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Altitudinal effect and multitemporal analysis of tree structure, distribution and richness in the Sierra Juárez of Ixtlán, Oaxaca, Mexico

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ABSTRACT

Objective: To determine the effect of altitude on tree structure, distribution, and species richness in the Sierra Juárez, Oaxaca, Mexico.
Design/methodology/approach: Satellite image analyses were conducted to assess the altitudinal effect and changes in vegetation health using the Normalized Difference Vegetation Index (NDVI).
Results: The relationship between biomes and altitude indicates that temperate forests at high elevations exhibit more than 55% species similarity. Tropical humid forests at lower elevations show approximately 48% similarity, while mountain humid forests at very high elevations present 45% similarity. Altitudinal and topographical effects in the Sierra Juárez are determining factors shaping the tree component.
Findings/Conclusions: This study contributes to the identification of altitudinal zones of tree assemblages distributed across different biomes.

Keywords: Comaltepec, Ixtepeji, Jaltianguis, NDVI, Oaxaca, tree stratum.

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INTRODUCTION

In Mexico, temperate ecosystems consist primarily of coniferous and oak forests that harbor high biological diversity distributed across broad areas, representing the cumulative effect of numerous regional differences in floristic composition, including several endemic and restricted-distribution species (Huerta-Martínez *et al.*, 2014). Various studies have addressed the structure, composition, richness, and diversity of temperate forests in different states of the country; however, analyses evaluating environmental and topographic parameters along altitudinal gradients remain relatively scarce (Sánchez-Gutiérrez, 2019; Holguín-Estrada *et al.*, 2021; García-García, 2023). Temperate ecosystems cover 17.4% of the national territory and are distributed across the Sierra Madre Oriental, Sierra Madre Occidental, Trans-Mexican Volcanic Belt, and Sierra Madre del Sur. They

form part of the typical vegetation of non-tropical latitudes, comprising vegetation that integrates distinct biomes and related ecosystems (Tamayo, 1990; Challenger, 2003). These temperate ecosystems depend not only on the presence of mountainous systems but also on climatic, edaphic, and orographic factors, as well as biogeographic history and the occurrence of specific floristic elements that are absent in temperate forests at higher elevations (Rzedowski, 1978; Challenger, 1998; Sánchez *et al.*, 2003; Holguín-Estrada *et al.*, 2021). Geographic variations such as climate, topography, and soil, which are associated with vegetation composition and structure, contribute to the establishment of boundaries between ecoregions (Torres-Robles *et al.*, 2015).

The influence of biotic and abiotic factors establishes species distribution patterns; likewise, structural analyses focus on understanding forest diversity in order to assess its response to different environmental changes (Cortés-Castelán & Islebe, 2005; Graciano-Ávila *et al.*, 2017). Vegetation and environmental conditions associated with ecoclimatic characteristics —such as radiation, precipitation, microrelief, and aspect— as well as microtopographic variables including steep slopes related to altitude and climate, affect soil properties and soil formation processes across landscapes, thereby determining vegetation assemblages typical of non-tropical latitudes (Llorente-Bousquets & Morrone, 2001; Sánchez *et al.*, 2003). Thus, the main factors determining the distribution of temperate ecosystems are altitude, rainfall abundance, and rainfall seasonality, which define the so-called ecological belts or distribution patterns (Challenger, 2003; Mazzola *et al.*, 2008). In contrast, the factors shaping the composition, diversity, and structure of plant communities depend on spatial scale, topographic features, temperature, and changes in precipitation levels associated with elevation (Cuyckens *et al.*, 2015).

Habitat fragmentation makes the implementation of classical sampling methodologies for assessing tree distribution and species richness more challenging. Currently, remote sensing has become a valuable tool because its spatial, spectral, radiometric, and temporal characteristics make it possible to measure biodiversity at large scales and to monitor ecosystem changes over time (Sánchez-Díaz, 2018).

In combination with field-based habitat data and land-cover maps derived from satellite image analysis, remote sensing enables more accurate estimation of species distribution, richness patterns, and temporal changes (Ledo *et al.*, 2012).

Vegetation distribution patterns are studied through latitudinal and altitudinal gradients of species richness, where transitions among different environmental variables represent gradients that may promote increases or decreases in vegetation cover and species frequency within a given area, considering elevation and range. Consequently, significant changes occur in floristic composition and community structure (Mazzola *et al.*, 2008; Zacarías-Eslava & Castillo, 2010; Valois-Cuesta *et al.*, 2016).

In a study conducted by Castellanos-Bolaños *et al.* (2010), it was established that tree species diversity and stand structure differ according to the phytosociological community. Similarly, Ruiz-Aquino *et al.* (2015), when evaluating the diversity and structure of a pine–oak forest in Ixtlán de Juárez, Oaxaca, determined that the analyzed species can coexist while modifying stand structure and horizontal distribution patterns. Currently, this type of research has gained importance for understanding natural species distribution patterns under different environmental conditions and their influence on biological interactions and plant community dynamics in terms of structure and composition. Such studies contribute to biodiversity conservation, inform the management of commercially important tree species in forestry, provide botanical and ecological information to support sustainable management strategies, help predict potential areas of influence of invasive species, and anticipate shifts in species distribution ranges that may result from global climate change (Huerta-Martínez *et al.*, 2014; Sánchez-Gutiérrez *et al.*, 2019; Holguín-Estrada *et al.*, 2021; García-García *et al.*, 2023).

