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Research article

Diurnal Change of *NDVI* from UAV in trees of a temperate unavenged forest stand

Cambio diurno de *NDVI* a partir de VANT en árboles de un rodal incoetáneo de un bosque templado

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Abstract

NDVI elucidates the ecophysiological mechanisms faced by vegetation. With the flexibility and versatility of unmanned aerial vehicles (UAVs), temporal, spatial and spectral resolutions have been useful in supporting decision-making. Here, we modeled diurnal change in the *NDVI* derived from UAV imagery for individual trees in a natural forest stand. Eight flights were conducted during daylight hours over one day to assess the dynamics of the *NDVI* of the genera *Pinus*, *Juniperus*, and *Quercus*. The results showed unstable *NDVI* values over time, with a parabolic quadratic trend in the model. The *NDVI* reached its maximum around 13:00 h and the values differed significantly according to genus: the highest value was found in *Pinus* with significant differences presented with *Juniperus* and *Quercus*, which showed similar values between them (p=0.533). As a validation strategy, we test the model generated using 124 trees independent of those that were sampled, which strengthened our results in terms of reliability. The similarities of statistical parameters confer a high variability of application of the results in models of simulation of similar forests ecosystems. We recommend to study more spectral indices of vegetation, including calibration of the sensor, particularly in longer-term seasonal studies. We conclude that the *NDVI* measured using UAV should consider image acquisition time to calibrate the records and thus improve the interpretation of results.

Key words: Drones, index vegetation, individual trees, spectral indices, uneven aged, vigor.

Resumen

El *NDVI* dilucida los mecanismos ecofisiológicos a los que se enfrenta la vegetación. Gracias a la flexibilidad y versatilidad de los vehículos aéreos no tripulados (VANT), las resoluciones temporales, espaciales y espectrales han sido útiles para apoyar la toma de decisiones. En este trabajo se modelizó el cambio diurno en el *NDVI* derivado de imágenes de VANT para árboles individuales en un rodal forestal natural incoetáneo. Se realizaron ocho vuelos durante las horas diurnas a lo largo de un día para evaluar la dinámica del *NDVI* de los géneros *Pinus*, *Juniperus* y *Quercus*. Los resultados mostraron valores de *NDVI* inestables en el tiempo, con una tendencia cuadrática parabólica en el modelo. El *NDVI* alcanzó su máximo alrededor de las 13:00 h y los valores difirieron significativamente según el género: el valor más alto se encontró en *Pinus* con diferencias significativas presentadas con *Juniperus* y *Quercus*, que mostraron valores similares entre ellos (*p*=0.533). Como estrategia de validación, probamos el modelo generado utilizando 124 árboles independientes de los muestreados, lo que reforzó nuestros resultados en términos de confiabilidad. Las similitudes de los parámetros estadísticos confieren una alta variabilidad de aplicación de los resultados en modelos de simulación de ecosistemas forestales similares. Recomendamos estudiar más índices espectrales de vegetación, incluyendo la calibración del sensor, particularmente en estudios estacionales de más largo plazo. Concluimos que el *NDVI* medido mediante VANT debe considerar el tiempo de adquisición de la imagen para calibrar los registros y así mejorar la interpretación de los resultados.

Palabras clave: Drones, índice de vegetación, árboles individuales, índices espectrales, edad desigual, vigor.

Introduction

The state of the art in the international agenda shows that UAV-derived information offers promising findings that elucidate novel ecological mechanisms (Dronova and Taddeo, 2022). For example, spectral indices of vegetation contain valuable information that is not normally perceived by the human eye at first glance. One of the vegetation indices most commonly used by the international scientific community is the Normalized Difference Vegetation Index (*NDVI*) (Huang *et al.*, 2021), which addresses the greenness index of vegetation. Its calculation is based on the ratio of infrared to near-infrared wavelengths. Likewise, the near-infrared depends on the amount of luminosity, which transforms into the differential reflectance of the received energy, and is influenced by shadows and mixed soil-plant pixel information (Huang *et al.*, 2021; Buchhart and Schmidhalter, 2022). This implies that the amount of light received by the canopy overtime must be influenced by various factors, such as the time of image capture (Li *et al.*, 2020), heterogeneity of the foliage, and canopy disposition (Fawcett *et al.*, 2021), such that the *NDVI* could vary consequently. For this reason, its temporal variation in forests remains to be investigated to improve the interpretation of reflectance results (Beneduzzi *et al.*, 2017).

