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Luis Manuel Morales-Gallegos , Tomás Martínez-Trinidad * , Patricia Hernández-de la Rosa , Armando Gómez-Guerrero , Dionicio Alvarado-Rosales , Luz de Lourdes Saavedra-Romero

Posted Date: 14 June 2023

doi: 10.20944/preprints202306.0977.v1

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Tree Health Condition in Urban Green Areas through Crown Indicators and Vegetation Indices

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Abstract: The urban environment induces stress on trees and the impact can be identified by observing the condition of the crown. The aim of this study is to correlate the variables crown density (Cdn), crown transparency (Ctr) and dieback (Cdie) with the following vegetation indices: normalized difference vegetation index (NDVI), enhanced vegetation index (EVI2), blue normalized difference vegetation index (BNDVI), green normalized difference vegetation index (GNDVI), green-red vegetation Index (GRVI) and red-green-blue vegetation index (RGBVI) of the tree crown located in urban green areas, as well as chlorophyll fluorescence (Fv/Fm) as an indirect indicator of tree health condition. A total of 549 trees were evaluated, represented in 24 families, 36 genera and 53 species; the variables had average values of 67.96 % in Cdn, 35.19 % in Ctr and 1 % in Cdie. Correlations were found between Fv/Fm, NDVI and BNDVI. NDVI and BNDVI correlated with variables such as Cdn and Ctr, mainly in species such as *Ligustrum lucidum*, *Jacaranda mimosifolia* and *Fraxinus uhdei*. Therefore, it is possible to evaluate tree health condition of trees in urban green environments through the identification of unfavorable conditions at the crown level by using vegetation indices for some of the species studied.

Keywords: urban trees; vegetation indices; chlorophyll fluorescence; forest health; crown density

1. Introduction

Population growth leads to an accelerated change from a natural environment to an urban landscape; therefore, it is advisable to conserve and increase vegetation through the creation of a greater number of urban green areas (UGAs) [1-3]. The most important vegetation in UGAs are trees, as they provide a wide range of environmental, ecological and social services [4-6]. However, urban trees face stressful conditions due to factors such as the heat island effect, soil compaction, limited growth space for roots, vandalism, inadequate management practices, and water and nutrient deficiency, among others [7-10]. The impact of stress on urban trees can be identified by observing the condition of their crowns. An alteration in their morphological characteristics negatively affects their vitality and general health condition, and also has an impact on the provision of services to the urban environment [6,11-15].

Tree crown assessment is used as an indicator of health condition in forest species, with some of these variables being crown density, crown transparency and dieback [11,16,17]. Recently, these indicators have been adapted and used to estimate the health condition of urban trees; however, obtaining this information involves *in situ* data collection by at least two people [4,6,17-19], which entails a considerable expenditure of time and is complicated when access to the terrain is restricted or dangerous; currently, this method is frequently used to obtain information on tree health condition in both forest and urban areas [4,6,10,20]. On the other hand, there are methods to evaluate physiological processes to quantify the response of trees to stress, one of them being chlorophyll

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fluorescence (Fv/Fm). This index indicates the photosynthetic efficiency of the system of the leaves; thus, a lower efficiency is related to a lower health condition of the vegetation [21,22].

However, a feasible method for studying tree crowns is the use of unmanned aerial vehicles (UAVs), since being equipped with high-resolution multispectral sensors allows obtaining precise information from large areas and reducing the time necessary for the analysis of various biophysical parameters compared to traditional methods [9,20,23-27]. Recent vegetation studies have made use of spectral bands to determine vegetation indices (VIs), among other applications; this remote sensing technology allows classifying and estimating health condition of vegetation in different ecosystems, as well as in urban areas [28-31]. Among the vegetation indices used in research are the normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI2), the green normalized difference vegetation index (GNDVI), the blue normalized difference vegetation index (BNDVI), the red-green-blue vegetation index (RGBVI), and the green-red vegetation index (GRVI) [5,9,20,26,32-35].

Vegetation indices have advantages over other methods, e.g., NDVI has a better correlation with tree canopy cover than with other ground-level vegetation covers, and high NDVI values indicate healthy vegetation conditions [2,34]. High GNDVI values effectively represent chlorophyll properties, while BNDVI allows the spatial distribution of chlorophyll to be analyzed [26,32,36]. These characteristics allow analyzing different options in determining the condition of the trees. Therefore, the aim of this study was to determine the degree of correlation between the absolute variables crown density, crown transparency, and dieback of trees located in urban green areas with the vegetation indices NDVI, EVI, BNDVI, GNDVI, GRVI, and RGBVI, as well as chlorophyll fluorescence with the purpose of identifying more efficient predictors of tree health condition.

2. Materials and Methods

2.1. Study Area

The study area were green areas (UGAs) of the city of Texcoco de Mora (19°30′52.30′′N and 98°52′57.73′′W) in the State of Mexico, Mexico (Figure 1), The city has an elevation of 2,240 m, a temperate climate with an average temperature of 15.9 °C and mean annual rainfall of 686 mm. The most representative soil has Vertisol-type characteristics; however, the soil has been considerably altered by anthropogenic activities [37].

