1):1-10. Doi: 10.14214/sf.10012.

Hernández-Gómez, I. U., D. Vázquez-Luna, C. R. Cerdán-Cabrera, A. Navarro-Martínez and E. A. Ellis. 2020. Mapping disturbance from selective logging in tropical forest of the Yucatan Peninsula, México. Tropical and Subtropical Agroecosystems 23(1):1-19. Doi: 10.56369/tsaes.2952.

Hernández-Ramos, J., X. García-Cuevas, R. Pérez-Miranda, A. González-Hernández y L. Martínez-Ángel. 2020. Inventario y mapeo de variables forestales mediante sensores remotos en el estado de Quintana Roo, México. Madera y Bosques 26(1):1-17. Doi: 10.21829/myb.2020.2611884.

Hernández-Stefanoni, J. L., G. Reyes-Palomeque, M. Á. Castillo-Santiago, S. P. George-Chacón, … and J. M. Dupuy. 2018. Effects of sample plot size and GPS location errors on aboveground biomass estimates from LiDAR in tropical dry forests. Remote Sensing 10(10):1586. Doi: 10.3390/rs10101586.

Hernández-Stefanoni, J. L., M. Á. Castillo-Santiago, J. Andres-Mauricio, C. A. Portillo-Quintero, F. Tun-Dzul and J. M. Dupuy. 2021. Carbon stocks, species diversity and their spatial relationships in the Yucatán Peninsula, Mexico. Remote Sensing 13(16):3179. Doi: 10.3390/rs13163179.

Hernández-Stefanoni, J. L., M. Á. Castillo-Santiago, J. F. Mas, C. E. Wheeler, … and J. M. Dupuy. 2020. Improving aboveground biomass maps of tropical dry forests by integrating LiDAR, ALOS PALSAR, climate and field data. Carbon Balance and Management 15:1-17. Doi: 10.1186/s13021-020-00151-6.

Huchin O., S. A., A. Navarro-Martínez, E. A. Ellis e I. U. Hernández G. 2022. Deforestación en el municipio de Bacalar, Quintana Roo, México durante el período 1993-2017. Madera y Bosques 28(3):1-13. Doi: 10.21829/myb.2022.2832396.

Huechacona-Ruiz, A. H., J. M. Dupuy, N. B. Schwartz, J. S. Powers, … and J. L. Hernández-Stefanoni. 2020. Mapping tree species deciduousness of tropical dry forests combining reflectance, spectral unmixing, and texture data from high-resolution imagery. Forest 11(11):1234. Doi: 10.3390/f11111234.

Instituto Nacional de Estadística y Geografía (Inegi). 2022. Índice de Vegetación de Diferencia Normalizada NDVI Landsat, 1984-2021. Aguascalientes, Ags., México. 7 p. https://www.inegi.org.mx/contenidos/productos/prod_serv/contenidos/espanol/bvinegi/productos/nueva_estruc/889463908272.pdf. (7 de enero de 2024).

Lemma, D. B., K. T. Gebretsadik and S. K. Debela. 2021. Forest cover change detection in relation to climate variability and LULC changes using GIS and RS techniques. A case of the Kafa zone, southwest Ethiopia. Journal of Water and Land Development (51):152-162. Doi: 10.24425/jwld.2021.139025.

Manrique, E. G. 1999. Índice de vegetación. Aplicación del NDVI. In: Asociación Española de Teledetección (Edit.). Teledetección. Avances y Aplicaciones. VIII Congreso Nacional de Teledetección. Asociación Española de Teledetección. Albacete, AB, España. pp. 217-219.

Márdero, S., E. Nickl, B. Schmook, L. Schneider, … y D. Lawrence. 2012. Sequías en el sur de la península de Yucatán: análisis de la variabilidad anual y estacional de la precipitación. Investigaciones Geográficas (78):19-33. https://www.scielo.org.mx/pdf/igeo/n78/n78a3.pdf. (22 de abril de 2023).

