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RESEARCH ARTICLE

High resolution thermal and multispectral remote sensing for detecting devitalized trees in Monarch Butterfly Biosphere Reserve

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Abstract

Aim of study: To identify different levels of devitalization in individuals of *Abies religiosa* (Kunth) Schltdl. & Cham. (oyamel) in the core zone of the Monarch Butterfly Biosphere Reserve (MBBR), using multispectral and thermal information captured with drone.

Area of study: The study area, comprising 26 ha, is located within the federal property of the MBBR. This area also belongs to the core zone of the Protected Natural Area.

Material and methods: Overflights were conducted with drones equipped with multispectral and thermographic sensors in monitoring plots. Using high-resolution images captured by drone and photogrammetric processing, the normalized difference vegetation index (NDVI), surface temperature (ST), and temperature-vegetation dryness index (TVDI) were calculated. These values were combined with field data to determine three different levels of tree devitalization (i.e., healthy, devitalized, and dead trees).

Main results: The results demonstrated that this technology can be used to statistically distinguish the different levels of devitalization in oyamel individuals.

Research highlights: This is the first research in Mexico that use Thermal and Multiespectral high resolution information related with field data applied to *Abies religiosa* and provides a methodological precedent for identify forest decline symptoms.

Keywords: drone; forest decline; NDVI; surface temperature; TVDI.

Teledetección térmica y multiespectral de alta resolución para la detección de árboles desvitalizados en la Reserva de la Biosfera de la Mariposa Monarca

Resumen

Objetivo de estudio: Identificar diferentes niveles de desvitalización en individuos de *Abies religiosa* (Kunth) Schltdl. & Cham. (oyamel) en la zona núcleo de la Reserva de la Biosfera de la Mariposa Monarca (RBMM), utilizando información multiespectral y termal capturada con drones.

Área de estudio: El área de estudio comprendió 26 ha ubicadas dentro de la propiedad federal de la RBMM. Este área también pertenece a la zona núcleo del Área Natural Protegida.

Materiales y Métodos: Se realizaron sobrevuelos con drones equipados con sensores multiespectrales y térmicos en parcelas de muestreo. Utilizando imágenes de alta resolución capturada con drones y mediante procedimientos fotogramétricos, se calcularon el índice de vegetación de diferencia normalizada (NDVI), la temperatura superficial (ST) y el índice de sequía de la vegetación por temperatura (TDVI). Estos valores se combinaron con datos de campo para determinar tres niveles diferentes de desvitalización (sano, desvitalizado y muerto).

Principales resultados: Los resultados demuestran que esta tecnología puede ser usada para distinguir estadísticamente entre diferentes niveles de desvitalización en individuos de oyamel.

Aspectos destacados de la investigación: Esta es la primera investigación en México que utiliza información térmica y multispectral de alta resolución relacionada con datos de campo aplicados para *A. religiosa* y provee un precedente metodológico para identificar síntomas de desvitalización forestal.

Palabras clave: desvitalización forestal; drones; NDVI; temperatura superficial; TVDI.

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Introduction

Climate change has many consequences at the global level. Worldwide, in mountain ecosystems, one of the most severe effects has been an increased forest decline, which can be defined as the accelerated decay and mortality of trees (Allen et al., 2010; Allen et al., 2015; Hammond et al., 2022). Scientific studies suggest that changes in precipitation regimes and increased temperatures induce hydric stress, which impairs tree vitality, rendering them more susceptible to attack by pests and disease and, in some cases, tree mortality (Sturrock et al., 2011; Martínez-Vilalta et al., 2012). In recent years, massive tree death events have been reported in the United States (Hicke et al., 2016; Tai et al., 2023) and in various regions of Europe (Senf et al., 2018; Senf et al., 2020).

Due to climate change, natural populations are exposed to unfavorable climatic conditions, leading them to shift towards higher altitudes and move northward. In addition, some forest populations face conditions that exceed their adaptive resistance limits, resulting in their devitalization (Sáenz-Romero, 2015). In this context, tree devitalization is defined as the progressive deterioration of their physiological state, characterized by symptoms such as loss of vigor, reduced foliage density, and increased susceptibility to stress-related factors (Randolph & Thompson, 2010).