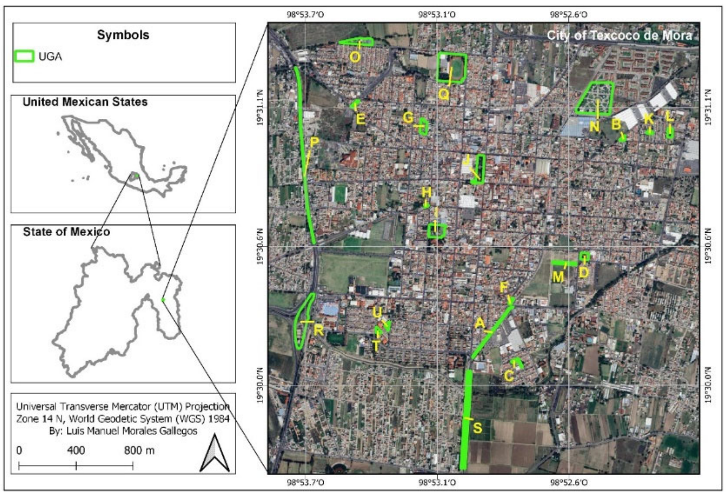

Figure 1. Location of green areas in the city of Texcoco de Mora.

Google Earth images from the year 2021 were used to locate, delimit and dimension 21 UGAs (Table 1) administered by the municipality of Texcoco [38,39]. The UGAs have mainly arboreal vegetation; however, there are also shrub and herbaceous species. A common management practice

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in the tree crowns is pruning, normally conducted for aesthetic purposes and to avoid contact with nearby infrastructure.

Table 1. Urban green areas in Texcoco de Mora, State of Mexico, Mexico.

ID	Name	Perimeter (m)	Area (m²)
A	Boulevard Jiménez Cantú	940.53	4,687.21
B	Valle de Santa Cruz 2	141.72	848.98
C	Jardín San Martín	259.84	1,379.92
D	Parque Niños Héroes	205.03	2,632.24
E	Parque las Américas	174.75	1,123.34
F	Parque del Ahuehuete	132.96	876.11
G	Parque Heberto Castillo	304.93	4,167.78
H	Parque Arteaga	92.05	435.07
I	Parque de la Tercera Edad	406.05	9,478.5
J	Jardín Municipal	549.66	9,765.82
K	Valle de Santa Cruz 3	118.35	717.83
L	Valle de Santa Cruz 1	192.78	2,128.93
M	Parque Municipal	366.93	2,694.09
N	Alameda Texcoco	849.57	43,898.99
O	Parque Xolache	517.07	7,436.39
P	Camellón Lechería	2,505.49	7,554.33
Q	Deportivo Silverio Pérez	765.46	37,159.45
R	Parque Bicentenario	859.26	21,397.46
S	Boulevard Chapingo	2,801.45	16,347.42
T	Las vegas 1	151.56	1,105.62
U	Las vegas 2	167.91	1,173.21

2.2. Collection of Tree Information

A database from a previous study was used in the 21 UGAs of Texcoco city, where the trees were surveyed; a representative sample of these was taken, implementing a simple random sampling for each UGA with a reliability of 95%, using equation 1 [41]. From the sampled trees, total height (Th) was evaluated with a Haglöf ECII D® electronic clinometer, diameter at breast height (Dbh) was measured with a diameter tape (Forestry Suppliers Inc®. Jackson, MS) and in cases where the trunk was found bifurcated below 1.3 m in height, each trunk was considered as an individual tree [41-43]. Species were identified through botanical keys and field guides; when a full identification was not possible by these means, a botanical collection of the specimen was made and taken to the Hortorio Herbarium (CHAPA) of the *Colegio de Postgraduados* for identification. Only dominant species with a Dbh ≥ 10.16 cm (4 in) were considered, because they provide more spectral information for further analysis. Finally, the recording of the information was carried out in a vegetative growth period (August-September 2021) [6,26,33,38,39]

$$n = \frac{N\,\sigma^2\ Z^2}{(N-1)\,e^2 + \sigma^2\ Z^2} \tag{1}$$

where:
n = minimum sample size
N = population size
σ = 0.5
Z = confidence level 1.96 (95 % confidence)

e = acceptable error limit (0.05)

2.3. Evaluation of Crown Variables

The following variables were assessed: crown density (Cdn), which is a biomass index that includes foliage, branches and reproductive structures; crown transparency (Ctr), which estimates the amount of light passing through the live crown; and dieback (Mrg), which indicates the extent of leafless branches at the periphery of the crown, generally increasing from the top to the bottom of the tree [44]. For this, the field assessment variables designed by the Forest Inventory and Analysis (FIA) program of the United States [17,45] was used; this was carried out visually by two people located at a distance proportional to the height of the tree to be measured. Variables were recorded with values in percentage increments of 5 % on a scale from 0 to 100 [4,6].

