forests

Article

Short-Term Tree-Ring Series of *Pinus hartwegii* Lindl. Taken at Ground Level Correlate to Normalized Difference Vegetation Index Series

Luis R. Montoya-Jiménez [1], Armando Gómez-Guerrero [1,*], Felipe J. A. Pedraza-Oropeza [2], Teresa M. González-Martínez [1] and Arian Correa-Díaz [3]

[1] Posgrado en Ciencias Forestales, Colegio de Postgraduados, Texcoco 56230, Mexico; montoya.luis@colpos.mx (L.R.M.-J.); teresa.gonzalez@colpos.mx (T.M.G.-M.)
[2] Posgrado en Hidrociencias, Colegio de Postgraduados, Texcoco 56230, Mexico; fpedraza@colpos.mx
[3] Centro Nacional de Investigación Disciplinaria en Conservación y Mejoramiento de Ecosistemas Forestales, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Av. Progreso 5, Barrio de Santa Catarina, Delegacion Coyoacán, Mexico City 04010, Mexico; correa.arian@inifap.gob.mx
* Correspondence: agomezg@colpos.mx

Abstract: In this work, we propose that small wood core samples (≤10 cm length), taken from 0.3 m above the soil, represent an accurate means of correlating forest growth with remote sensing data. Short-term correlations between the Normalized Difference Vegetation Index (NDVI) and tree-ring components of the last three to four decades were tested, using 210 *Pinus hartwegii* wood cores collected at two locations, Tláloc (TLA) and Jocotitlán (JOCO) in central Mexico. The NDVI time series were generated with the Google Earth Engine (GEE) using Landsat 8 images. Also, seasonal trends in NDVI (e.g., spring, summer, autumn, winter) were analyzed through longitudinal analysis. The results showed more statistically significant dendrochronological indices in TLA than in JOCO, but both locations consistently showed an NDVI decrease in 2018 and 2020, indicating a reduction in vegetation vigor. At the two locations, the minimum and maximum NDVI occurred in April and October, respectively. Seasonal NDVI changes for spring were mainly seen at TLA with a decreasing trend, which may be related to a less defined dry season. The significant correlations ($p < 0.05$) between tree-ring components and the NDVI occurred in the dry season, indicating that the productivity of a given year is defined by the tree vigor shown in April and May, in the case of TLA, and between January and March, for JOCO. Although the NDVI values of JOCO were higher than those of TLA, tree growth, expressed by tree-ring indices, was lower. Our proposed field method to correlate tree-ring information and the NDVI is reliable and can be used in other coniferous forests.

Keywords: highland forest; radial growth; dendrochronology; vegetation index; *Pinus hartwegii*; NDVI; tree-ring correlation methods; remote sensing

check for updates

Citation: Montoya-Jiménez, L.R.; Gómez-Guerrero, A.; Pedraza-Oropeza, F.J.A.; González-Martínez, T.M.; Correa-Díaz, A. Short-Term Tree-Ring Series of *Pinus hartwegii* Lindl. Taken at Ground Level Correlate to Normalized Difference Vegetation Index Series. *Forests* **2024**, *15*, 324. https://doi.org/10.3390/f15020324

Academic Editors: Li Qin, Lushuang Gao, Vladimir V. Shishov and Ruibo Zhang

Received: 8 January 2024
Revised: 28 January 2024
Accepted: 1 February 2024
Published: 8 February 2024

1. Introduction

Pinus hartwegii Lindl. inhabits elevated areas of Mexico and Guatemala [1]. In Mexico, it is found mainly from elevations of 3500 m along the Trans-Mexican Volcanic Belt, defining the tree-zone limit in the study area [2]. It is a species adapted to the hostile climate and soil conditions that prevail at high elevations, such as high temperature oscillations of more than 30 °C in a single day and sandy shallow soils of low fertility [3]. According to vegetation prediction models, the natural distribution area of *Pinus hartwegii* will decrease because of climate change impacts [4]. The conditions preventing the migration of this species to higher elevations include shallow and low-fertility soils with slow rates of formation. Specifically, phosphorus is an element of low availability in *Pinus hartwegii* forests [3]. In addition to the reduction in habitable area, changes in the chemical composition of plant components and nutrient dynamics are likely to occur in these forests as climate change progresses [5].

One strategy to investigate how tree growth is influenced by recent climate variation is to correlate tree-ring width measurements with remotely sensed data. Recently, dendrochronological methods have been used to explain the response of forests to climate change and whether their resistance and resilience are changing [6–8]. The historical information recorded in tree rings helps us to understand other changes occurring in the ecosystem, such as droughts [9].

The advantage of using information from remote sensing is that the vegetation vigor can be inferred from red and near-infrared bands, allowing for spatial evaluation. Remote sensing captures forest canopy reflectance and stores the information of different bands (wavelengths), allowing for the calculation of vegetation indices, which can provide information about vegetation vigor and tree growth [10].

The series of annual tree rings provide information on radial growth rates, and their correlation with vegetation indices is possible because, if the vegetation shows good vigor, it is likely that there are favorable conditions for tree growth and therefore tree rings are wider [11,12]. However, topographic variation in sites and their climatic conditions also influence the degree of correlation between rings and vegetation indices [13]. The Normalized Difference Vegetation Index (NDVI) is a well-known vegetation index that was developed by Rouse et al. (1973) and that has been shown to be reliable in representing vegetation vigor variation [12,14,15].

The correlation analysis between vegetation indices and tree-ring series is a reliable strategy to understand forest growth. Studies such as Beck, et al. [16] confirmed the link between the NDVI, ring width index (RWI), and maximum latewood density (MXD) in Alaska and western Canada. Correa-Díaz et al. [12] also confirmed significant correlations in *Pinus hartwegii* forests using MODIS sensor data.