The satellite-derived Normalized Difference Vegetation Index (NDVI) is currently one of the most widely used analytical tools for interpreting multispectral imagery, primarily aimed at assessing vegetation condition and quantifying vegetation attributes (Huang *et al.*, 2021). Across multiple spatial resolutions, NDVI is considered one of the most reliable indicators of vegetation health, as it is calculated from the reflectance relationship between the red (R) and near-infrared (NIR) bands, which together contain more than 90% of the information related to Earth's vegetation (Baret *et al.*, 1989; Li *et al.*, 2021). Pesaresi *et al.* (2020), in evaluating NDVI time series to support phytosociological analyses, concluded that remote sensing makes it possible to differentiate and distinguish plant communities in an objective manner. Similarly, Zhu *et al.* (2011) used the Normalized Difference Vegetation Index to assess the spatial distribution of vegetation in the Qaidam Basin, identifying four factors affecting plant distribution in the area: precipitation, altitude, hydrological conditions, and human activities, which fragment the distribution pattern.

Matas-Granados *et al.* (2022) quantified vegetation changes over a 35-year period in protected areas hosting threatened plant species using NDVI, concluding that remote sensing-based monitoring can help assess the effects of slow processes and drastic events by identifying patterns across extensive regions, thereby supporting effective conservation actions. Structural modifications and spatial redistribution of plant communities are not driven solely by anthropogenic activities; climate change has also become a significant factor in recent years. Fayech and Tarhouni (2021) analyzed the impact of climate variability on vegetation using the NDVI and precipitation data in the arid region of Gabes, finding that vegetation growth is strongly influenced by rainfall patterns. Knowledge of vegetation in relation to terrain topographic characteristics contributes to the establishment of restoration and management actions, as well as to the selection of species best adapted to specific ecological sites, thereby enhancing survival and promoting faster development (Díaz *et al.*, 2012). The objective of this study was to determine the effect of altitude on tree structure, distribution and species richness in the Sierra Juárez, Oaxaca, Mexico, through satellite image analysis to identify altitudinal effects and changes in vegetation health using the Normalized Difference Vegetation Index.

MATERIALS AND METHODS

Study Area

Ixtlán de Juárez is one of the 30 districts that constitute the state of Oaxaca. It comprises 154 localities distributed across 26 municipalities and is one of the three districts into which the Sierra Norte region is divided. The district is located at the following extreme Universal Transverse Mercator (UTM) coordinates: 1,968,430.194 N; 805,198.532 E; 736,547.067 W; and 1,829,266.633 S, covering a total area of 2,885.54 km^2 (INEGI, 2023). The area encompasses diverse biomes, among which temperate forest, mountain cloud forest, and seasonally humid forest are prominent. The district boundaries were delineated using the open-access geographic information system QGIS version 3.4.8 (2019; Figure 1).

Data Acquisition

Tree species data were obtained from the National Biodiversity Information System (SNIB) of the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), a system developed to compile, organize, generate, and disseminate information on Mexico's biological diversity. The database is based on records of specimens collected in the country and housed in national and international scientific collections

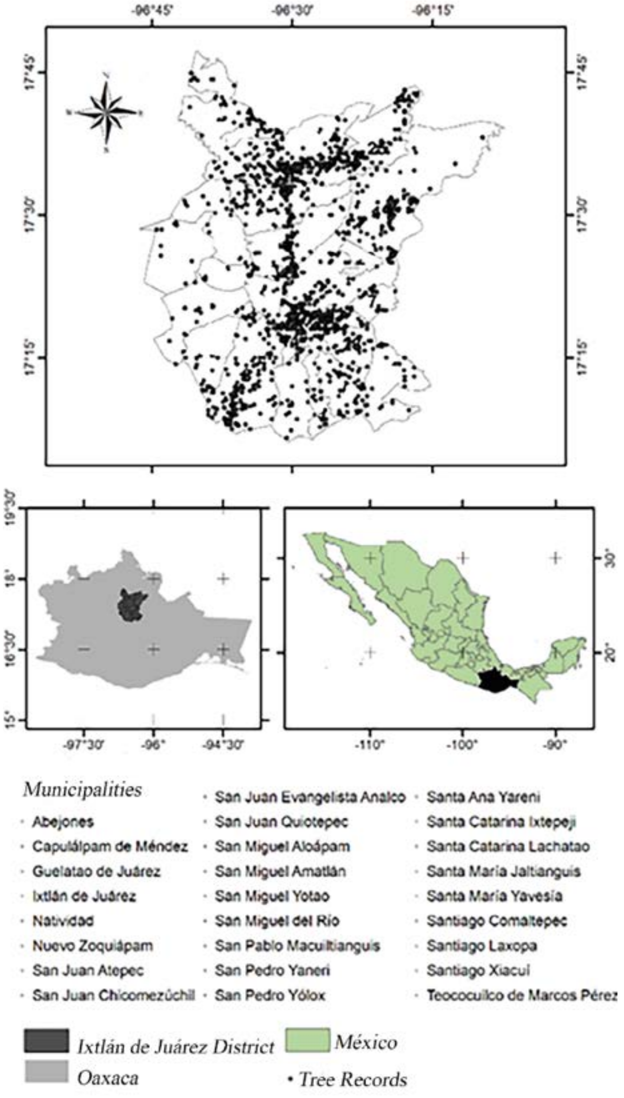

Figure 1. Geographic location of tree species in the District of Ixtlán, Oaxaca.