2.4. UAV Multispectral Images

We used a DJI PHANTOM 4© UAV equipped with six 1/2.9" CMOS sensors, one RGB sensor and five monochrome sensors with the ability to capture images in the blue (B: 450 nm ± 16 nm), green (G: 560 nm ± 16 nm), red (R: 650 ± 16 nm), red edge (RE: 730 ± 16 nm) and near infrared (NIR: 840 ± 26 nm) spectra, which are widely used in the study of both forest and urban vegetation [9.26]. The UAV has a resolution of 9.52 cm/pixel at an altitude of 180 m, with a vertical and lateral overlap of 80 and 60 %, respectively, and a maximum operating area of 0.63 km^2; it has a field of view of 62.7° (HFOV) and a weight of 1,487 g. The DJI GS Pro© was used to establish the UAV flight plan; photography was performed at a flight altitude of 60 m, which allowed obtaining images with a resolution of 0.3 m. Radiometric calibration was performed through the Calibrated Reflectance Panel (CRP) and the camera's incident light sensor. The UAV has an integrated GPS/GLONASS system, allowing for faster and more accurate satellite acquisition during flights, as well as eight pre-set checkpoints on each UGA to ensure correct image positioning. Finally, ortho- mosaics (.tiff) of each UGA were created using Pix4D Mapper software (Lausanne, Switzerland) [26,27,46]. Flights were conducted in late August and early September 2021 in the summer season, a time of year in which the vegetation is in a state of vegetative growth, due to constant rainfall and temperatures above the annual average, at times from 11:00 to 13:00 h, with a wind < 5 km / h to avoid distortions due to movement.

2.5. Vegetation Indices

Multispectral images (B, G, R, NIR) from the UAV were used to calculate the NDVI, EVI, GNDVI, BNDVI, RGBVI and GRVI indices (Table 2) [26]. Given the precision of the UAV images (0.3 m), it was possible to delimit the crowns of the trees defined in the previous sampling manually (digitization) [27]; this information was transformed from raster to vector format for processing and analyzed through the QGIS version 3.28.4 Firenze geographic information system (GIS) [9,20,24]. This provided greater precision in choosing the pixels of each tree's crown and allowed excluding background information such as that of another type of vegetation (shrub or herbaceous) or of nearby trees not belonging to the study, to later obtain average values of the pixels that make up the image of each tree [2,9,26] (Figure 2).

Table 2. Equations used to determine vegetation indices.

Formulas	Where
$\text{NDVI} = \frac{Nir-Red}{Nir+Red}$	*NDVI* = Normalized difference vegetation index Nir = Near infrared *Red* = Red band
$\text{EVI2} = \frac{2.5*(Nir-Red)}{Nir+Red+1}$	*EVI2* = Enhanced Vegetation Index Nir = Near infrared *Green* = Green band

GNDVI= $\frac{Nir-Green}{Nir+Green}$	*GNDVI* = Green normalized difference vegetation index *Nir* = Near infrared *Green* = Green band
BNDVI= $\frac{Nir-Blue}{Nir+Blue}$	*BNDVI* = Blue normalized difference vegetation index *Nir* = Near infrared *Blue* = Blue band
GRVI = $\frac{Green-Red}{Green+Red}$	*GRVI* = Green-red vegetation index *Red* = Red band *Green* = Green band
RGBVI= $\frac{Green^2-(Red*Blue)}{Green^2+(Red*Blue)}$	*RGBVI* = Red-green-blue vegetation index *Red* = Red band *Green* = Green band *Blue* = Blue band

Also, the coefficient of variation (equation 2) of each vegetation index per crown was determined, this for a better comparison between indices and because it is a widely used measure in vegetation research that reflects the discrete degree of the data. CV was categorized into High and Low using the percentiles > 3rd percentile and < 3rd percentile, respectively [35,47,48].

$$CV = \frac{\sigma}{\bar{x}} * 100 \quad (2)$$

where:
σ = Standard deviation
$\bar{x}$ = Arithmetic mean

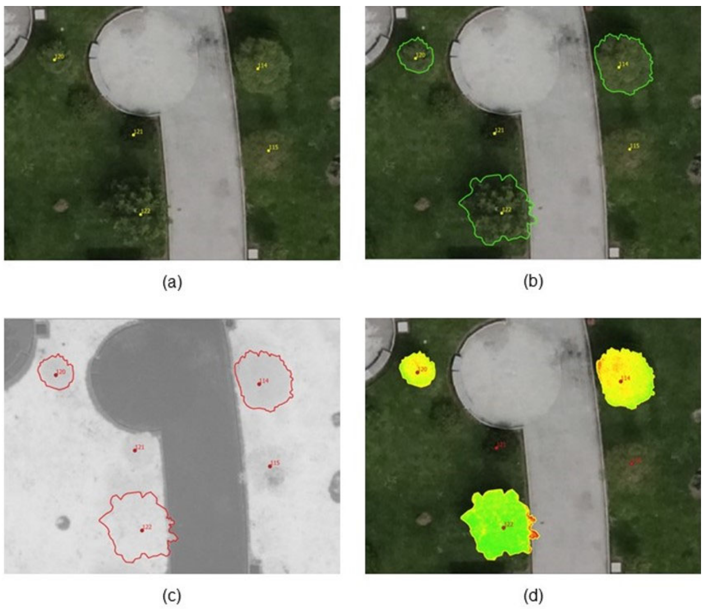

Figure 2. Example applied to the six evaluated indices and 21 UGAs studied. (a) Location of the tree species under study prior to sampling. (b) Digitization of crowns. (c) Calculation of the vegetation index. (d) Extraction of pixel values of each tree's crown index.