These values have normally been available from satellite-mounted sensors, covering large areas at a regional level (*e. g.* too coarse (>10 m)) (Huang *et al.*, 2021), but scarcely at the level of individual trees as ecological units (Gallardo-Salazar and Pompa-García, 2020). The most important studies on the use of UAV-derived *NDVI* recommend acquiring images at midday at least in the agricultural sector (Maresma *et al.*, 2020; Hama *et al.*, 2021), but quantitative data regarding their dynamics and comparative parameters in tree vegetation are limited. Knowledge of such metrics would therefore support the findings of the greenness indices and improve our interpretation of the results of forest management strategies. This understanding is crucial given the adverse climate variability currently faced by terrestrial ecosystems (Prăvălie *et al.*, 2022).

The occurrence of mixed species in natural forest stands represents ideal laboratories in which to test the variability of *NDVI* at tree level. The diversity of species under management in these plots is ideal for conducting such studies. In addition, drones present great versatility for configuring missions according to users' interests. For example, when access to sites of interest or the weather conditions limit image acquisition at the desired time, the user can execute the missions when conditions permit, simply adjusting the model parameters to the respective time.

In northern Mexico, there are an uneven-aged forest experimental area with the presence of *Pinus engelmannii* Carrière, *Quercus grisea* Liebm., *Arbutus bicolor* S. González, M. González & P. D. Sørensen, and *Juniperus deppeana* Steud. species under management and of great ecological importance, which makes it ideal for conducting experiments to further our knowledge regarding the spatial and temporal dynamics of *NDVI* (Vivar-Vivar *et al.*, 2022). This area also provides goods and services for the surrounding communities, most of which are indigenous, as well as a refuge for a range of faunal species.

The aim of this research is therefore to model the diurnal variation of reflectance values in a mixed forest stand in northern Mexico. We hypothesize an unstable reflectance value over time, with potential implication in image acquisition time to calibrate the records and thus improve the interpretation of *NDVI* values.

Materials and Methods

A 1 ha plot was used in the *Sierra Madre Occidental* Mountain range (27°80’57’’ N, 107°60’41’’ W; 2,400 masl), where species of the genus *Pinus*, *Quercus*, *Juniperus*, and *Arbutus* coexist (Table 1). The dominant species is *P. engelmannii*, followed by *Q. grisea* and *J. deppeana*, with a low presence of *A. bicolor*. Within the shrub stratum, individuals of *Ceanothus buxifolius* Willd. *ex* Schult. f. is prominent, while a great diversity of herbaceous plants is characterized by *Bouvardia ternifolia* (Cav.) Schltdl., *Houstonia rubra* Cav., *Eryngium heterophyllum* Engelm., *Dysphania graveolens* Mosyakin & Clemants, *Bouteloua gracilis* (Kunth) Lag. *ex* Griffiths, *Cyperus esculentus* L., among others (González-Elizondo *et al.*, 2012). This area presents a gentle slope and sparse stoniness. The study site soils are Cambisol in type with thin layers of organic matter and the area is subjected to commercial forest management for timber (González-Elizondo *et al.*, 2012). This region has a temperate climate, with an average annual temperature of 13.7 °C, the minimum temperature is -15 °C and there is highly variable rainfall ranging from 470 to 683 mm per year, with an average annual rainfall of 540.4 mm and an average of 75 days of rain per year (Gallardo-Salazar and Pompa-García, 2020).