Millano-Tudare, J. L., F. J. Paredes-Trejo, E. Jaimes, N. Pineda, … e I. Pineda. 2017. Patrones fenológicos de cinco tipos de cobertura en bosque seco tropical, sur-cojedes, Venezuela. Revista Agrollania 14:106-112. http://www.postgradovipi.50webs.com/archivos/agrollania/2017/agro16.pdf. (14 de septiembre de 2023).

Moizo M., P. 2004. La percepción remota y la tecnología SIG: una aplicación en Ecología de Paisaje. GeoFocus Revista Internacional de Ciencia y Tecnología de la Información

Geográfica (4):1-24. https://www.geofocus.org/index.php/geofocus/article/view/40. (12 de septiembre de 2023).

Navarro M., M. A. 2015. Diagnóstico del estado actual de *Swietenia macrophylla* King (caoba) en los bosques manejados de Quintana Roo, México: perspectivas para su manejo. Tesis de Doctorado. Centro de Investigaciones Tropicales, Universidad Veracruzana. Xalapa-Enríquez, Ver., México. 132 p.

Navarro M., M. A. y D. Granados S. 1997. Dinámica sucesional en un bosque tropical afectado por disturbios en la zona norte de Quintana Roo. Revista Chapingo Ciencias Forestales 1:5-16. https://es.scribd.com/document/456410413/rchscfaIII2164-pdf. (18 de agosto de 2023).

Navarro M., M. A., B. Schmook y J. Martínez C. 2000. Manejo tradicional de hubches en una comunidad maya de Quintana Roo. Foresta Veracruzana 2(1):19-30. https://www.redalyc.org/articulo.oa?id=49720102. (20 de agosto de 2023).

Navarro-Martínez, A., R. Durán-García y M. Méndez-González. 2012. El impacto del huracán *Dean* sobre la estructura y composición arbórea de un bosque manejado en Quintana Roo, México. Madera y Bosques 18(1):57-76. Doi: 10.21829/myb.2012.1811138.

Navarro-Martínez, M. A. 2011. La caoba. Más de un siglo de aprovechamiento. In: Pozo, C., N. Armijo C. y S. Calmé (Edits.). Riqueza biológica de Quintana Roo. Un análisis para su conservación. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio), Colegio de la Frontera Sur (Ecosur) y Gobierno del Estado de Quintana Roo. Tlalpan, México D. F., México. pp. 212-220.

Parenti, M. S. 2015. Hurricane effects on mangrove canopies observed from MODIS and SPOT imagery. Cornell University. Ithaca, NY, United States of America. 48 p.

Pat-Aké, I., L. del C. Cámara-Cabrales, S. Ward, P. Martínez-Zurimendi, … y N. Sorensen. 2018. Efecto del huracán Dean en la dinámica estructural de selvas bajo manejo forestal en Quintana Roo, México. Madera y Bosques 24(2):1-17. Doi: 10.21829/myb.2018.2421585.

Pettorelli, N., J. O. Vik, A. Mysterud, J. M. Gaillard, C. J. Tucker and N. C. Stenseth. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends in Ecology & Evolution 20(9):503-510. Doi: 10.1016/j.tree.2005.05.011.

Rivera-Monroy, V. H., L. M. Farfán, L. Brito-Castillo, J. Cortés-Ramos, … and J. I. Euan-Ávila. 2020. Tropical cyclone landfall frequency and large-scale environmental impacts along Karstic Coastal Regions (Yucatan Peninsula, Mexico). Applied Sciences 10(17):5815. Doi: 10.3390/app10175815.

Rodstrom, C., S. Olivieri y L. Tangley. 1999. Un enfoque regional de la conservación en la Selva Maya. In: Primack, R. B., D. Bray, H. A. Galletti e I. Ponciano (Edits.). La Selva Maya: conservación y desarrollo. Siglo XXI Editores. Coyoacán, México D. F., México. pp. 23-42.