In the case of Mexico, Sáenz-Romero et al. (2020) provided evidence of tree devitalization symptoms in the temperate forests in the Transmexican Volcanic Belt and in northwestern Mexico. For example, the aforementioned authors reported massive infestations of dwarf mistletoe (*Arceuthobium* spp.) in *Pinus hartwegii* Lindl. trees in Nevado de Toluca and Monte Tlaloc; indications of inbreeding and defoliation in endangered *Picea chihuahuana* Martínez, *Picea martinezii* T.F. Patterson, *Picea mexicana* Martínez, and extreme southern populations of *Pseudotsuga menziesii* (Mirb.) Franco, and a high percentage of devitalized individuals and insufficient recruitment of *Abies religiosa* (Kunth) Schltdl. & Cham (oyamel) seedlings in the monarch butterfly Biosphere Reserve (MBBR). These forests are particularly important because they host the monarch butterfly (*Danaus plexippus* Linnaeus) populations that hibernate there every year following their migration from Canada and the United States (Rendón-Salinas et al., 2023). The canopies of these trees provide protection to the monarch butterfly colonies, preventing their wings from becoming wet in the presence of rain and protecting them from extreme temperatures (Anderson & Bower, 1996; Brower et al., 2011).

Consequently, the presence of optimal conditions for the *A. religiosa* populations is crucial for the survival of the monarch butterfly (Sáenz-Romero et al., 2011).

Monitoring of *A. religiosa* forests is essential to identify symptoms of forest decline in a timely manner (Choi & Park, 2019). However, traditional ground-based forest monitoring is often time-consuming, costly, and limited in areas that are difficult to access (Preti et al., 2021). Although airborne photography (Leautaud-Valenzuela & López-García, 2017) and low- and medium-resolution satellite imagery (Flores-Martínez et al., 2019) have been employed to investigate the causes of forest decline in the MBBR, these efforts are constrained to regional scales. Uncrewed aerial vehicles (UAVs, commonly referred to as drones) represent a promising tool for monitoring and effective decision-making to protect *A. religiosa* forests and the ecosystem services they provide (Duarte et al., 2022; Ecke et al., 2022). In recent decades, the use of sensors adapted to UAVs has become increasingly prevalent because: 1) they provide data with centimetric resolution; 2) the temporal resolution is adaptable to the needs of the user; 3) they have greater efficiency in terms of the time required to obtain data; and 4) there is a wide diversity of sensors available (i.e., RGB (visible light spectrum), multispectral, thermal, and hyperspectral) (Ecke et al., 2022). A number of studies have demonstrated the effectiveness of using multispectral information acquired with UAVs to identify stress levels in vegetation, mainly with the application of spectral indices (Dash et al., 2017; Näsi et al., 2018; Klouček et al., 2019; Campbell et al., 2020; Gallardo-Salazar et al., 2023a). High spatial and spectral resolution data acquired with UAVs is a valuable alternative that can provide higher quality information to improve our understanding of the ecological mechanisms to which trees are subjected (Gallardo-Salazar et al., 2022).

There are precedents of UAV use with applications similar to those intended in this study. For example, Campbell et al. (2020) conducted a classification of individuals in high-resolution images based on the following characteristics: alive (< 25% of the tree canopy dead), dead (> 75% of the tree canopy dead), or partially dead (between 25 and 75% of the tree canopy dead). Dash et al. (2017) reported that the normalized difference vegetation index (NDVI) was the most important indicator for demonstrating physiological stress in *Pinus radiata* individuals, demonstrating the close relationship between signs of stress in the field and NDVI data. Näsi et al. (2018) compared the efficacy of an RGB sensor to that of a hyperspectral sensor in identifying different levels of bark beetle (*Ips typographus*) infestation. The authors found that hyperspectral information captured with UAVs can enhance forest monitoring activities, reducing both the cost and workload of forestry teams.

Similarly, thermal information (e.g., surface temperature, ST) acquired with UAVs has been employed as an effective indicator of tree transpiration rates, demonstrating this parameter to be responsive to tree stress levels (Maes et al., 2018). Given their potential utility in identifying stress conditions in vegetation using thermal and multispectral information, indices have been developed that combine both sources of information. One illustrative example is the temperature-vegetation dryness index (TVDI). This index enables the identification of changes in vegetation ST, even before any visible symptoms of vigor loss (Sandholt et al., 2002).