This work aimed to find a short-term correlation between standardized tree-ring measurements and the NDVI, but, in contrast to previous studies, incorporated a high-spatial-resolution data set (using series from LANDSAT8 from 2013 to 2021) and collected short-term samples at 0.3 m above the ground (at stump height), where tree rings are wider. Two levels of elevation and aspect were considered to better capture the variation in the landscape and test our method. The NDVI variation is related to the growing season and can be useful in detecting whether extended periods of tree growth are occurring [17]. The hypotheses proposed were: (i) there are statistically significant correlations between standardized tree-ring measurements and the NDVI, and (ii) annual and seasonal variations in NDVI are different at the two studied locations, TLA and JOCO.

2. Materials and Methods

2.1. Study Area

The study sites were two mountains in central Mexico: Tláloc (TLA), located at coordinates 19°24′44.86″ N and 98°42′45.34″ W, with 4125 m of maximum elevation, and Jocotitlán (JOCO), with coordinates 19°42′26″ N 99°47′12″ W and 3910 m of maximum elevation. The vegetation at the two locations is represented by natural monospecific stands of *Pinus hartwegii* that grow from 3500 and 3700 m of elevation for TLA and JOCO, respectively (Figure 1). The predominant climate for both elevations is C(E)(W_2) (W)b(i), which is described as a semi-cold, sub-humid climate with summer rainfall [18]. A reconstruction of the climatic variables from 1980 to 2021 for the two study areas is shown in Figure S1 in the Supplementary Information. The database procedure used for this reconstruction is as indicated by Thornton et al. (2022) [19]. Daily temperatures recorded with HOBO (®) dataloggers, every four hours, from 2017 to 2023, for the two study locations, are shown in Figure S2 of the Supplementary Information.

Mean tree density for the sites is 156 and 180 tree ha^{-1}, with tree volume of 220 and 183 m^3 ha^{-1}, and mean tree age ranging from 40 to 80 years and from 52 to 89 years for TLA and JOCO, respectively [20,21].

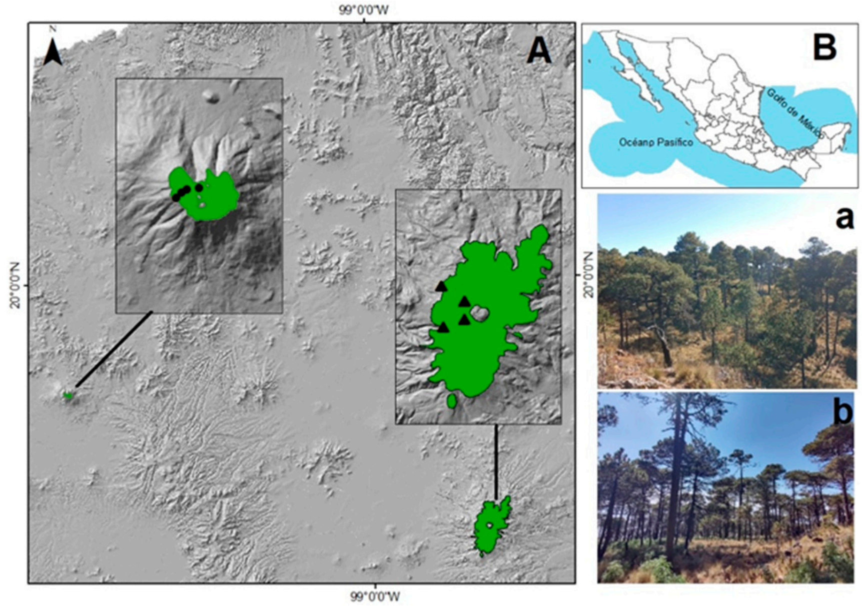


Figure 1. Location of the two study areas. (**A**) From left to right, the Jocotitlán and Tláloc mountains, highlighted with green polygons, respectively. Black triangles and circles represent sampling sites within each mountain area. (**B**) Macro location of the study areas. General views of the forests studied (**a**,**b**).

The soils at both sites are Andosols, developed from volcanic material, and are characterized by their dark color, high water-retention capacity and richness in organic matter [3]. To capture the higher variability of the landscape, sites were distributed along two elevations and two aspects. For TLA, the elevations were 3500 and 3900 m and the aspects were northwest (NW) and southwest (SW). For JOCO, the elevations were 3700 and 3800 m, with NW and SW aspects.

2.2. Dendrochronological Sampling

At each site, 30 wood cores of *P. hartwegii* were extracted at 0.30 m above ground level, ensuring that information was obtained from at least the last three or four decades (30 or 40 tree rings). The tree-ring segments were sampled in 2022, because we had to wait for the complete formation of the 2021 tree ring. It is important to note that tree-ring samples are usually taken at 1.3 m from the ground, to correlate the information with regular forest inventories, but in this study, we took samples at 0.3 m above ground level because at this height, the tree rings are wider, ensuring more accurate measurements. Nevertheless, a preliminary sampling indicated high linear correlation ($R^2 = 0.96$, $p < 0.001$) between measurements at 1.3 m and 0.3 m. Diameter at stump height (0.3) is not an unknown variable in forestry; its use can improve volume estimations, and it is useful in estimating volume removals after disturbances [22]. The diameter at stump height of the sampled trees ranged from 45 to 50 cm (9.7 sd) in TLA, and from 32 to 36 cm (6.5 sd) in JOCO.

We used a 10 cm wood core sampler (Haglöf) because it is faster to obtain tree-ring samples with wider rings that also perfectly correspond to the historical period of LANDSAT 8 images. Sampled trees were dominant and/or codominant, healthy, and without apparent mechanical damage.

2.3. Tree-Ring Sample Dating and Measurement

Wood core samples were air-dried then mounted and glued onto pieces of wood to prevent twisting. Although we planned to collect 240 tree-ring samples from the two mountains, only 210 were collected due to a recent forest fire (JOCO, one site) that allowed for dense undergrowth, creating risks to sampling due to the rocky soil surface and sloping terrain. However, historical NDVI was calculated for all the sites at the two locations.