(SEMARNAT, 2018). Additionally, field records were collected, with particular emphasis on Ixtlán de Juárez and Santa Catarina Ixtepeji, as these municipalities exhibit a complex altitudinal gradient and sustain active forest management practices.

The consulted plant databases were curated to retain only species with tree and shrub life forms occurring within the District of Ixtlán. Duplicate records were removed, and specimen labels deposited in open-access scientific collections were reviewed, including the National Herbarium (MEXU) of the Universidad Nacional Autónoma de México. Field verification was also conducted in areas surrounding the Universidad de la Sierra Juárez, located in Ixtlán de Juárez, Oaxaca.

The cartographic layers used in this study included state political boundaries, municipal political boundaries, and land use and vegetation maps (INEGI, 2001, 2021, 2022; CONABIO, 2023). Based on the land use and vegetation data, biomes were defined according to the classification proposed by Suárez-Mota and Villaseñor (2011) and Villaseñor and Ortiz (2014). Agricultural areas, cultivated forests, human settlements, and water bodies were excluded from the analysis.

The Digital Elevation Model (DEM) was obtained from the official portal of the Instituto Nacional de Estadística y Geografía (INEGI, 2023) at a spatial resolution of 90 m. Using this dataset, the polygon corresponding to the District of Ixtlán was delineated. The altitudinal gradient was classified into five categories to assess its correspondence with the defined biomes. The selected species distribution data were overlaid onto these altitudinal classes for spatial analysis.

Image processing

Satellite imagery was obtained from Landsat 5, Landsat 7, and Landsat 8 corresponding to the years 1995, 2000, 2005, 2010, 2015, and 2023, sourced from the United States Geological Survey (USGS, 2023). Image selection for the study area was conducted using a cloud cover filter of $<40\%$. The selected imagery covered four seasonal periods, each comprising three months: January-March, April-June, July-September, and October-December. This approach allowed for the assessment of seasonal variations in vegetation health throughout the year across the analyzed temporal intervals.

After downloading, each image was clipped using a mask layer corresponding to the polygon of the District of Ixtlán through a Geographic Information System (GIS), specifically QGIS version 3.4.8 (2019). Individual spectral bands were processed separately for each year, as combinations of the red and near-infrared bands were required to calculate the Normalized Difference Vegetation Index (NDVI). This index was used to detect differences in vegetation cover and to distinguish vegetated areas from rocky and deforested zones.

NDVI values were calculated to determine vegetation health within the study area. The index ranges from -1 to 1; values closer to 1 indicate healthier vegetation due to higher reflectance in the near-infrared spectrum and greater absorption in the red band, which is typically associated with vigorous green biomass (Suárez-Mota *et al.*, 2023). This procedure was applied to all analyzed years. For Landsat 5 and Landsat 7, as well as Landsat 8, the red visible and near-infrared (NIR) bands were used according to the spectral configuration of each sensor. The NDVI was calculated using the following formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where: *NDVI*=Normalized Difference Vegetation Index; *NIR*=reflected light in the near-infrared spectrum; and *RED*=reflected light in the red portion of the spectrum.

Subsequently, using the Geographic Information System (GIS), the calculated NDVI values were extracted and assigned to the tree occurrence records, along with the corresponding altitudinal gradient values at which the collected data were located.

Data analysis

Frequency distributions and Kernel density plots were generated for the comparative analysis of NDVI values, biomes, and altitude using the *histogram* and *density* functions in SAS version 9.4 (SAS Institute Inc., 2013). Mean comparisons were evaluated using box-and-whisker plots generated with the vbox function in SAS® 9.4 (SAS Institute Inc., 2013). Similarity analyses were performed using PAST version 4.04 (Hammer *et al.*, 2001) and SAS® 9.4. In PAST, binary species data were processed to determine the similarity between biomes and altitudinal ranges using the Jaccard index, which evaluates similarity based on shared species presence (values closer to 100% indicate greater similarity). Species diversity indices, including Shannon, Simpson, and Dominance indices, were calculated, and beta diversity was estimated using the Whittaker index.

RESULTS AND DISCUSSION

Diversity and Altitude

Species distribution along the altitudinal gradient was not uniform; a greater number of species was recorded at mid and high elevations (539 and 530 species, respectively), whereas lower elevations exhibited fewer species (255 species; Table 1).

Regarding biomes, temperate forests and mountain cloud forests showed the highest species richness, with 726 and 508 species, respectively, while xerophilous scrubland

Table 1. Species richness by biome and altitudinal range.

Biome	Number of species	Altitudinal range (msnm)	Number of species
BHM	508	1) 126-736.4	255
BTEMP	726	2) 763.4-1346.8	335
BTES	172	3) 1346.8-1957.2	539
BTH	436	4) 1957.2-2567.6	530
MXE	6	5) 2567.6-3178	426

MCF=mountain cloud forest; TF=temperate forest; SDTF=seasonally dry tropical forest; THF=tropical humid forest; XS=xerophilous scrubland; 1=very low; 2=low; 3=medium; 4=high; 5=very high.

recorded only six species. These results indicate that higher altitudinal gradients associated with forested biomes tend to support greater species diversity. However, it is important to note that sampling effort was more concentrated along roadsides and surrounding accessible areas (Table 1), which may have influenced species records.

Analysis of the Tree Stratum of the District of Ixtlán Based on NDVI

A total of 24 NDVI images were generated from the proposed analysis, corresponding to four seasonal periods for each evaluated year (1995, 2000, 2005, 2010, 2015, and 2023). The results indicate that vegetation exhibited better health conditions in 1995 compared to 2023, as the latter showed an increase in disturbed vegetation indices.