2.6. Health Condition

Chlorophyll fluorescence (Fv/Fm) was assessed in the sampled tree species, as an indirect measure of tree health through their physiological stress condition (Zhang *et al.*, 2016). A portable

 doi:10.20944/preprints202306.0977.v1

Pocket PEA fluorometer (Hansatech Instruments Ltd., King's Lynn, UK) was used, with a detection parameter of 1s and light emission at a wavelength of 650 nm with an intensity of 3,500 μmol m^{-2} s^{-1} [22]. The measurements were made by adapting to the dark, using the fluorimeter clips for 10 minutes and a total of 5 leaves chosen at random around each tree's crown [50]. All activities were carried out between August and September 2021, and are integrated in the Figure 3.

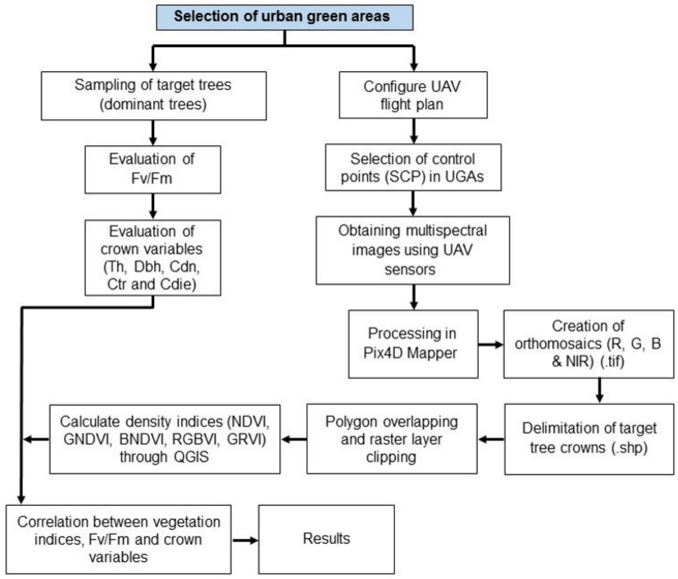

Figure 3. Methodological diagram of the study.

2.7. Data Anaslysis

A database was created in Microsoft Excel® using dynamic tables to organize the information and the "grouping" function of the same software to establish intervals of diameter and height classes, which facilitated its analysis [42]. The assumptions of normality and homoscedasticity of the data were verified, and an analysis of variance (ANOVA) was performed; when the assumptions were not met, the Kruskal-Wallis nonparametric test was used. Differences in the mean rank of the samples were obtained through the Wilcoxon rank sum. Correlations (Pearson) were carried out between the variables Fv/Fm, NDVI, EVI2, BNDVI, GRVI, RGBVI, Cdn, Ctr, Cdie, Dbh and Th at the species level considering only the 5 most frequent species (species with the best establishment) and UGA to find associations. In addition, linear regressions were carried out to investigate the possibility of generating predictive models. Statistical analyses were carried out in RStudio software [51].

3. Results

A total of 549 trees were evaluated, represented in 24 families, 36 genera and 53 species, of which Cupressaceae, Rosaceae, Fabaceae, Oleaceae, Bignoniaceae and Pinaceae were the most frequent, representing more than 50 % of the evaluated species. The diameters indicated that 70.49 % of the trees were found within the first diameter class (5.09-25.09) (Figure 4A). Regarding heights, the first two categories represent 68.12 % of the evaluated medium-sized trees (Figure 4B).

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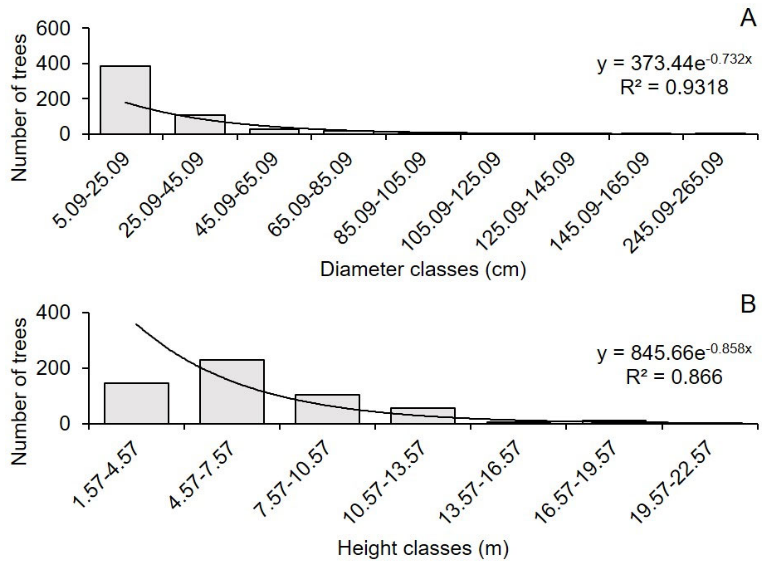

Figure 4. Diameter (A) and height (B) categories in 549 trees located in UGAs in the city of Texcoco de Mora.