Wood core samples were sanded with sandpaper of different grain size (80, 120, 240, 240, 280, 360, 600, and 1200) to clarify the earlywood and latewood bands. After that, samples were scanned in an EPSON scanner (HP MODEL J131B) at a resolution of 4200 dpi. Tree-ring measurements were performed with the WinDENDRO® software 2008a (Regent Instruments, Quebec, QC, Canada), following standard dendrochronological procedures [23,24].

2.4. Tree-Ring Standardization and Short-Term Chronologies

Tree-ring measurements were analyzed with the dendrochronology library dplR in R version 4.1.1 [25,26]. For detrending purposes, we used a spline function with the criteria of 50% response frequency and 67% of the length of the series [27,28]. Standardized series for ring width (TRW), earlywood (EW) and latewood (LW) were generated for both locations. As we measured the diameter of the trunk at 0.3 m and the bark width of every tree, we used the bai.out instruction of the dplR library to calculate the basal area increment (BAI), assuming concentric tree rings.

2.5. NDVI Data Processing through Google Earth Engine (GEE)

To construct the NDVI time series in GEE, we used a JavaScript code to access the Landsat 8 OLI images from 2013 to 2021 and to identify pixels contaminated with clouds, snow, or shadows. The OLI sensor contains 10 multispectral bands, with pixel sizes of 15 or 30 m, depending on the band. The NDVI is the ratio between red and near-infrared light reflected by the canopy and is an indirect measurement of photosynthesis and forest productivity. NDVI series were calculated for the two locations, and for the four sites within every location. The trends in NDVI series were analyzed for the 2013–2021 period, using average monthly values, and conducting the analysis according to the season of the year. We also found that in this study, the NDVI was statistically correlated to other indices, such as the soil-adjusted vegetation index (SAVI) and the enhanced vegetation index (EVI) (see Supplementary Information). However, for the purposes of this work, we only considered the most common vegetation index, the NDVI.

2.6. Tree Ring and NDVI Correlation

To investigate the correlation of NDVI values with the standardized measurements of TRW, EW, and LW, we used the treeclim R package [29]. Although treeclim is normally used with temperature and precipitation data, in this study, NDVI values were used to temporally correlate tree-ring components using a significant level of 5%.

2.7. Statistical Analysis of the NDVI Time Series

The NDVI time series were analyzed in two ways. First, a smoothed curve regression model (spline) was fitted with the PROC TRANSREG SAS procedure, in order to maximize correlation and to represent monthly NDVI fluctuations for the period from 2013 to 2021. The SAS output of the spline was plotted with the R package. Second, the monthly mean values for the twelve months of the year were analyzed and a cubic regression model was fitted with longitudinal analysis procedures, as explained by Fitzmaurice et al. [30]. The longitudinal analysis was conducted with the SAS software (V. 9.4), using the PROC MIXED module and an autoregressive variance–covariance matrix. The output of predicted values was plotted with an Excel spreadsheet. To investigate the seasonal changes in NDVI at each elevation, the effect of time and the time × season interaction were tested at 5% statistical significance, using longitudinal analysis [30].

3. Results and Discussion

3.1. Dendrochronological Analysis

When the data were analyzed for each location, inter-correlation series equal or greater than 0.32 were not obtained for any tree-ring component (Table 1). The best dendrochronological indices were seen for the total tree ring (TRW), and for this reason, dendroecological details for the EW and LW components are not shown. The low inter-correlation at each mountain is due to the high variability between trees and environmental conditions at each site. However, when the series were analyzed by site, and grouped by combinations of elevation and aspect, the results improved significantly. In the case of TLA, all four sites, except site S-3900, reached the minimum inter-correlation of 0.32 with only 30 trees. In the case of JOCO, the correlations did not improve when separating the series by site (Table 1).

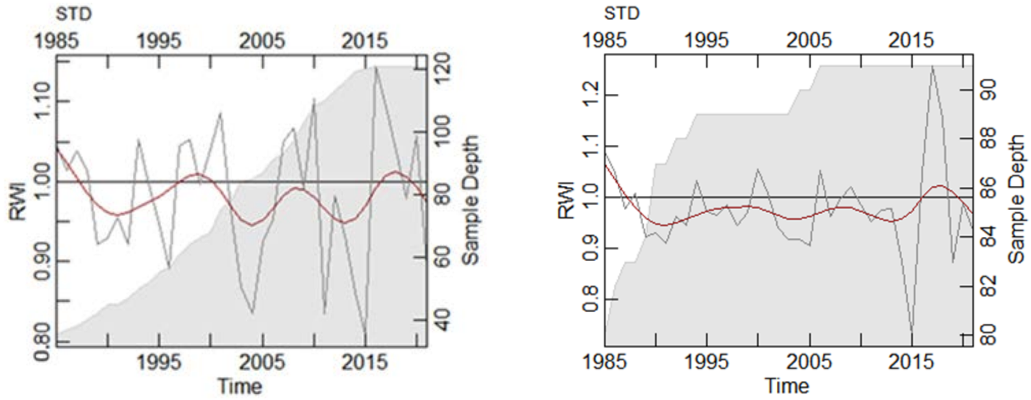
Table 1. Dendrochronological analysis for the sample trees at the two mountain sites.

Mountain	Site	Trees	Expressed Population Signal (EPS)	Mean Sensitivity	Inter-Correlation Series	Chronology Extension	Period (Year)
TLA	3900-NO	30	0.754	0.36	0.33	37	1985–2021
	3900-SO	30	0.703	0.38	0.17	37	1985–2021
	3500-NO	30	0.348	0.31	0.40	37	1985–2021
	3500-SO	30	0.428	0.37	0.42	37	1985–2021
	(four sites)	120	0.826	0.37	0.23	37	1985–2021
JOCO	3700-NO	30	0.547	0.42	0.15	37	1985–2021
	3800-NO	30	0.65	0.38	0.21	37	1985–2021
	3800-SO	30	0.594	0.38	0.19	37	1985–2021
	(three sites)	90	0.768	0.40	0.20	37	1985–2021

The probable explanation for not finding correlations higher than 0.32 in JOCO is that on this mountain, other abiotic factors, such as soil variability and microclimate conditions, were more important in explaining the variation in tree-ring growth. Another possible explanation is that we did not collect full wood core samples down to the center or pith of the tree; we sampled the last three to four decades, when the global climate has been more variable [31]. Despite these results, it is worth highlighting the good inter-correlation for most TLA sites with a sample of 30 trees with values higher than 0.32.