NDVI values (Figure 2) ranged from −1 to 1, with a color scale extending from red (disturbed vegetation) to green (healthy vegetation). In 2023 and January 2015, predominant colors were mainly red to yellow tones, indicating lower vegetation vigor. In contrast, January and May 1995, as well as May and July 2005, displayed greener tones (higher NDVI values), suggesting healthier vegetation conditions with fewer disturbed patches. A particular case was observed in July 2015, when NDVI values remained within a positive range. By November 2015, vegetation conditions appeared more balanced, with yellow-green tones predominating, the latter approaching values close to 1 (Figure 3).

Mean NDVI values indicate that the year 2000 exhibited one of the highest vegetation health levels, with a minimum value of −0.22 and a maximum of 0.77. In contrast, 2005 showed comparatively lower vegetation health, with a minimum of −0.45 and a maximum of 0.56 (Table 2).

NDVI Density by Biome

Rainier months favor improved vegetation health. In 1995, NDVI values during the rainy season ranged from 0 to 0.8, with the highest biome concentrations occurring

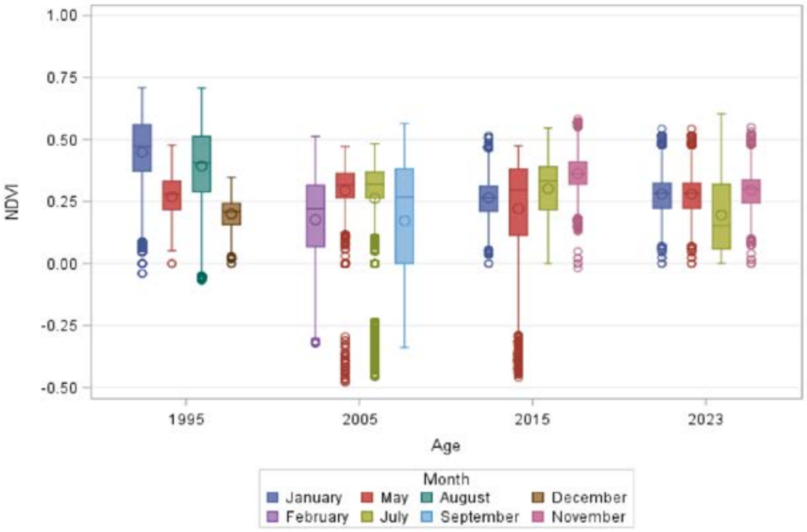

Figure 2. Ranges of Normalized Difference Vegetation Index (NDVI) values obtained from tree species records by month and year in the District of Ixtlán.

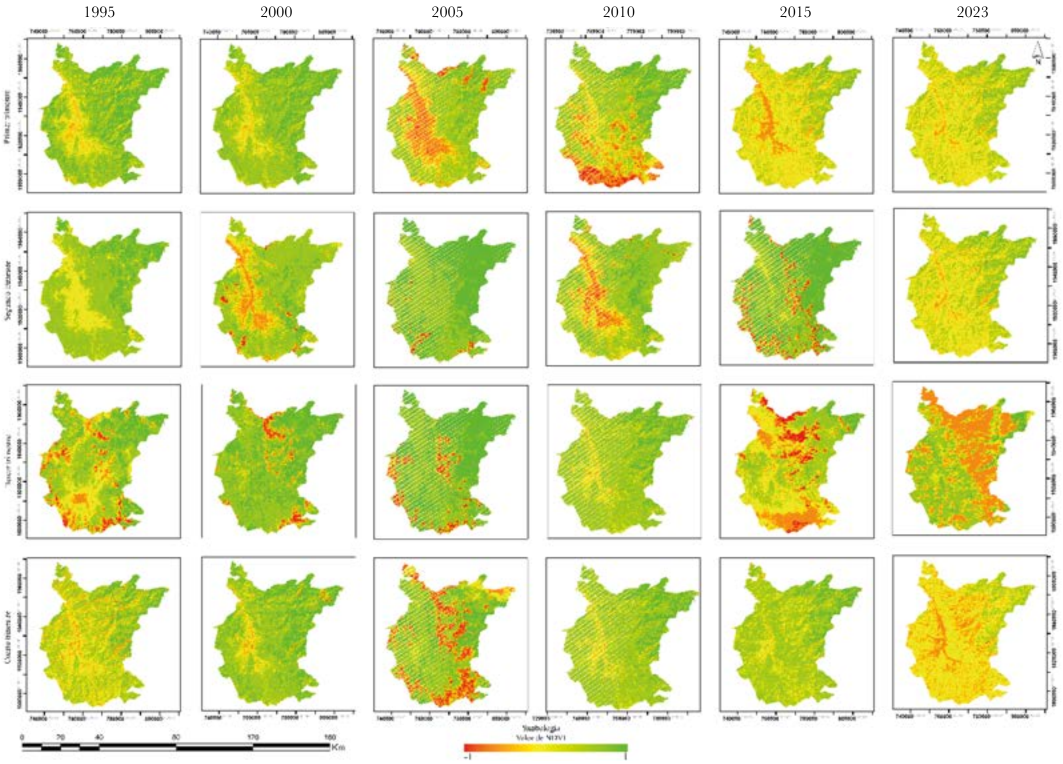

Figure 3. Normalized Difference Vegetation Index (NDVI) values for the District of Ixtlán in the years 1995, 2000, 2005, 2010, 2015, and 2023.