On the other hand, tree density was estimated at 50 individuals on average per UGA, giving a density of 130 trees per hectare. At the species level, Dbh and Th presented significant statistical differences ($p < 0.05$) finding that *S. molle* presented the largest diameter and *C. equisetifolia* the greatest height. Conversely, *C. sempervirens* had the smallest diameter and *F. benjamina* the lowest height (Table 3).

Table 3. Average of forest measurement variables for the 10 most frequent species in UGAs in the city of Texcoco de Mora.

Species	# of trees	Diameter (cm)	Height (m)
Cupressus lusitanica Mill.	53	24.76^{bc}	6.84^{bc}
Fraxinus uhdei (Wenz.) Lingelsh.	48	25.57^{bcd}	7.38^{ab}
Jacaranda mimosifolia D. Don	44	22.38^{de}	7.46^{b}
Cupressus sempervirens L.	41	13.54^{e}	6.92^{b}
Ligustrum lucidum W.T. Aiton	40	16.39^{cde}	4.94^{d}
Ficus microcarpa L.f.	38	20.60^{bcd}	6.27^{bc}
Cupressus macrocarpa Hartw.	38	15.40^{de}	5.20^{cd}
Schinus molle L.	31	52.65^{a}	8.40^{a}
Casuarina equisetifolia L.	28	28.26^{b}	9.38^{a}
Ficus benjamina L.	27	21.53b^{c}	4.53^{d}

^{abcde}: Different letters indicate significant statistical differences ($p < 0.05$).

The tree crown variables were located between a range of 5 % to 95 % with a tendency towards a mostly dense crown (Figure 5A); Ctr showed a similar range from 5 % to 95 % (Figure 5B), indicating

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that most of the trees have low crown transparency values. Finally, Cdie showed a very low percentage, that is, little damage due to this degenerative condition (Figure 5C).

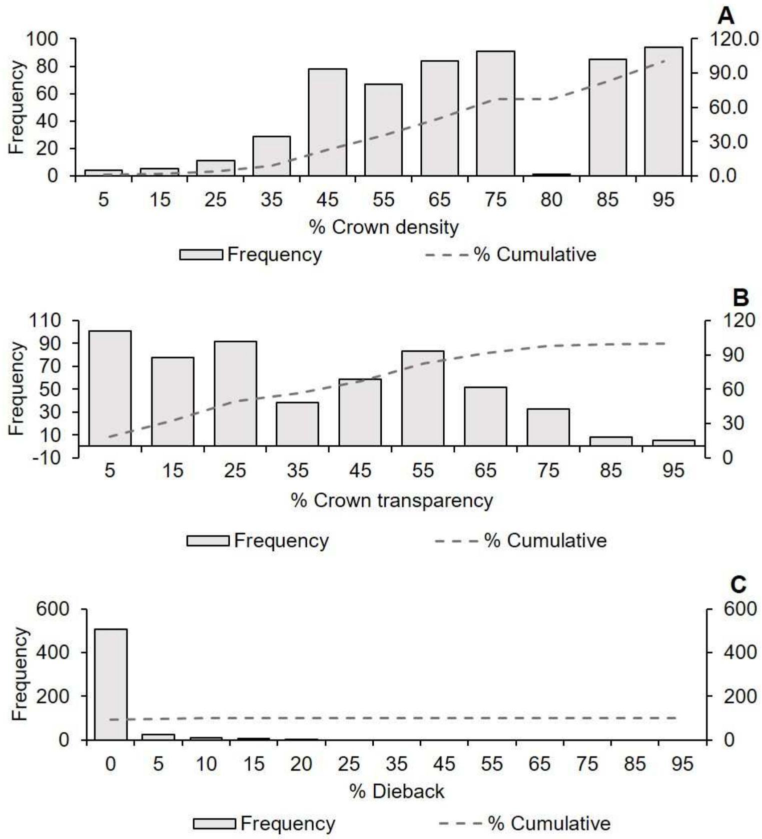

Figure 5. Histograms of frequencies and cumulative frequencies for the variables crown density (Cdn), crown transparency (Ctr) and dieback (Cdie) in UGAs in the city of Texcoco de Mora.

3.1. Correlations between the Variables Studied

The correlations studied between vegetation indices, crown variables and chlorophyll fluorescence indicated some associations (Figure 6).

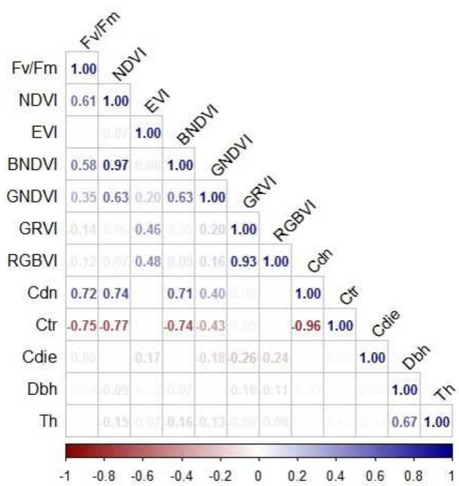

Figure 6. Pearson correlation matrix (r) between vegetation indices, chlorophyll fluorescence and tree variables ($p < 0.05$). FvFm: chlorophyll fluorescence, NDVI: Normalized difference vegetation index, EVI: Enhanced vegetation index, BNDVI: Blue normalized difference vegetation index, GNDVI: Green normalized difference vegetation index, GRVI: Green-red vegetation index, RGBVI: Red-green-

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blue vegetation index, Cdn: Crown density, Ctr: Crown transparency, Cdie: Crown dieback, Dbh: diameter at breast height and Th: Total height.