The TRW series at the mountain level and for the period from 1985 to 2021 are shown in Figure 2. Despite the low inter-correlations at most sites, for both mountains, a slight increase in radial growth is observed around 2017, but this episode of good growth has decreased considerably by the year 2021. It is noticeable that, from 1985 to date, neither mountain has returned to growth levels close to the historical mean corresponding to the value of 1.0 in Figure 2, which could be evidence of the recent loss of forest resilience indicated by other authors [6].

We found an expressed population signal (EPS) lower than the threshold of 0.85 suggested by other authors [32]. This result indicates that a larger sample size is required to find a more defined trend for the tree-ring series. However, it is evident that when pooling all the ring series by mountain, the EPS reached values of 0.83 and 0.77 for TLA and JOCO, respectively. Other studies for the same species, carried out at the Trans-Mexican Volcanic Belt, have also reported EPS values of the same 0.80 to 0.88, which are close to those we found in TLA [33,34]. The mean sensitivity values at all sites were low, ranging from 0.31 to 0.42, indicating the low influence of the previous year's measurements on the actual year values. A possible explanation for this result is the high yearly climate variability in recent decades [31], which prevents the sites from reaching sensitivities that are 0.5 greater than those reported in other studies [34].



(**A**) (**B**)

Figure 2. Standardized measurements of total ring width (RWI) in the period from 1985 to 2021 for *Pinus hartwegii* on Mount Tláloc (**A**) and Jocotitlán (**B**).

3.2. Temporal Analysis of the NDVI

The monthly NDVI mean values at the two mountain sites show a seasonal change corresponding to the expected vegetation vigor variation over the year. According to the fitted longitudinal model, the extreme low and high NDVI values occur in April and October, respectively (Figure 3a). This period corresponds to the observed minimum and maximum values for *Pinus hartwegii* forests across the Trans-Mexican Volcanic Belt, which defines the growing season [17]. The historical NDVI in TLA fluctuated between 0.5 and 0.7, depending on the season of the year; however, in the dry seasons of 2013, 2018, and 2021, there was a considerable decrease in NDVI that could denote periods of stress in the vegetation (Figure 3b). The NDVI variation in JOCO is similar to that of TLA, but two points should be highlighted. First, the NDVI values for JOCO were statistically higher than those for TLA ($p < 0.05$), despite its lower tree growth, as indicated by the tree-ring index (Figures 2 and 3c, Table 2). This is extremely important since NDVI values cannot be assumed to be indicators of forest growth, as other studies have suggested [12]. Direct measurements from the tree stand are required to infer the productivity of each site. The second point is that the decrease in NDVI in JOCO is also seen in the years 2013, 2018, and 2021 (Figure 3d).

Table 2. Type III Tests of Fixed Effects for the monthly NDVI.

Effect	DF	Den DF [a]	F Value	Pr > F
TIME	1	178	90.93	<0.0001
$TIME^2$	1	178	97.69	<0.0001
$TIME^3$	1	178	83.63	<0.0001
MOUNTAIN [b]	1	178	4.23	0.0411
TIME × MOUNTAIN	1	178	1.41	0.2358

[a] Degrees of freedom associated to the model errors. [b] Mountains are Tláloc or Jocotiltán.