Table 1. Descriptive statistics of the sampled trees in the study area.

	BD						***DBH***						***CH***						***TH***					
Statistic	***Pinus***		***Juniperus***		***Quercus***		***Pinus***		***Juniperus***		***Quercus***		***Pinus***		***Juniperus***		***Quercus***		***Pinus***		***Juniperus***		***Quercus***	
	+	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****	**+**	*****
Mean	34.9	15.1	18.4	10.4	45.2	16.6	28.6	11.2	13.3	7.2	35.9	11.5	6.6	2.9	2.1	1.8	3.1	1.9	13.9	6.7	5.2	3.6	12.2	6.5
Standard deviation	9.3	3.9	4.4	3.1	10.7	5.8	8.1	3.2	3.7	2.4	9.7	5.0	3.1	0.8	0.3	0.3	1.6	0.7	2.9	1.5	1.1	0.8	1.9	2.3
Range	45.6	17.3	18.8	10.7	41.8	18.6	40.4	13.5	14	8	41.6	18.8	10.1	5.1	1.4	1.2	8.5	3.1	13.8	74.8	4.9	3.4	8.6	8
Min	20.8	9.7	13.6	5.3	26.8	6.3	16	6.4	11	3.5	20.7	3.5	2.5	1.6	1.5	1.2	0.7	0.9	7.6	4.3	2.9	2.3	8.2	2.9
Max	66.4	27	32.4	16	68.6	24.9	56.4	19.9	25	11.5	62.3	22.3	12.5	6.7	2.8	2.4	9.2	4.1	21.4	12.1	7.8	5.7	16.8	10.9
Count	52	71	26	35	46	18	52	71	26	35	46	18	52	71	26	35	46	18	52	71	26	35	46	18

BD = Basal diameter (cm); *DBH* = Diameter at breast height (cm); *CH* = Commercial height (m); *TH* = Total height (m); + = Data used for generation model; * = Data used for validation model.

Data collection

Under clear sky conditions from 7:00 am to 7:00 pm on May 17th of 2022 (late spring), eight flights were conducted over this area in a north-south direction, covering the entire presence of the sun's luminosity. For this purpose, the respective missions were programmed into the model Phantom 4 Multispectral DJI® quadcopter. The P4M camera has one RGB sensor and five multispectral sensors (bands: blue=450±16 nm, green=560±16 nm, red=650±16 nm, red edge=730±16 nm, near infrared=840±26 nm), all with a 2 MP shooter. The flight recorded photographs in JPG format (24 bits, for images taken with the RGB sensor) and TIF format (16 bits, for those acquired with the multispectral sensors) at an altitude of 60 m, with the camera at an angle of 90° and an overlap of 80 %, and 75 % between the images and lines (Figure 1).

Figure 1. Flight parameters for the Phantom 4 Multispectral.

For the purposes of the study, we assume here that the sensor reflectance correction provided by the manufacturer of DJI® is sufficient. However, it is known that no sensor is perfect, so specific radiometric corrections will be required in future studies (Mamaghani and Salvaggio, 2019), above all in those conducted over monthly or seasonal periods.

Image processing and statistical analysis

The images were processed by digital photogrammetry techniques using the open-source software OpenDroneMap (ODM, version 2.8.4; Cleveland Metroparks, Ohio, USA) (Vivar-Vivar *et al.*, 2022) through the Structure from motion and Multi-View Stereo algorithm to produce a 3D point cloud. Geotagging of the images was not necessary because the drone has an integrated georeferencing system with vertical and horizontal accuracies of ±0.1 and ±0.3 m, respectively, according to the DJI® dealer.