Chlorophyll fluorescence (Fv/Fm) was found to correlate positively with NDVI ($r = 0.61$, $p < 0.05$), as well as with Cdn (r 0 0.72, $p < 0.05$) and negatively with Ctr ($r = -0.75$, $p < 0.05$), and to a lesser degree correlated with BNDVI ($r = 0.58$, $p < 0.05$). NDVI also correlated positively with Cdn ($r = 0.74$, $p < 0.05$) and negatively with Ctr ($r = -0.77$, $p < 0.05$). On the other hand, BNDVI presented a correlation similar to NDVI with the variables Cdn ($r = 0.71$, $p < 0.05$) and Ctr ($r = -0.74$, $p < 0.05$). Other correlations found were between Cdn and Ctr ($r = -0.96$, $p < 0.05$) and diameter with tree height ($r = 0.67$, $p < 0.05$) (Figure 6).

Some linear regressions were found (Figure 7), mainly between NDVI, BNDVI, Cdn and Ctr of the most frequent studied species.

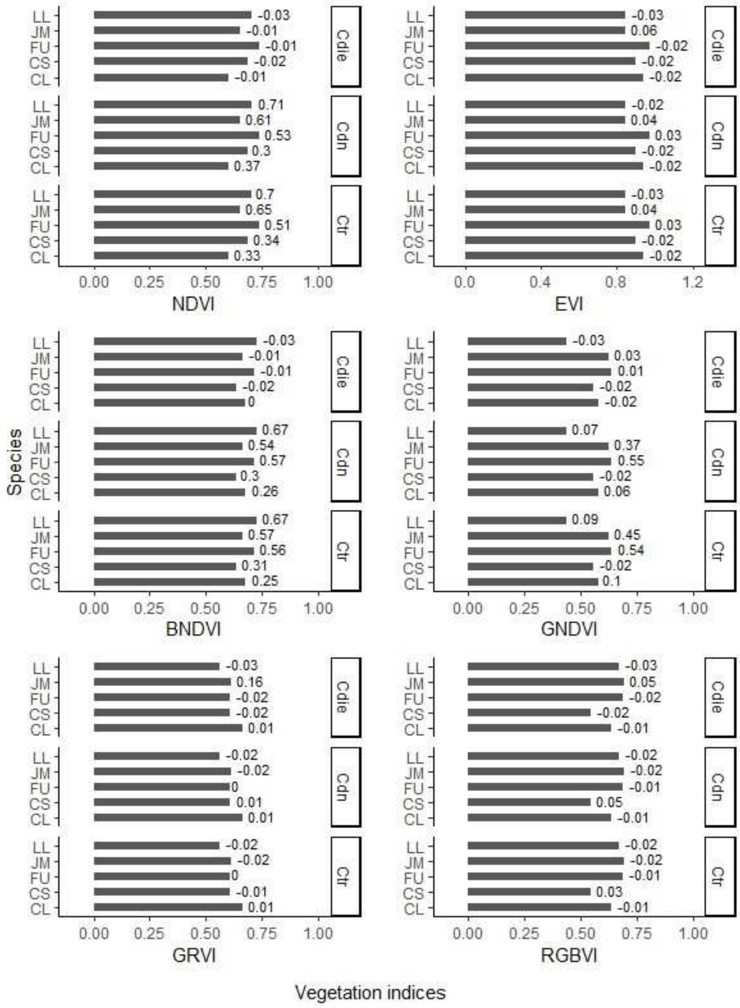

Figure 7. Adjusted R^2 of the linear regressions between the five most frequent tree species in the study area, crown indicators and vegetation indices evaluated. LL: *Ligustrum lucidum* W. T. Aiton; JM: *Jacaranda mimosifolia* D. Don; FU: *Fraxinus uhdei* (Wenz.) Lingelsh.; CS: *Cupressus sempervirens* L.; CL: *Cupressus lusitanica* Mill.; NDVI: Normalized difference vegetation index; EVI: Enhanced vegetation index; BNDVI: Blue normalized difference vegetation index; GNDVI: Green normalized difference vegetation index; GRVI: Green-red vegetation index; RGBVI: Red-green-blue vegetation index; Cdn: Crown density; Ctr: Crown transparency; and Cdie: Crown dieback.