Table 2. Ranges of Normalized Difference Vegetation Index (NDVI) values obtained for the different years analyzed in the District of Ixtlán.

Year	Range of NDVI		
	Minimum	Average	Maximum
1995	−0.22325	0.196	0.6145
2000	−0.222	0.277	0.7755
2005	−0.45925	0.053	0.56525
2010	−0.44925	0.100	0.6495
2015	−0.19425	0.242	0.6785
2023	−0.13275	0.26	0.65175

between 0.2 and 0.6. Ten years later, during the same rainy months, NDVI values fluctuated between −0.4 and 0.5, with greater density concentrated between 0.2 and 0.4. By July 2023, NDVI values ranged from 0 to 0.6; however, the highest concentration occurred between 0 and 0.4, indicating a progressive deterioration in vegetation condition over time. Changes in vegetation health are evident across the analyzed years. The mountain cloud forest exhibited a mean NDVI value of 0.5 during the rainy season in 1995, whereas in 2023 the mean decreased to 0.15, reflecting a marked decline in vegetation health (Figure 4).

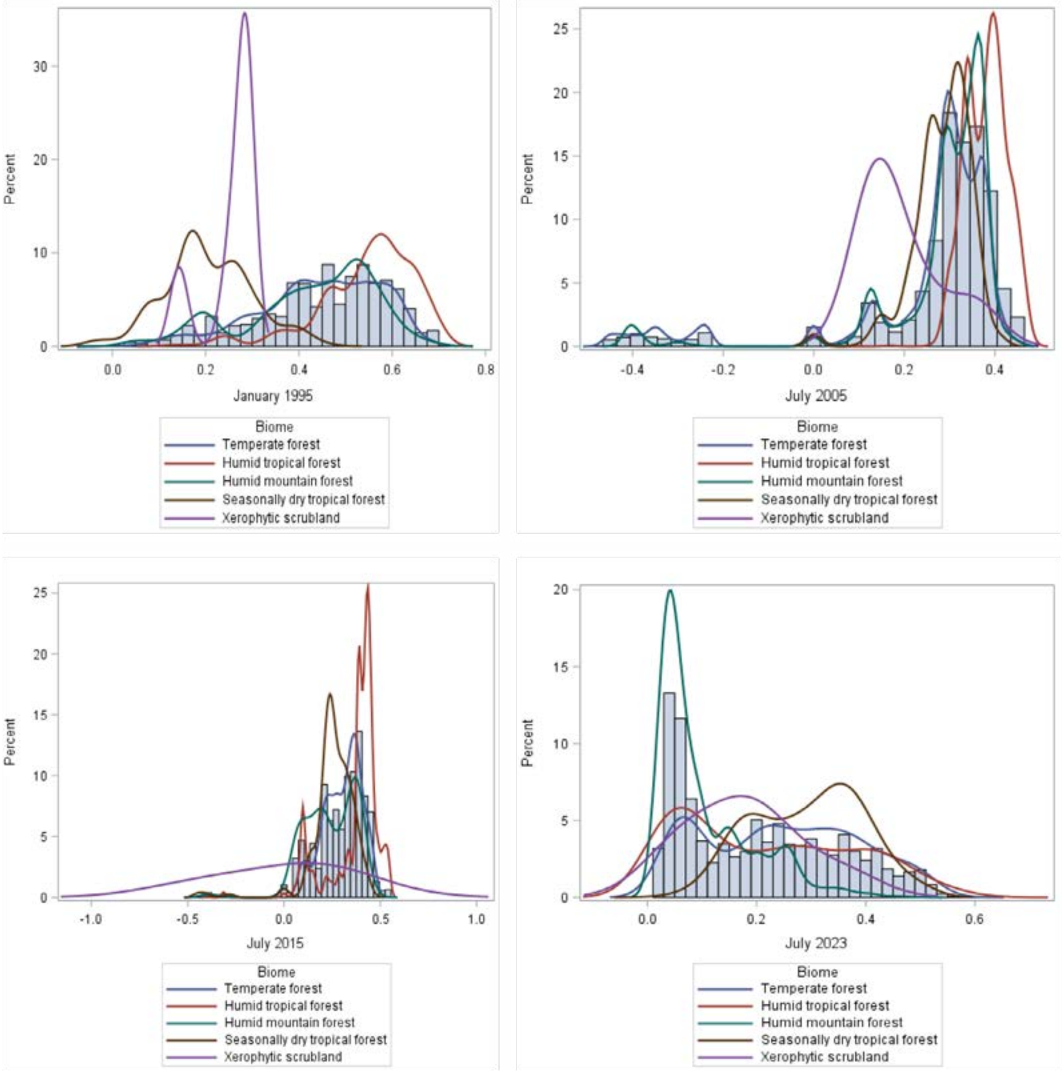

Figure 4. Normalized Difference Vegetation Index (NDVI) values for the biomes distributed in the District of Ixtlán, Oaxaca, Mexico, obtained through Kernel density analysis.

NDVI Density by Altitude

Altitudinal gradients play an important role in plant species distribution. NDVI values obtained in 1995 ranged from 0 to 0.8; in 2005, from −0.6 to 0.6; in 2015, from −0.5 to 0.6; and in 2023, from 0 to 0.6, making vegetation degradation evident over time.