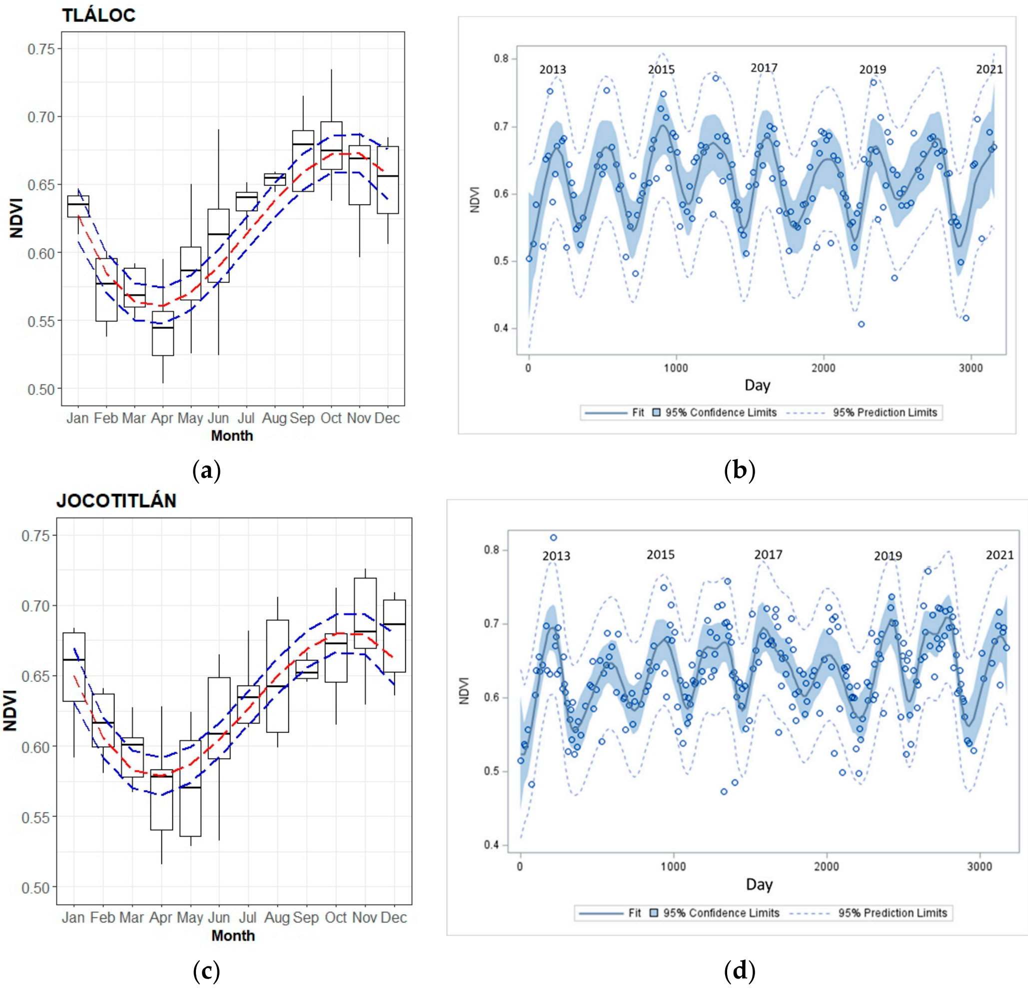


Figure 3. Box plot and cubic model fitted via longitudinal analysis (**a**,**c**). The blue lines represent the 95% confidence intervals. Fitted spline for the NDVI values at the Tláloc (**b**) and Jocotitlán (**d**) mountains for the period 2013 to 2021. The R^2 for the spline is 0.53 ($p < 0.05$) and 0.52 ($p < 0.05$) for Tláloc and Jocotitlán, respectively.

3.3. Tree-Ring and NDVI Correlation

We found significant and positive correlations ($p < 0.01$, $p < 0.05$) between the monthly NDVI and ring components at the mountain level (Table 3). As we found a highly significant correlation ($p < 0.001$) between the standardized tree-ring measurements and the BAI, we assumed these two variables as proxies of tree growth (see supplementary information). In the case of TLA, there were significant correlations from the previous year ("december") to spring of the actual year (APRIL–MAY). For JOCO, correlations were observed from winter (JANUARY) of the current year to early spring (MARCH). The correlations found were observed in all wood components (TRW, EW, LW). Our results agree with those found by Kaufmann et al. [35], who reported a statistically significant correlation between ring width and the NDVI in the Northern Hemisphere, but the authors pointed out that the correlation depends on the season. Tree species located south of 40° exhibited the best correlations in early spring, while for species located north of 40°, summer was the best season to find significant correlations. Other authors have also found significant relationships with the NDVI from the previous year "december" to March of the actual year, but using the MODIS sensor at Tlaloc Mountain [12]. Likewise, Bunn et al. [36] reported significant correlations between the NDVI and ring width for species of three genera (Pinus, Picea, and Larix) in the Siberian Taiga. This confirms the reliability of tree-ring measurements in supporting remote sensing information to better understand forest growth and related processes, like carbon sequestration [37].

Table 3. Main correlations between the tree-ring components of *Pinus hartwegii* and the NDVI at sites on two mountains, Tláloc and Jocotitlán.

Mountain	Variable	Tree-Ring Component	Correlation to the NDVI
Tláloc	$NDVI_{APRIL}$	TRW	0.664 *
	$NDVI_{MAY}$	TRW	0.866 **
	$NDVI_{MAY}$	EW	0.851 **
	$NDVI_{MAY}$	LW	0.772 *
	$NDVI_{\text{“december”}}$	LW	0.727 *
Jocotitlán	$NDVI_{MARCH}$	TRW	0.646 *
	$NDVI_{MARCH}$	EW	0.570 *
	$NDVI_{MARCH}$	LW	0.798 *
	$NDVI_{JANUARY}$	LW	0.687 *

Note: Months of the previous year are in lowercase letters, while those of the current year are in capital letters. Significance levels ($p < 0.01$ **, $p < 0.05$ *).

Some authors have reported weak and divergent correlations between the NDVI and tree-ring measurements of coniferous and deciduous species [38–40], but they used data from sensors of lower spatial resolution, which may explain this lack of significance. Mašek et al. [13] reported that tree rings and the NDVI were decoupled for *Pinus sylvetris* and *Abies picea*; however, they suggested that topography is very important in explaining NDVI variation and tree growth. This is in agreement with our results, and explains why, when our data were grouped by elevation and aspect, better dendrochronological parameters could be identified. It is also known that NDVI variation is influenced by a synergistic effect of temperature and precipitation [41]. Although, in general, the relationship between the NDVI and precipitation and temperature is positive, this result is not always consistent, especially for temperature [42]. Our results show higher historical maximum temperatures (Tmax) in JOCO, which is consistent with the positive effect on the NDVI (Figure S1). However, in both locations, the variation in Tmax has increased since 2019 (Figures S1 and S2).

The correlations between the NDVI and tree-ring components indicate that the NDVI values of the dry season (March–May) are critical in explaining the expected tree growth in a given year. The use of a standardized index for tree rings allows us to compare the NDVI and tree growth relationships for both locations. All correlations are positive, indicating that the higher the NDVI of the dry season, the higher the tree growth expected, which applies to both mountains. Kaufmann et al. [43] found a positive correlation between tree rings and the NDVI from April to July and in October in coniferous forests in North America and Eurasia, concluding that summer changes may have important implications for Northern Hemisphere forests.

However, it was not expected that the “december” NDVI of the previous year would correlate significantly with the latewood width in the subsequent year (0.73). This memory effect between the wood formed during the previous winter and the autumn of the following year is not easy to explain but can be attributed in part to the marginal memory effect of the previous and subsequent year measurements, as shown in Table 1 (mean sensitivity: 0.31 to 0.42). In addition, it is possible that the level of vigor with which forests finish the previous year determines the overall tree growth during the following year.