3.2. Coefficient of Variation (CV) of Vegetation Indices

The analysis of the CV of the vegetation indices indicated a greater variation in the trees with low index values (< 3rd Quartile); this was for all the indices evaluated. On the contrary, the trees with high index values had a lower dispersion of the data (Figure 8)

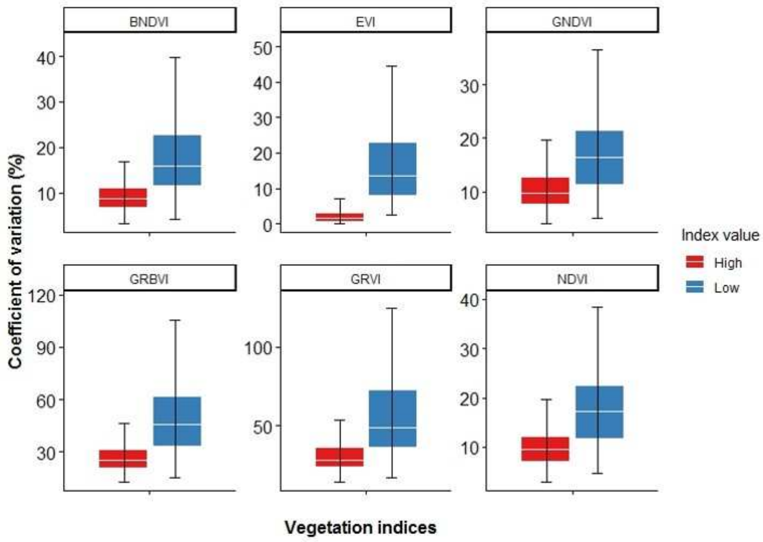

Figure 8. Differences in the coefficient of variation (CV) between High (> 3rd Quartile) and Low (< 3rd Quartile) values of the evaluated vegetation indices ($p < 0.05$). NDVI: Normalized difference vegetation index; EVI: Enhanced vegetation index; BNDVI: Blue normalized difference vegetation index; GNDVI: Green normalized difference vegetation index; GRVI: Green-red vegetation index; and RGBVI: Red-green-blue vegetation index.

4. Discussion

The smaller diameters and heights of the evaluated trees (Figure 4) indicate that the species may be mostly young (Figure 4A) [20]. It was also found that they are short (Figure 4B), which may be due to pruning activities on the tree crowns. The result is contrary to what was found, for example, in the city of Montemorelos, Nuevo León, Mexico, where the urban trees are larger [52], which may indicate that cultural practices are an important factor affecting the structure and composition of tree vegetation in urban areas. On the other hand, older trees would be expected to have crowns with high density (Cdn) values and low percentages of crown transparency (Ctr) and dieback (Cdie); however, maintenance actions carried out on the crowns (formation pruning) alter their shape and condition, diminishing the vitality of the trees and in extreme cases leading to their death [6,20].

In general, trees are considered healthy when they present values of Cdn > 50 %, Ctr < 30 % and Cdie < 5 % (Saavedra-Romero *et al.*, 2016). The values of Cdn, Ctr and Cdie found in the trees located in the 21 UGAs of the city of Texcoco have average values of 67.96 % in Cdn, 35.19 % in Ctr and 1 % in Cdie (Figure 5). A high crown density value indicates that the tree has a large number of leaves, which translates into greater photosynthetic capacity and therefore better growth and development [9,14]. In contrast, a low Cdn value translates into little foliage, which can result in physiological stress and greater susceptibility to pest and disease attack [20,46]. As for Ctr, it showed values above 30 % (Figure 5B), indicating that these trees are under stress; however, an annual monitoring of the increase in crown transparency in the trees would help to determine if their growth is compromised, indicating medium-term damage to their reproductive potential and long-term consequences for their survival. Cdn and Ctr can vary by species, age, genotype and evaluation periods. Despite this, at present, these variables are widely used as useful indicators in the evaluation of tree crown condition in both natural and urban environments [6,22]. Regarding Cdie, it presented lower frequency within the trees in the 21 UGAs evaluated (Figure 5C). Trees with high Cdie values generally exhibit poor structural conditions, an irregular crown shape and little foliage; therefore, a value higher than 5 % in Cdie would indicate that they are not healthy trees [6,14]. The urban environment is a stress factor for trees, with a lack of water being one of the factors present in urban areas and which mainly affects variables such as Cdie [4,6]

One way of estimating the vitality of vegetation is based on the amount of chlorophyll present in its leaves, with the use of multispectral images having become a fast and low-cost alternative for estimating chlorophyll content [48]. This work found that NDVI correlated positively with Fv/Fm (Figure 6), given that chlorophyll fluorescence evaluates the photosynthetic activity of the leaves and NDVI is sensitive to chlorophyll. An association was found between these variables which can help to better evaluate the condition of the tree crown than other type of indices. This is due to the polyfunctionality of NDVI and good results achieved in different environments; it also serves as a point of comparison with other indices [2,34,53]. On the other hand, a low correlation may be due to several reasons; one that has been studied recently is the flowering phenology that interferes with the spectral bands, that is, the degree and variety of colors present in the flowers that alter the "greenness" recorded by the index and that may vary according to the time of the year in which it is evaluated [24,36]. BNDVI instead showed a lower correlation with Fv/Fm (Figure 6), despite the fact that this index helps in the analysis of spatial heterogeneity and chlorophyll distribution; in contrast, a study on bryophytes found a positive correlation between BDNVI and Fv/Fm, which is attributed to the characteristics of the vegetation studied (non-vascular plants), as well as the diversity of species studied [32,54].