The highest altitudinal gradient showed mean NDVI values of 0.2, 0.4, and 0.58 in 1995; in 2005, this average decreased to 0.3; in 2015, the mean for this altitude was between 0.22 and 0.3; and in 2023, it was 0.1 (Figure 5).

Alpha diversity

The Dominance index indicates the probability that a single species completely dominates a biome; lower values reflect greater species richness, whereas values closer to 1 indicate lower species numbers (Medrano *et al.*, 2017). In this study, temperate forest and

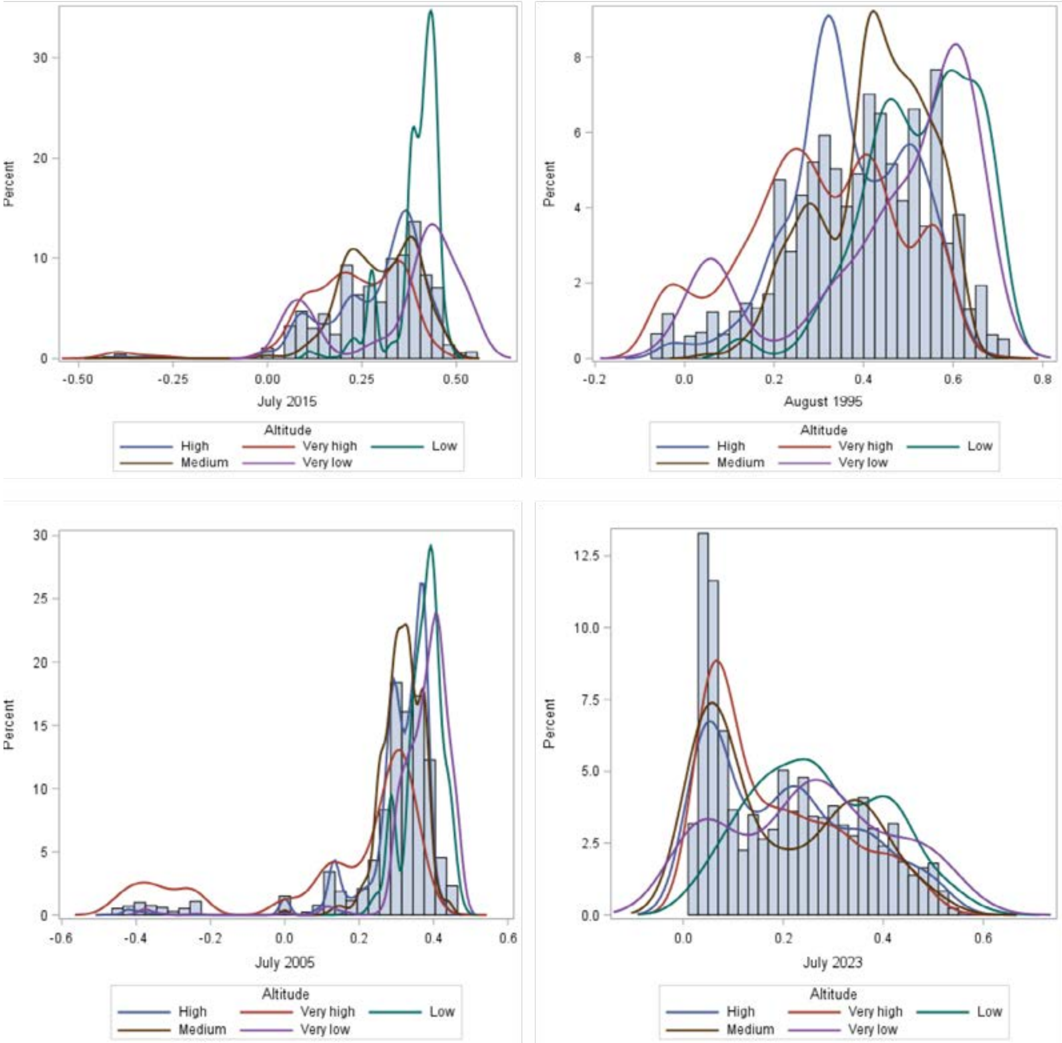

Figure 5. Normalized Difference Vegetation Index (NDVI) values by month and altitude obtained through Kernel density analysis.

mountain cloud forest exhibited the lowest dominance values (0.001377 and 0.001969, respectively). In contrast, xerophilous scrubland showed the highest dominance (0.1667), corresponding to only six recorded species. The Shannon index reflects species diversity. Values <2 indicate low diversity, values between 2 and 3.5 indicate moderate diversity, and values >3.5 are interpreted as high diversity (Carmona-Galindo & Carmona, 2013). Most biomes presented values greater than 3.5; temperate forest showed the highest value (6.58), whereas xerophilous scrubland had a value of 1.79, making it the least diverse (Figure 6). The Simpson index ranges from 0 to 1, with values closer to 1 indicating higher diversity and values near 0 reflecting dominance by one or few species (Simpson, 1949; Del Río *et al.*, 2003). Most biomes showed high diversity, with values close to 1 (mountain cloud forest=0.9; temperate forest=0.9). However, xerophilous scrubland presented the lowest diversity, consistent with its reduced species number (six species). The Menhinick index is a measure of species richness; higher values indicate greater richness. Temperate forest recorded the highest value (26.94), followed by mountain cloud forest (22.54), while xerophilous scrubland showed the lowest value (2.45) (Figure 6).

Beta diversity

Beta diversity among biomes was calculated using the Whittaker index, which measures species turnover between communities. Values of zero in the matrix indicate no species turnover; however, species replacement was observed among several biome pairs.