3.4. Seasonal Trends in NDVI

The longitudinal analysis indicated statistically significant interaction of time × season; therefore, seasonal NDVI trends have different patterns at each mountain (Figure 4). However, the most evident seasonal change was seen in TLA, as the NDVI of spring decreased in the years 2019 to 2021. The NDVI trends for JOCO are more uniform, as NDVI changes for spring and summer behave similarly, and for fall and summer, no significant changes are seen over time. Other studies have suggested that seasonal changes in NDVI in the Trans-Mexican Volcanic Belt are due to a shift in maximum NDVI values later in the year for several mountains [17]. In contrast, our data for TLA showed a trend of reduced vegetation vigor in summer. Beck et al. [16] used MODIS and NDVI data to spatially represent early spring and late autumn in northern Europe and found a trend of earlier autumn onset in southernmost Sweden. The results of this study show that autumn has been the most stable season for both mountains. The distribution of precipitation over time in TLA is greater, even compared to JOCO (Figure S1). This fact could explain why TLA is more sensitive to seasonal changes in NDVI that depend on precipitation. The JOCO location shows two sharp dry seasons, before and after the growing season, and that may be related to the higher NDVI. Additionally, TLA is a site more affected by changes in temperature and precipitation in the most recent years (Figures S1 and S2).

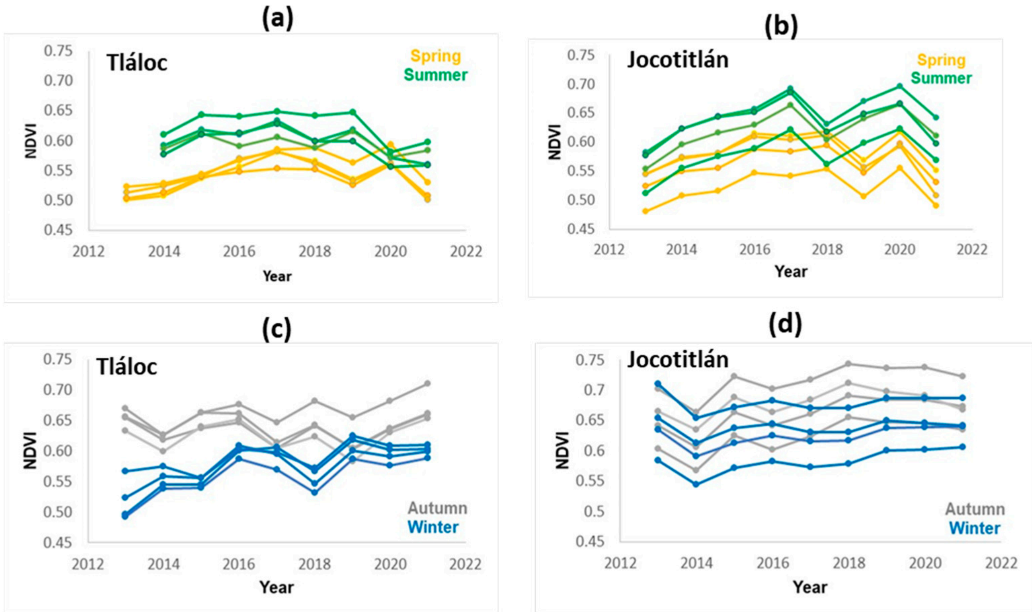


Figure 4. Predicted values of NDVI trends estimated via longitudinal analysis.

4. Conclusions

Short-term series of radial growth taken at the base of the tree (0.3 m from the ground) with a small wood core sample (10 cm length) had acceptable dendrochronological parameters and allowed us to determine a statistical correlation to remote sensing data. Standardized short-term tree-ring series are statistically correlated to the NDVI and reliable for understanding tree growth. The annual and seasonal NDVI were different between the mountains, but the NDVI of the dry season is what defines the annual tree growth for each site. The location with more defined dry periods, before and after the growing season, showed a higher NDVI. The previous year's "december" NDVI correlated with the latewood width of the actual year. Although this result was not fully explained, it may be related to a natural memory effect that occurs in coniferous forests. Most importantly, the NDVI cannot always be used as a proxy of forest growth without terrain-based data, like tree-ring measurements. In this study, the Jocotitlán mountain had statistically higher NDVI values than the Tláloc mountain, but its tree growth was lower. Therefore, for this type of study, it is essential to calibrate the information from remote sensing with the direct measurement of tree parameters, such as tree-ring width.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15020324/s1, Figure S1: Temporal distribution of climatic variables for the two study sites, from 1980 to 2021. (a) Daily precipitation, (b) Minimum temperature and (c) Maximum temperature. Estimations were performed according to Thornton et al. (2022) [19]. Note that daily precipitation is more even distributed at TLÁLOC site, while at JOCOTILÁN, two sharp dry periods are defined before and after the growing season. Minimum temperatures in the growing season are higher at JOCOTILTÁN. Also note that at TLÁLOC maximum temperatures, before the growing season have increased in recent years; Figure S2: Daily temperatures recorded with HOBO (®) dataloggers every four hours for three sites in the TLÁLOC location. Note the increase in temperatures in the year 2020 and 2021, specially in plots (a,c); Figure S3: Daily temperatures recorded with HOBO (®) dataloggers every four hours for three sites in the JOCOTILÁN location. Note the higher contrast in temperature variation between the 3800-SW site (a) and the 3700-NO site (c); Figure S4: The standardized values of ring width (RWI) are highly correlated to Basal area increments (BAI) indicating that RWI is a reasonable a proxy of tree growth. BAI area in cm^2 $year^{-1}$; Table S1: Correlation Matrix for the vegetation indices, NDVI, EVI and SAVI for the two studied mountains. Note that in all cases the correlation is highly significant ($p < 0.05$), implying that all indices would generate similar results and conclusions. However, we emphasized on one of the most common vegetation indices like the NDVI.