We then generated the spectral orthomosaics (2.9 cm/pixel). Within the arbitrarily plot selected a total of 124 trees were recorder (Table 1), for which the *NDVI* was calculated at the individual tree level using the Q-Gis raster calculator (Gallardo-Salazar and Pompa-García, 2020) using the following expression:

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

Where:

NDVI = Normalized Difference Vegetation Index

NIR = Near infrared band

RED = Red band

Variation of the *NDVI* as a function of time of day was fitted to a quadratic-type model using the following equation:

$$NDVI = Y_0 + Y_1 t + Y_2 t \quad (2)$$

Where:

NDVI = Normalized Difference Vegetation Index

t = Time of the *NDVI* reading

Y_0, Y_1 and Y_2 = Model fit parameters. Note that Y_2 is the parameter of the quadratic term

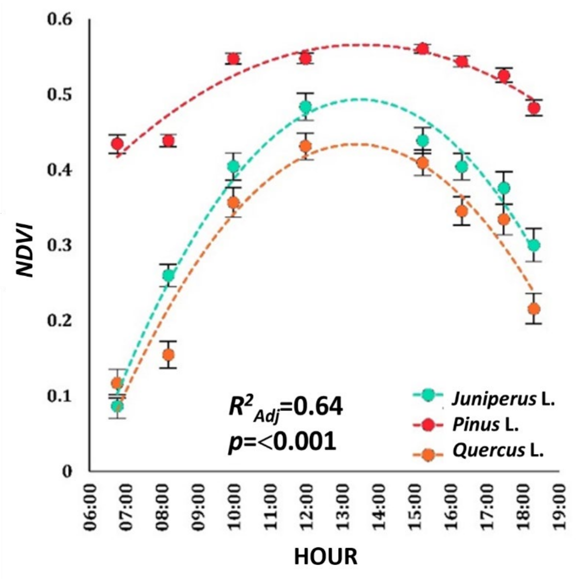
Model fitting was conducted with the *lm* function of the 'stats' package in R software version 4.1.1 (R Core Team, 2021) and regression assumptions were tested (Gujarati and Porter, 2009). Differences in the model parameters among tree genera were analyzed statistically by applying predefined orthogonal contrasts. Validation of the model fit was analyzed by graphical exploration between two sources of data.

As a validation strategy to evaluate the prediction performance of our model, we evaluate the prediction performance using new independent data set of 124 trees, (Table 1), then we plotted results.

Results

During each flight, a total of 141 RGB and 705 multispectral images were acquired with the UAV, which were used to create the multispectral orthomosaic.

The diurnal variation of the *NDVI* presented a quadratic behavior (Figure 2). The values start to increase from the first mission and reach a maximum at around 13:00 h, before decreasing over the rest of the day. Although all three genera showed quadratic behavior, the model parameters varied significantly depending on the genus (Table 2). In general, *Pinus* showed higher *NDVI* values throughout the day and with lower variation (from 0.41 to 0.54). On the other hand, *Juniperus* and *Quercus* showed similar behavior between them and higher diurnal variation of the *NDVI*, with values starting at 0.1 on average in the morning and reaching a maximum of around 0.45 (Figure 2).



The points represent the mean values observed at different times of the day. The dashed lines represent the values predicted by the fitted model, including genus as a source of variation. Bars denotes descriptive error bars.

Figure 2. Diurnal variation of the *NDVI* in three tree genera in the studied area.

Table 2. Parameter estimates of the of the quadratic-type model fitted to the ratio of *NDVI* values as a function of time of day and tree genus.

Parameter		Estimate	Std. Error	*t* value	*Pr*(>|*t*|)
γ_0	*Pinus* L.	-0.02819	0.06231	-0.452	0.651
	Juniperus L.	-1.05212	0.10783	-9.757	<2e-16
	Quercus L.	-0.98353	0.09088	-10.822	<2e-16
γ_1	*Pinus* L.	2.10006	0.2573	8.162	1.01e-15
	Juniperus L.	3.49121	0.44527	7.841	1.17e-14
	Quercus L.	3.07798	0.3753	8.201	7.40e-16
γ_2	*Pinus* L.	-1.85688	0.24246	-7.659	4.50e-14
	Juniperus L.	-3.11087	0.41964	-7.413	2.66e-13
	Quercus L.	-2.78068	0.35368	-7.862	9.92e-15

Table 2 gives the estimated parameters and the corresponding goodness-of-fit statistics of the models developed, indicating that the estimated parameters are unbiased. For example, the model explained more than 60 % of the variance. The best fits were obtained for the genus *Pinus*, while the worst fits were obtained for *Quercus*, a finding that we attribute to sample size differentiation.