The highest turnover values were recorded between xerophilous scrubland and the other biomes, particularly with mountain cloud forest (0.99) and seasonally dry tropical forest (0.99). In contrast, the lowest species replacement occurred between mountain cloud forest and temperate forest (0.50), as well as between mountain cloud forest and tropical humid forest (0.47246) (Table 3).

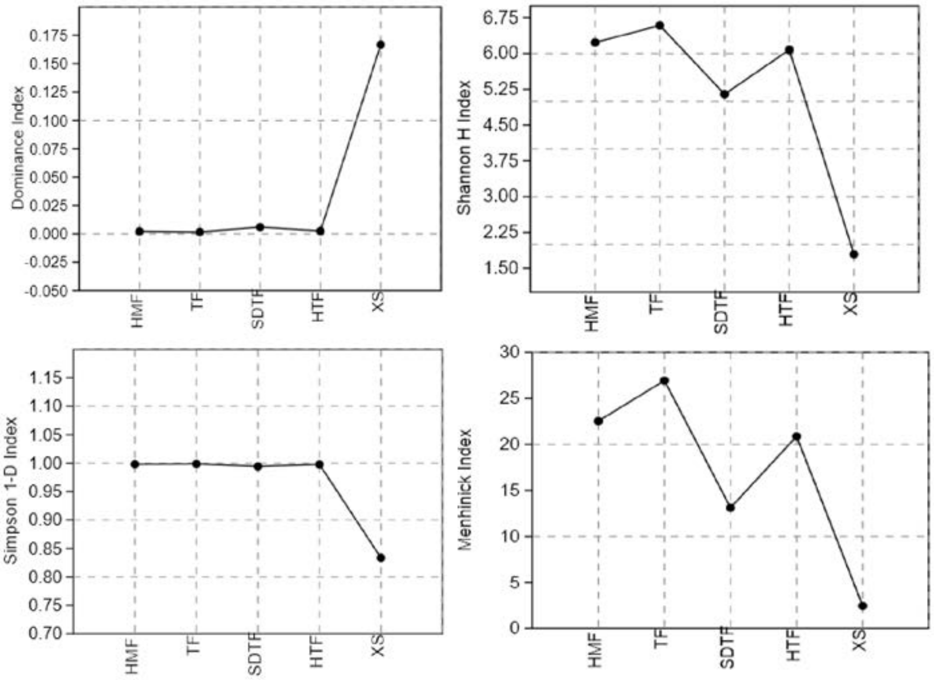

Figure 6. Diversity indices under biome-based analysis.
A) Dominance index; B) Shannon index; C) Simpson index; D) Menhinick index; MCF=mountain cloud forest; TF=temperate forest; SDTF=seasonally dry tropical forest; THF=tropical humid forest; XS=xerophilous scrubland.

Table 3. Beta diversity values among biomes based on the Whittaker index.

	BHM	BTEMP	BTES	BTH	MXE
BHM	1				
BTEMP	0.50405	1			
BTES	0.82941	0.72829	1		
BTH	0.47246	0.65232	0.93421	1	
MXE	0.98833	0.98361	0.98876	0.99095	1

BHM=humid mountain forest, BTEMP=temperate forest; BTES=seasonally dry tropical forest; BTH=humid tropical forest; MXE=xerophytic scrubland.

Biome Similarity

The relationship between biomes and altitude, based on species presence, indicates that temperate forest and high altitude share more than 55% similarity. Likewise, tropical humid forest and low altitude show approximately 48% similarity, while mountain cloud forest and very high altitude present 45% similarity. A particular case is xerophilous scrubland, which shows 0% similarity. This may be attributed to its low species richness (only six species), making similarity with other biomes unlikely and suggesting that it represents a distinct biome (Figure 7). Additionally, a clustering trend was observed, forming two main groups. The first group comprises low altitudes associated with tropical humid forest, while the second includes medium, high, and very high altitudes grouped with mountain cloud forest and temperate forest. These two groups exhibit approximately 20% similarity. Finally, seasonally dry tropical forest shows only about 12% similarity with the two previously mentioned groups, likely due to its relatively lower species richness (172 species).

Regarding shrub presence across altitudinal levels, 228 species were recorded, in contrast to Bautista-Bello *et al.* (2019), who reported 132 species concentrated within the altitudinal range of 1957-3178 m. This differs from the findings of Mijango-Ramos *et al.* (2020), who suggest that species diversity decreases with increasing elevation due to less favorable climatic conditions (a decrease of 0.6 °C per 100 m in altitude). However, in the present case, greater species diversity was observed at higher elevations.

Vegetation vigor decreased over the years, as evidenced by the satellite imagery. These findings are consistent with Mamani and Román (2021), who reported a progressive decline in vegetation vigor over time. Additionally, they evaluated temperature and precipitation variables, identifying a relationship between increasing temperature, decreasing precipitation, and vegetation health. In contrast, Chambe *et al.* (2021) indicate that NDVI is more strongly influenced by temperature than by precipitation. Consequently, increasing temperature may promote vegetation development under more favorable environmental conditions, resulting in higher productivity and biomass accumulation.