The objective of this study was to identify different levels of devitalization in individuals of *A. religiosa* in the core zone of the MBBR, using multispectral and thermal information captured with UAVs. For this, the following questions were addressed: Does the use of multispectral and thermal information captured with UAVs (i.e. NDVI, ST, and TVDI) allow the differentiation of distinct levels of vitality of individuals of *A. religiosa*? Is it possible to associate the information on tree devitalization recorded in the field with the information generated by UAVs? Which of the three indices tested is most effective in terms of the identification of different levels of tree vitality?

Material and methods

Study area

The study area, comprising 26 ha, is located within the federal property of the MBBR. This area also belongs to the core zone of the Protected Natural Area (CONANP, 2001). It is located approximately 1.5 km from the entrance to the Sierra Chincua Monarch Butterfly Sanctuary and 5 km from the municipality of Angangueo, in the Mexican state of Michoacán (Figure 1), within the physiographic province of the Transmexican Volcanic Belt, in the Mil Cumbres subprovince. The terrain consists of a system of landforms composed of complex volcanic mountain, with altitude ranging from 2,500 m to 3,600 m, slopes between 10% and 50%, and predominantly north and northwest-facing exposure (Hernández-Moreno et al., 2020).

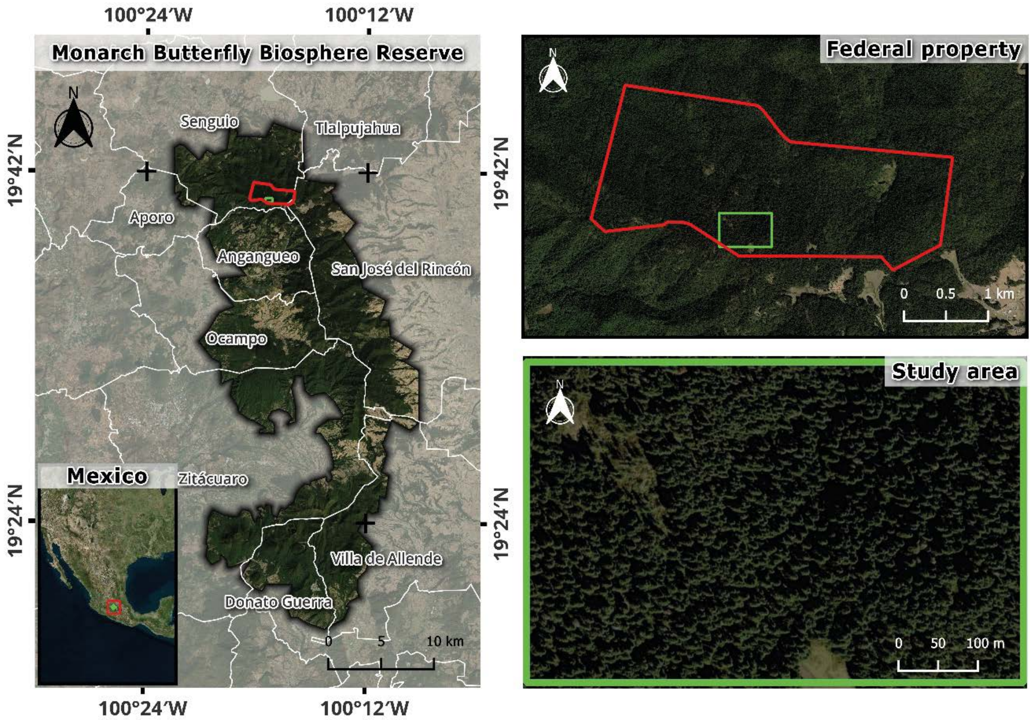

Figure 1. Location of the study area within the federal property of the core zone of the Monarch Butterfly Biosphere Reserve, Mexico.

The site is known as "Llano de las Catarinas" and exhibits a mean annual temperature of 10.2 °C and a mean annual precipitation of 1045 mm (Rehfeldt, 2006; Sáenz-Romero, 2010). The vegetation type is coniferous forest, with a dominance of oyamel (*A. religiosa*) trees reaching a top height of 20 to 40 m, with a low presence of *Pinus pseudostrobus* and *Quercus* spp (Cornejo-Tenorio & Ibarra-Manriquez, 2017).