Overall, the models are similar around 13:00 h, suggesting that this time presents a maximum value for both data. This result highlights the importance of taking into account the time of measuring *NDVI*, and not simply flight the mission at any time, as is commonly practiced. Our study shows that the generated model is an advantageous tool for forest management studies that can be used to predict *NDVI* values according to time data acquisition.

Discussion

This pioneering study in Mexican mixed forests has shown that the diurnal timing of *NDVI* acquisition is unstable over the course of the day, making this a decisive factor in the interpretation of the greenness index for subsequent decision-making. Most of the scientifically documented studies undertaken during the fast-paced advent of drones have addressed applications in crops (Heinemann *et al.*, 2022), while little attention has been paid to forests despite the promising perspective that drones offer for studying these ecosystems (Gallardo-Salazar and Pompa-García, 2020).

The findings of this study represent an opportunity to refine our knowledge of spectral reflectance variation at the individual tree level according to diurnal variation. The results show significant differences according to time of measurement, as well as among the genera studied. However, an in-depth analysis of the causes of the marginal differences between *NDVI* values is beyond the scope of the study (Vivar-Vivar *et al.*, 2022).

The diurnal pattern of *NDVI* values follows a parabolic quadratic trend, reaching a maximum at 13:00 h for all of the vegetation studied (Figure 2). These values have been attributed to the better reception of light energy from the sun in the foliage. A consequent decrease in reflectance is evident at the beginning and end of the day, compared to when the sun is at its zenith, which is directly related to changes in the angle of the sun and the resulting shadows of the vegetation (Maresma *et al.*, 2020; Hama *et al.*, 2021). Interestingly, Beneduzzi *et al.* (2017) report that *NDVI* is affected by radiation, presenting opposite graph trends to our findings. We believe that sensor type, species phenology, and cloudiness are among the causes of these differences. Another possible cause is the *NDVI*-climate relationship, as has been seen in Ghebrezgabher *et al.* (2020).

The *NDVI* trend with the generated model produced results consistent with those derived from the validation since the parabolic trend is similar for all genera, with a maximum around 13:00 h. This indicates that our model has good predictive capabilities, although the causes of the marginal differences (*e. g.* canopy structure, individual physiological characteristics, etc.) remain to be determined. For example, some species have deciduous leaves throughout the seasons of the year. Also, our sensor has limitations as poor penetrating capacity of sunlight in overlapped canopies.

The results are important given that forest access conditions and sudden changes in the climate can often limit flight missions at specific times. In this way, our *NDVI* model makes it possible to make adjustments even after completion of the fieldwork, according to the time of sampling (Maresma *et al.*, 2020). Likewise, in the forest, the complexity and magnitude of phenological changes also raise the need for analysis in future studies of greater temporality and seasonality (*e. g.* months) (Li *et al.*, 2021).

However, thresholds of temporal heterogeneity of reflectance have been a reliable starting point and have made a contribution to the knowledge, which cannot always be achieved with satellite imagery. It has been demonstrated that UAVs calculate *NDVI* more accurately than the 10-m Sentinel-2, including as part of studies to monitor canopy phenology (Khaliq *et al.*, 2019).

NDVI values should not be confused with photosynthetic activity *per se* (not studied here) since this variable requires thorough investigation, including actual field measurements beyond the leaf level. Moreover, the plant water status and leaf orientation during the day can contribute to diurnal differences in reflectance (Rischbeck *et al.*, 2014). According to Buchhart and Schmidhalter (2022), measurements should be taken hourly, although the authors did make this recommendation for crops rather than for trees.