Another evaluated vegetation index which is an indicator of the greenness of the tree canopy is the GNDVI; in this case it did not show a significant correlation with Fv/Fm (Figure 6), possibly due to the same flowering condition mentioned above. However, a study on the species *Coffea arabica* found that some of the indicators related to the leaf content (chlorophyll) of this species were NDVI and GNDVI [48]; it should also be noted that GNDVI has recently been used to estimate the floral proportion in tree crowns located in natural forests at the pixel level with an accuracy > 85 % [36]. In this case, it is important to point out that among the tree species that flowered to different degrees during the study were *Bauhinia variegata* L. (pink, purple, and white flowering), *Spathodea campanulata* P.Beauv. (orange flowering), *Talipariti tiliaceum* (L.) Fryxell (pink and yellow flowering), *Jacaranda mimosifolia* D Don. (purple flowering) and *Grevillea robusta* A. Cunn. ex R. Br. (yellow and orange flowering), of which only jacaranda was among the most frequent species in the UGA. Although the correlations between Fv/Fm and the vegetation indices were low, it is also important to note that significant statistical differences were found ($p < 0.05$).

On the other hand, the correlations between Fv/Fm with Cdn and Ctr (Figure 6) indicate a reference to the health condition of the trees, since it is known that the presence of sparse crowns or those with high percentages of transparency are indicative of stress, which can be evaluated through Fv/Fm [22,50]. Fv/Fm is widely used in crop analysis; however, its use has rapidly spread to other natural and non-natural environments, so it is also used in urban tree stress assessment [32,49]. For example, some studies have detected stress in tree plant species through Fv/Fm under various cultural practices within UGAs, which include management and maintenance activities, particularly crown pruning or transplanting of urban trees [6,22,49]. Finally, NDVI and BNDVI were found to correlate with Cdn and Ctr, this given that they use a similar mathematical relationship [48]; however, crown variables are better related to NDVI.

The association between indices, such as the high correlation found between BNDVI and GNDVI (Figure 6), indicates that the variability not explained by one index can be explained by the other, and, therefore, they complement each other [26,32]; this allows the development of predictive models [48]. In this sense, the regressions between crown variables and vegetation indices showed associations between NDVI, BNDVI, Cdn and Ctr, which have been described in other studies [9,26,34,55]; one of the most noteworthy is NDVI with tree density and r^2 values greater than 0.7. This indicates that with these data it is possible to generate predictive models [28]. With the growth of urban areas and the incorporation of various artificial elements, the generation of predictive vegetation index models with greater accuracy becomes essential. In this sense, a study classified vegetation using NDVI, GNDVI, BNDVI, RGBVI, GRVI and SAVI (Soil Adjusted Vegetation Index)

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and developed an index that discriminates urban elements such as steel roofs and waterproofing, among others, when these predominate in the images [26].

The CV revealed instead that there are differences between high and low values of the indices (Figure 8). The results suggest that the evaluation of chlorophyll (green color) is not uniform with low values of the indices, which may be caused by some anthropogenic damage [35,48]. Studies on crops such as coffee (*Coffea arabica* L.), in which various plant indices are evaluated in diseased and healthy leaves, indicate that a high CV may represent a non-uniform distribution of chlorophyll for diseased leaves and this may be due to various factors that cause the degradation of the pigment (chlorophyll), such as trauma, chemicals, infectious agents, and senescence stages, among others [28,48].

5. Conclusions

It is possible to evaluate tree urban health condition by using vegetation indices such as NDVI, BNDVI, and GNDVI using drones. Variables such as chlorophyll fluorescence and crown density and transparency were significantly related to the vegetation indices using the near infrared (NIR) band, so it is feasible to use them and include them in the design of new indices to assess the condition of urban tree vegetation. Generating predictive health condition models is possible by considering positive correlations between vegetation indices with low coefficient of variation values. The identification of unfavorable conditions at tree-crown level through the use of vegetation indices allows taking timely actions related to their management, making this a pioneering study on urban trees in Mexico. Although the correlations between chlorophyll fluorescence and vegetation indices were low, what is important is the acceptable statistical significance ($p < 0.05$). Finally, the use of other types of indices such as the greenness index (GR) or the atmospheric resistant vegetation index (ARVI) are recommended to reduce the effects of flowering in urban trees and to improve the assessment of their health condition with the use of multispectral images.

Author Contributions: Conceptualization, L.M.M.-G., T.M.-T. and L.L.S.-R.; methodology, L.M.M.-G., T.M.-T., P.H.-R., D.A.-R., A.G.-G.; validation, L.M.M.-G., T.M.-T., and P.H.-R.; formal analysis, L.M.M.-G., T.M.-T., D.A.-R. and P.H.-R.; investigation, L.M.M.-G., T.M.-T., D.A.-R. and L.L.S.-R.; writing—original draft preparation, L.M.M.-G., T.M.-T. and A.G.-G.; writing—review and editing, L.M.M.-G., T.M.-T., D.A.-R., P.H.-R. and L.L.S.-R.; visualization, L.M.M.-G. and T.M.-T.; supervision, T.M.-T., D.A.-R., and P.H.-R.; project administration, L.M.M.-G. and T.M.-T.; funding acquisition, L.M.M.-G. and T.M.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially supported by the *Colegio de Postgraduados*' Structural and Functional Improvement of Forest Ecosystems' Knowledge Generation and Application Line.

Acknowledgments: The authors thank to the National Council of Science and Technology (CONACYT) in terms of the scholarship granted to the first author for graduate studies.

Conflicts of Interest: The authors declare no conflict of interest.

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