Tree vigor field data

Field data were collected in 15 circular sites of 0.1 ha randomly distributed across the 26 ha of the study area (Figures 2a and 2b). Site selection excluded roads and non-forested areas (particularly grasslands). Additionally, a minimum distance of at least 50 meters between the center of each site was established to prevent overlap. Upon reaching the center of the plot, a visual assessment was conducted to ascertain the vigor of all the dominant individuals (i.e., those discernible in the images captured by the UAVs) within the monitoring plot. The center of each site was identified using a Garmin eTrex® 10 GPS device. Once at the center, the trees within the site were recorded on field data sheets and high-resolution UAV images of each site. To subsequently identify each tree in the orthomosaic based on its azimuth relative to north and its distance from the site center. The tree vigor classification proposed by Campbell et al. (2020) was applied. This classification defines three vitality categories in coniferous forests: live trees (with less than 25% of the visible crown dead), partially dead trees (with 25% to 75% of the visible crown dead), and dead trees (with more than 75% of the visible crown dead). The percentage thresholds for crown mortality remained unchanged and they were determined through ground-level visualization. In order to focus on the devitalization process, the category names were slightly modified to classify trees as healthy, devitalized, and dead (Figures 2c, 2d, and 2e). The vigor and location of the trees selected in each circular site were recorded on field forms. Moreover, the Diameter at Breast Height (DBH) (cm) and height (m) of each tree were recorded. Field data were recorded for 35 trees.

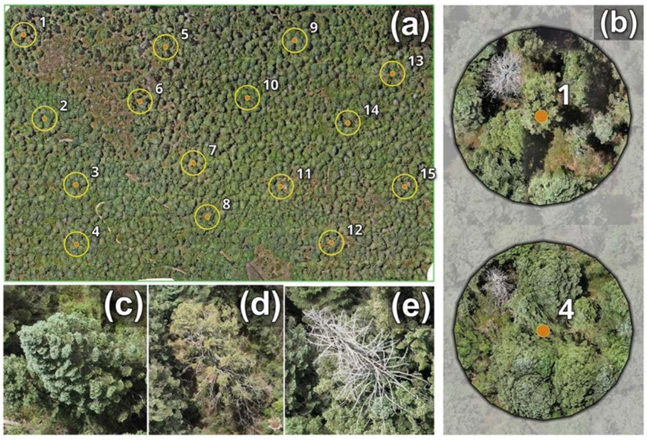

Figure 2. Sampling sites and *Abies religiosa* trees within the Monarch Butterfly Biosphere Reserve, Mexico; (a) distribution of the 0.1 ha sampling sites; (b) example of the aerial view of sampling sites 1 and 4; (c), (d), and (e) healthy, devitalized and dead individual trees, respectively.

Acquisition of images by UAV

To identify potential distinctions between the three categories of tree vitality within the study area, one multispectral and one thermal UAV flights were conducted on June 24th, 2023. A DJI Mavic 3 Multispectral quadcopter (Dajiang Innovation Technology Co., Shenzhen, China) was employed to capture the multispectral data. The UAV was equipped with a digital RGB camera (20 megapixels) and a set of four multispectral cameras of 5 megapixels in resolution, covering the green (560 nm ± 16 nm), red (650 nm ± 16 nm), red edge (730 nm ± 16 nm), and near-infrared (860 nm ± 26 nm) wavelength bands. For the thermal data, a DJI Mavic 2 Enterprise Advanced (Dajiang Innovation Technology Co., Shenzhen, China) was employed. This UAV was equipped with a thermal sensor with a resolution of 640 x 512 pixels at 30 Hz and a spectral range of 8 to 14 µm. The flight parameters for the Mavic 3 Multispectral were an altitude of 70 meters above the ground, with a frontal overlap of 80% and lateral overlap of 70%. For the Mavic 2 Enterprise Advanced, the flight parameters were an altitude of 70 meters and frontal and lateral overlaps of 85%. These flight parameters were derived from previous flight experiences (Gallardo-Salazar et al., 2023a; Gallardo-Salazar et al., 2023b). With these flight parameters, an orthomosaic was generated with a spatial resolution of 2 cm for RGB images, 3 cm for NDVI images, and 18 cm for thermal images, ensuring high precision in the identification of tree vitality categories. The DJI Pilot 2 flight application was employed to execute the flights in an automated and safe manner (Figure 3).

Figure 3. Screenshot of the DJI Pilot 2 application for real-time monitoring of the UAV flight over *Abies religiosa* trees in the Monarch Butterfly Biosphere Reserve, Mexico.