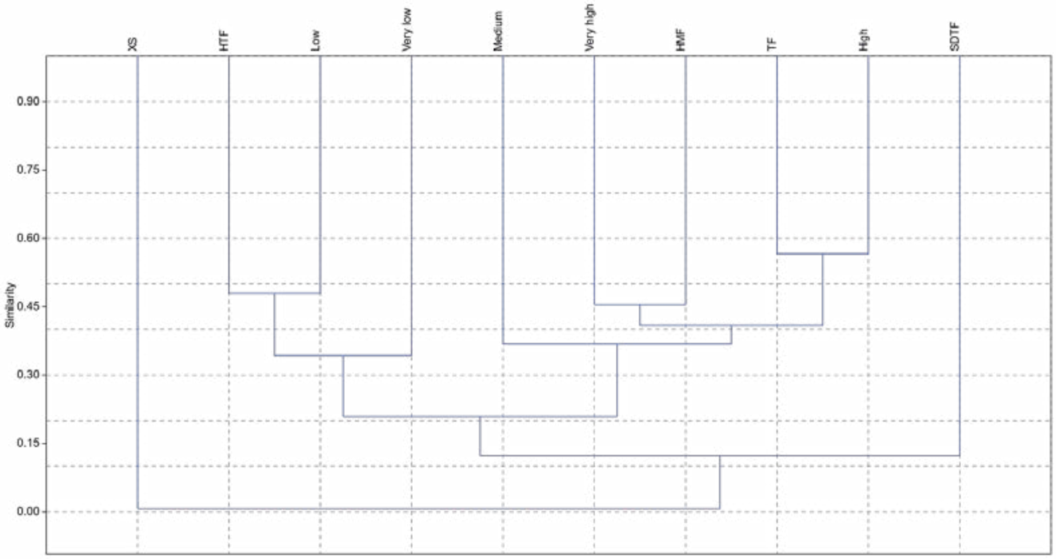

Figure 7. Similarity values between altitude and biome based on species presence, using the Jaccard index.

The images used in this study corresponded to multiple years and different seasons, in contrast to Ruiz *et al.* (2017), who employed only two images per year across four time periods. They assessed land-use and vegetation change, as well as the increase in human activities, and reported NDVI values ranging from 0.1 to 0.5 for xerophilous scrubland and oak forest. These values differ from those obtained in the present study, which range from −0.13 to 0.77 across the analyzed biomes, where higher altitudes exhibited lower NDVI values.

On the other hand, Olivares and López-Beltrán (2019) state that vegetation follows an annual cycle in response to regular rainfall patterns and soil water storage. Consistent with this, lower NDVI values were recorded during periods outside the rainy season, for example, in January 1995 and 2000, September 2010, and July 2023. Conversely, the highest values were recorded during the rainy season, specifically in July 2000 and November 2015 and 2023, in the Sierra Juárez of Ixtlán, Oaxaca.

Human activities affect ecosystem resilience, resulting in the loss, reduction, and delayed recovery of vegetation cover, as reported by Kafy *et al.* (2022). Remote sensing analysis based on NDVI shows the gradual deterioration of vegetation cover in the district of Ixtlán de Juárez. A similar effect was identified by Tuesta *et al.* (2023), who conducted a systematic review of multitemporal analyses using satellite imagery and found forest decline at the global level. However, in some Asian countries, they reported an increase in forested areas, possibly as a result of passive restoration processes. At the regional level, Suárez-Mota *et al.* (2023) evaluated the degree of ecological restoration at a university campus (UNSIJ) in the Sierra Norte of Oaxaca using satellite imagery and the Normalized Difference Vegetation Index. They found that arboreal vegetation and secondary vegetation increased by 10 to 24.6%, concluding that vegetation has shown notable improvement in area despite urban expansion within the university. At the state level, Gómez-Mendoza *et al.* (2008) analyzed variations in NDVI in the state of Oaxaca, southern Mexico. Using satellite information, they found that NDVI values during extremely dry periods were generally low, reflecting the predominant vegetation conditions of the state; however, analysis during the rainy season indicated rapid recovery of vegetation cover.

Seasonal analysis reflects dynamic NDVI values, as this index decreases during the dry season and increases during the rainy season within each year. However, when analyzed annually, NDVI shows a declining trend, indicating a loss of vegetation health. Barbosa *et al.* (2006), through satellite image analysis using the Normalized Difference Vegetation Index (NDVI), identified vegetation loss and deterioration across years and seasons. These findings are consistent with the results observed in the present study, as the changes in the Sierra Juárez, Oaxaca (Figure 3) are considerably evident.

Ecosystem degradation is a global concern, and various methods have been employed to assess this issue in specific areas. Currently, methodologies based on satellite imagery have been widely implemented, with NDVI being the most commonly used index to evaluate trends in ecosystem health, as noted by Gaitán *et al.* (2015).

As previously mentioned, in 1995 forest health was better than in the other evaluated years, with an average NDVI value of approximately 0.48. However, from 2005 onward, the highest average NDVI value recorded was 0.30. NDVI ranges vary depending on the months analyzed, decreasing during the dry season and increasing during the rainy season. Nevertheless, the decline in vegetation health over the years has been evident: the highest NDVI levels were recorded in 1995 and the lowest in 2023, demonstrating limited ecosystem recovery (Figure 2).

Several biomes were evaluated, finding that the highest Shannon index values are presented by BTEM, BHM, and BTH, indicating that there is greater diversity than that evaluated by Dávila-Lara *et al.* (2019), mentioning that there is high diversity in forested areas; however, in areas with forest exploitation there is a tendency for dominance to exist, despite the fact that some temperate forest zones in the study were located within the analyzed area, they continue to be biomes with the presence of arboreal and shrub species.

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