Author Contributions: Conceptualization, A.G.-G.; Data Curation, A.G.-G. and L.R.M.-J.; Investigation, A.G.-G. and L.R.M.-J.; Original draft, A.G.-G. and L.R.M.-J.; Writing—review and editing, A.G.-G., A.C.-D., T.M.G.-M. and F.J.A.P.-O.; Methodology, A.G.-G. and L.R.M.-J.; Visualization, A.G.-G. and A.C.-D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the National Council of Humanities, Science and Technology (CONAHCYT) with a graduate studies scholarship granted to the first author.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

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

References

1. García-Amorena, I.; Moreno-Amat, E.; Aulló-Maestro, M.E.; Mateo-Sánchez, M.C.; Merino-De-Miguel, S.; Ribalaygua, J.; Marchant, R. Combining Remote Sensing and Species Distribution Modelling to Assess Pinus hartwegii Response to Climate Change and Land Use from Izta-Popo National Park, Mexico. *Land* **2021**, *10*, 1037. [CrossRef]
2. Farjon, A.; de la Rosa, J.A.P.; Styles, B.T. *A Field Guide to the Pines of Mexico and Central America*; Royal Botanic Gardens: Kew, UK, 1997.
3. Marín, L.E.; Escolero-Fuentes, O.; Trinidad-Santos, A. Physical geography, hydrogeology, and forest soils of the basin of Mexico. In *Urban Air Pollution and Forests: Resources at Risk in the Mexico City Air Basin*; Springer: Berlin/Heidelberg, Germany, 2002; pp. 44–67.
4. Guitérrez, E.; Trejo, I. Efecto del cambio climático en la distribución potencial de cinco especies arbóreas de bosque templado en México. *Rev. Mex. Biodivers.* **2014**, *85*, 179–188. [CrossRef]
5. Gómez-Guerrero, A.; Doane, T. The response of forest ecosystems to climate change. In *Developments in Soil Science*; Elsevier: Amsterdam, The Netherlands, 2018; Volume 35, pp. 185–206.
6. Correa-Díaz, A.; Villanueva-Díaz, J.; Gómez-Guerrero, A.; Martínez-Bautista, H.; Castruita-Esparza, L.; Horwath, W.; Silva, L. A comprehensive resilience assessment of Mexican tree species and their relationship with drought events over the last century. *Glob. Chang. Biol.* **2023**, *29*, 3652–3666. [CrossRef]
7. Gómez-Guerrero, A.; Correa-Díaz, A.; Castruita-Esparza, L. Cambio Climático y Dinámica de Los Ecosistemas Forestales. *Rev. Fitotec. Mex.* **2021**, *44*, 673–682. [CrossRef]
8. Lloret, F.; Keeling, E.G.; Sala, A. Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. *Oikos* **2011**, *120*, 1909–1920. [CrossRef]
9. Gartner, B.L.; Aloni, R.; Funada, R.; Lichtfuss-Gautier, A.N.; Roig, F.A. Clues for dendrochronology from studies of wood structure and function. *Dendrochronologia* **2002**, *20*, 53–61. [CrossRef]
10. Pandey, P.C.; Sharma, L.K. *Advances in Remote Sensing for Natural Resource Monitoring*; John Wiley & Sons: Hoboken, NJ, USA, 2021.
11. Vicente-Serrano, S.M.; Camarero, J.J.; Olano, J.M.; Martín-Hernández, N.; Peña-Gallardo, M.; Tomás-Burguera, M.; Gazol, A.; Azorin-Molina, C.; Bhuyan, U.; El Kenawy, A. Diverse relationships between forest growth and the Normalized Difference Vegetation Index at a global scale. *Remote Sens. Environ.* **2016**, *187*, 14–29. [CrossRef]
12. Correa-Díaz, A.; Silva, L.C.R.; Horwath, W.R.; Gómez-Guerrero, A.; Vargas-Hernández, J.; Villanueva-Díaz, J.; Velázquez-Martínez, A.; Suárez-Espinoza, J. Linking remote sensing and dendrochronology to quantify climate-induced shifts in high-elevation forests over space and time. *J. Geophys. Res. Biogeosci.* **2019**, *124*, 166–183. [CrossRef]
13. Mašek, J.; Tumajer, J.; Lange, J.; Kaczka, R.; Fišer, P.; Treml, V. Variability in Tree-ring Width and NDVI Responses to Climate at a Landscape Level. *Ecosystems* **2023**, *26*, 1144–1157. [CrossRef]