Ruiz D., M. E., M. E. Orozco H., R. Granados R. y G. Álvarez A. 2017. Cambio de uso de suelo e índice de vegetación de diferencia normalizada (*NDVI*), subcuenta del Río Salado, México. Geografía y Sistemas de Información Geográfica 9(9):39-50. http://ri.uaemex.mx/bitstream/handle/20.500.11799/68525/02%20Cambio%20de%20uso%20de%20suelo.pdf?sequence=1&isAllowed=y. (14 de abril de 2023).

Sánchez-Rivera, G. and L. Gómez-Mendoza. 2022. Tropical cyclone effects on vegetation resilience in the Yucatan Peninsula, México, between 2000-2012. Investigaciones Geográficas (77):203-220. Doi: 10.14198/INGEO.18499.

Secretaría de Seguridad y Protección Ciudadana (SSPC) y Centro Nacional de Prevención de Desastres (Cenapred). 2021. Guía básica para la elaboración de Atlas Estatales y Municipales de peligros y riesgos. Evaluación de la vulnerabilidad física y social. SSPC y Cenapred. Coyoacán, Cd. Mx., México. 166 p. https://www.cenapred.unam.mx/es/Publicaciones/archivos/57.pdf. (20 de agosto de 2023).

Snook, L. K. 1993. Stand dynamics of mahogany (*Swietenia macrophylla* King) and associated species after fire and hurricane in the tropical forest of the Yucatan Peninsula, Mexico. Dissertation, Doctor of Forestry. Faculty of the School of Forestry and Environmental Studies, Yale University. 254 p.

Snook, L. K. 2005. Aprovechamiento sostenido de caoba en la Selva Maya de México. De la conservación fortuita al manejo sostenible. Recursos Naturales y Ambiente (44):9-18. https://www.cifor.org/publications/pdf_files/articles/ASnook0505.pdf. (12 de abril de 2023).

Suárez, E., A. M. Sánchez, E. F. Cabrera y T. Pulido. 1994. Estudio integral de la frontera México-Belice, Recursos Naturales. Centro de Investigaciones de Quintana Roo A. C. Chetumal, Q. Roo, México. 211 p.

Tecuapetla-Gómez, I., A. Carbajal-Domínguez y V. Montesinos-Chica. 2022. Clasificación de tendencias de NDVI en la Península de Yucatán, México, de 2014 a 2020. Investigaciones Geográficas (109):1-19. Doi: 10.14350/rig.60629.

Tobasura M., D. 2017. Mitigación del cambio climático en Felipe Carrillo Puerto, México: Expectativas y divisiones por el territorio. Ecología Política (53):80-83. https://dialnet.unirioja.es/servlet/articulo?codigo=6063837. (15 de mayo de 2023).

Torres-Rojas, G., M. E. Romero-Sánchez, E. Velasco-Bautista y A. González-Hernández. 2016. Estimación de parámetros forestales en bosques de coníferas con técnicas de percepción remota. Revista Mexicana de Ciencias Forestales 7(36):7-24. Doi: 10.29298/rmcf.v7i36.56.

Vázquez, P., E. Adema y B. Fernández. 2013. Dinámica de la fenología de la vegetación a partir de series temporales de NDVI de largo plazo en la provincia de La Pampa. Ecología Austral 23:77-86. http://www.scielo.org.ar/pdf/ecoaus/v23n2/v23n2a01.pdf. (13 de junio de 2023).

Vega G., Á., J. López-García y L. de L. Manzo D. 2008. Análisis espectral y visual de vegetación y uso del suelo con imágenes Landsat ETM+ con apoyo de fotografías aéreas digitales en el Corredor Biológico Chichinautzin, Morelos, México. Investigaciones Geográficas Boletín del Instituto de Geografía (67):59-75. Doi: 10.14350/rig.17990.

Vester, H. F. M. y M. A. Navarro M. 2007. Árboles maderables de Quintana Roo: fichas ecológicas. El Colegio de la Frontera Sur (Ecosur), Consejo Nacional de Ciencia y Tecnología (Conacyt), Gobierno del Estado de Quintana Roo y Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio). Chetumal, QR, México. 139 p.