Although we documented that the diurnal greenness indices of canopies follow a heterogeneity pattern, the magnitude of photosynthetic variability in studied species remains a challenge that merits further analysis, including beyond the leaf level (Pompa-García *et al.*, 2022). It is well known that the spectral reflectance captured by a UAV sensor can be associated with canopy geometry and foliage structure. Thus, a potential limitation could be the spurious spectral variation that can be confused with the potential photosynthesis (Vivar-Vivar *et al.*, 2022).

The maximum *NDVI* values found at 13:00 h should therefore not necessarily be interpreted as the time of maximum "photosynthetic activity", but rather these metrics correspond to the reflectance of the energy captured by the sensor at that time (Vivar-Vivar *et al.*, 2022), for which reason they must be treated with some caution, although the scientific community recommends this time of day unless adverse weather conditions prevent it.

This implies the need for further research to refine the estimates in these experimental studies. For example, flight duration must be considered to determine the spectral variation between the start and end of each mission, as well as radiance, temperature, and humidity data (Hama *et al.*, 2021), as well as considering the vegetation characteristics (Jacquemoud *et al.*, 2009) and the specific assessment of the foliage structure and arrangement (Li *et al.*, 2020). It is well known that the quality of spectral information depends on the flight configuration parameters a paths and altitude, among others that configure the flight missions (Vivar-Vivar *et al.*, 2022). Thus, flights should be configurated to obtain the best perspective of the variable of interest. However, it is necessary to balance the costs and benefits of management strategies that are developed in the field. Accurate *NDVI* information is essential to evaluate the efficiency of silvicultural practices in the field or to make adjustments to predictions since it is known that the *NDVI* can be a potential proxy of vigor and plant stress levels, among others (Huang *et al.*, 2021).

We found heterogeneity in reflectance responses to time of image capture, within the different genus, which puts into perspective the need to configure specific actions towards sustainability, because these forests are subject to forest management. The causes can still be refined with more flight missions and a better knowledge on the true estimations of photosynthetic capacities. The heterogeneity of *NDVI* in responses to time data acquisition is crucial to design strategies of conservation and management in megadiverse ecosystems.

The strategy of using independent data for validation strengthened our results. Our methodology provides the use of a model that is statistically sound and functional. Acquisition of data from representative trees, such as those sampled here, guarantees that the results are reliable due to their relevance of direct application by the forest manager. Given these trees are under management, with fully developed crowns, they represent a valuable input data for subsequent research.

Conclusions

The *NDVI* does not remain fixed throughout the day, which is presumably attributed to the angle of the sun. The maximum values were found at 13:00 h for all genera and decreased as the solar zenith angle subsequently decreased.

Moreover, environmental parameters and equipment configurations must be evaluated, and this experiment should be replicated at seasonal time horizons and at higher vegetation resolutions (*e. g.* at the species level).

The uneven-aged forests and their exceptional tree diversity constituted an ideal setting to identify *NDVI* tree interactions. This gained knowledge has great implications to facilitate sustainable management in multi-species mountain forests, which are the most widely distributed in Mexican territory.

Analysis of *NDVI* should be integrated as a tool for forest management, but with-out replacing the use of data *in situ* that still provide essential information regarding the forest structure. In addition, more spectral indices of vegetation should be studied, as well as calibration of the sensor performed, particularly in longer-term seasonal studies.

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Conflicts of Interest

The authors declare no conflict of interest.

Contribution by author

Marín Pompa-García: conceptualization, data gathering, investigation, resources and writing-original draft preparation; José Ángel Sigala-Rodríguez: methodology, software, validation and editing; Eduardo Daniel Vivar-Vivar: methodology, experimental design, and formal analysis; Felipa de Jesús Rodríguez-Flores: methodology, experimental design, and resources; Joel Rascón-Solano: review, editing, and supervision. All authors have read and agreed to the published version of the manuscript.

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