14. Gessesse, A.A.; Melesse, A.M. Temporal relationships between time series CHIRPS-rainfall estimation and eMODIS-NDVI satellite images in Amhara Region, Ethiopia. In *Extreme Hydrology and Climate Variability*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 81–92.
15. Ma, Y.; Guan, Q.; Sun, Y.; Zhang, J.; Yang, L.; Yang, E.; Li, H.; Du, Q. Three-dimensional dynamic characteristics of vegetation and its response to climatic factors in the Qilian Mountains. *Catena* **2022**, *208*, 105694. [CrossRef]
16. Beck, P.S.; Andreu-Hayles, L.; D'Arrigo, R.; Anchukaitis, K.J.; Tucker, C.J.; Pinzón, J.E.; Goetz, S.J. A large-scale coherent signal of canopy status in maximum latewood density of tree rings at arctic treeline in North America. *Glob. Planet. Chang.* **2013**, *100*, 109–118. [CrossRef]
17. Correa-Díaz, A.; Romero-Sánchez, M.; Villanueva-Díaz, J. The greening effect characterized by the Normalized Difference Vegetation Index was not coupled with phenological trends and tree growth rates in eight protected mountains of central Mexico. *For. Ecol. Manag.* **2021**, *496*, 119402. [CrossRef]
18. García, E. *Modificaciones al Sistema de Clasificación Climática de Köpen (Para Adaptarlo a las Condiciones de la República Mexicana)*, 5th ed.; Instituto de Geografía UNAM: Mexico City, Mexico, 2004; p. 98.
19. Thornton, M.; Shrestha, R.; Wei, Y.; Thornton, P.; Kao, S.; Wilson, B. *Daymet: Daily Surface Weather Data on a 1-Km Grid for North America*; Version 4; ORNL DAAC: Oak Ridge, TN, USA, 2022. [CrossRef]
20. Acosta Mireles, M.; Carrillo Anzures, F.; Delgado, D.; Velasco Bautista, E. Establecimiento de parcelas permanentes para evaluar impactos del cambio climático en el Parque Nacional Izta-Popo. *Rev. Mex. Cienc. For.* **2014**, *5*, 6–29.
21. Nuñez-Garcia, A.; Gomez-Guerrero, A.; Terrazas-Salgado, T.M.; Vargas-Hernández, J.J.; Villanueva-Diaz, J. Analysis of basal area increment of Pinus hartwegii Lindl. at different elevations and aspects on Jocotitlan Mountain, State of Mexico. *Rev. Chapingo Ser. Ciencias For. Ambient* **2020**, *27*, 77–88.
22. Pond, N.C.; Froese, R.E. Evaluating published approaches for modelling diameter at breast height from stump dimensions. *For. Int. J. For. Res.* **2014**, *87*, 683–696. [CrossRef]
23. Fritts, H. *Rings and Climate*; Academic Press: Cambridge, MA, USA, 1976.
24. Stokes, M.; Smiley, T. *An Introduction to Tree-Ring Dating*; University of Arizona Press: Tucson, AZ, USA, 1968.
25. Bunn, A.G. A dendrochronology program library in R (dplR). *Dendrochronologia* **2008**, *26*, 115–124. [CrossRef]
26. Bunn, A.G. Statistical and visual crossdating in R using the dplR library. *Dendrochronologia* **2010**, *28*, 251–258. [CrossRef]
27. Cook, E.R. The decomposition of tree-ring series for environmental studies. *Tree-Ring Bull.* **1987**, *47*, 37–59.
28. Cook, E.R.; Peters, K. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bull.* **1981**, *41*, 45–53.
29. Zang, C.; Biondi, F. treeclim: An R package for the numerical calibration of proxy-climate relationships. *Ecography* **2015**, *38*, 431–436. [CrossRef]
30. Fitzmaurice, G.M.; Laird, N.M.; Ware, J.H. *Applied Longitudinal Analysis*; Wiley: Hoboken, NJ, USA, 2004.
31. Williams, A.P.; Allen, C.D.; Macalady, A.K.; Griffin, D.; Woodhouse, C.A.; Meko, D.M.; Swetnam, T.W.; Rauscher, S.A.; Seager, R.; Grissino-Mayer, H.D. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nat. Clim. Chang.* **2013**, *3*, 292–297. [CrossRef]
32. Briffa, K.R.; Jones, P.D. *Basic Chronology Statistics and Assessment in Methods of Dendrochronology: Applications in the Environmental Sciences*; Cook, E.R., Kairiukstis, L.A., Eds.; Kluwer Academic Publishers: Boston, MA, USA, 1990; pp. 137–152.
33. Manzanilla-Quinones, U.; Aguirre-Calderón, Ó.A.; Jimenez-Perez, J.; Treviño-Garza, E.J.; Yerena-Yamallel, J.I. Current and future distribution of the Pinus hartwegii Lindl subalpine forest in the Tranverse Neovolcanic Belt. *Madera Bosques* **2019**, *25*, e2521804.
34. Manzanilla-Quiñones, U.; Aguirre-Calderón, Ó.A.; Jiménez-Pérez, J.; Villanueva-Díaz, J. Sensibilidad climática en anchuras de anillos de crecimiento de Pinus hartwegii: Una especie alpina mexicana con potencial dendroclimático. *Rev. Mex. Biodivers.* **2020**, *91*, abril-junio. [CrossRef]
35. Kaufmann, R.; D'arrigo, R.; Paletta, L.; Tian, H.; Jolly, W.M.; Myneni, R. Identifying climatic controls on ring width: The timing of correlations between tree rings and NDVI. *Earth Interact.* **2008**, *12*, 1–14. [CrossRef]
36. Bunn, A.G.; Hughes, M.K.; Kirdyanov, A.V.; Losleben, M.; Shishov, V.V.; Berner, L.T.; Oltchev, A.; Vaganov, E.A. Comparing forest measurements from tree rings and a space-based index of vegetation activity in Siberia. *Environ. Res. Lett.* **2013**, *8*, 035034. [CrossRef]
37. Evans, M.E.; DeRose, R.J.; Klesse, S.; Girardin, M.P.; Heilman, K.A.; Alexander, M.R.; Arsenault, A.; Babst, F.; Bouchard, M.; Cahoon, S.M. Adding tree rings to North America's national forest inventories: An essential tool to guide drawdown of atmospheric CO_2. *Bioscience* **2022**, *72*, 233–246. [CrossRef]
38. Brehaut, L.; Danby, R.K. Inconsistent relationships between annual tree ring-widths and satellite-measured NDVI in a mountainous subarctic environment. *Ecol. Indic.* **2018**, *91*, 698–711. [CrossRef]
39. D'Andrea, G.; Šimůnek, V.; Castellaneta, M.; Vacek, Z.; Vacek, S.; Pericolo, O.; Zito, R.G.; Ripullone, F. Mismatch between annual tree-ring width growth and NDVI index in Norway spruce stands of Central Europe. *Forests* **2022**, *13*, 1417. [CrossRef]
40. Wen, Y.; Jiang, Y.; Jiao, L.; Hou, C.; Xu, H. Inconsistent relationships between tree ring width and normalized difference vegetation index in montane evergreen coniferous forests in arid regions. *Trees* **2022**, *36*, 379–391. [CrossRef]
41. Chen, Y.; Ma, L.; Liu, T.; Huang, X.; Sun, G. The Synergistic Effect between Precipitation and Temperature for the NDVI in Northern China from 2000 to 2018. *Appl. Sci.* **2023**, *13*, 8425. [CrossRef]

42. Garai, S.; Khatun, M.; Singh, R.; Sharma, J.; Pradhan, M.; Ranjan, A.; Rahaman, S.M.; Khan, M.L.; Tiwari, S. Assessing correlation between Rainfall, normalized difference Vegetation Index (NDVI) and land surface temperature (LST) in Eastern India. *Saf. Extrem. Environ.* **2022**, *4*, 119–127. [CrossRef]
43. Kaufmann, R.K.; D'Arrigo, R.D.; Laskowski, C.; Myneni, R.B.; Zhou, L.; Davi, N. The effect of growing season and summer greenness on northern forests. *Geophys. Res. Lett.* **2004**, *31*, L09205. [CrossRef]