Photogrammetric processing and calculation of spectral indices

The multispectral images captured by UAVs were processed with the DJI Terra software version 4.0.1 (Dajiang Innovation Technology Co., Shenzhen, China, https://enterprise.dji.com/dji-terra, consulted April 1st, 2024). The processing workflow included high-accuracy image alignment and georeferencing with RTK corrections applied during the flight. The generated orthomosaic had a spatial resolution of 3 cm per pixel for NDVI and 2 cm per pixel for RGB images. This software also facilitated the automatic calculation of different vegetation indices, including the NDVI.

Thermal image processing was conducted in two stages. First, DJI Thermal SDK (version 1.5) (Dajiang Innovation Technology Co., Shenzhen, China, https://www.dji.com/downloads/softwares/dji-thermal-sdk, consulted April 1st, 2024) was used to extract precise surface temperature (ST) values from the raw thermal images captured by the Mavic 2 Enterprise Advanced. Temperature range correction was automatically adjusted based on ambient conditions at the time of data acquisition. In the second stage, the thermal images were processed with DJI Terra to generate a thermal orthomosaic with a final spatial resolution of 18 cm per pixel. Georeferencing was refined using RTK-based spatial correction, and the final raster outputs were generated in GeoTIFF format to ensure compatibility with GIS software for further analysis pertaining to the crowns of each tree analyzed.

Calculation of NDVI

NDVI was calculated to ascertain vegetation condition, physiological stress, and photosynthetic activity (Huang et al., 2021) (Eq. 1), using the near infrared (NIR) and red (RED) wavelength bands.

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

This operation was performed automatically in the DJI Terra software.

Calculation of TVDI

The Temperature-Vegetation Dryness Index (TVDI) relates the ST and NDVI information, which initially provides information on the moisture content of the surface. The equation proposed by Sandholt et al. (2002) is used to calculate the TVDI (Eq. 2) by relating the ST and NDVI information, where ST is the surface temperature in °C observed in a given pixel, TS_{min} is the minimum temperature value in the triangle defining the wet edge, NDVI is the observed value of the Normalized Difference Vegetation Index, while a and b are parameters defining the dry edge modeled as a linear fit to the data (Ts_{max} = a + bNDVI), where Ts_{max} is the maximum temperature observation for a given NDVI.

$$TDVI = \frac{TS - TS_{min}}{(\mathrm{a+bNDVI}) - Ts_{min}} \quad \text{(Eq. 2)}$$

The TVDI values lie between 0 and 1. Values close to 1 indicate the “dry edge” (with limited water availability) and values close to 0 indicate the “wet edge” (with seemingly unlimited water availability) (Sandholt et al., 2002). In other words, the TVDI values close to 0 represent vegetation under lower hydric stress, while values close to 1 show areas with higher temperature and lower NDVI values, i.e., areas with greater hydric stress.

Relationship between field data and spectral indices

Regarding the high-resolution RGB orthomosaic, the selected trees were identified and located on the screen (supported by the azimuth and distance recorded in the field) at each of the 15 sampling sites. Once the sampled trees were identified, manual digitization was performed in the form of irregular polygons to delineate the perimeter of the tree crowns using the QGIS software version 3.28.15 (Rosas-Chavoya et al., 2022) (Figure 4).

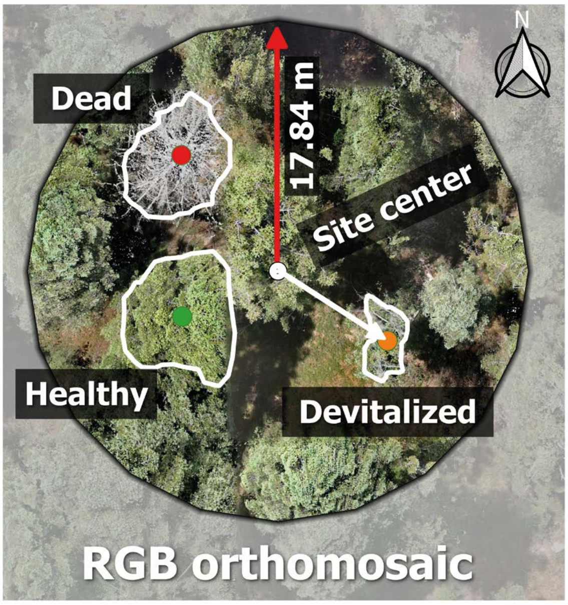

Figure 4. Example of visual classification (on screen) of vitality categories s (healthy, devitalized, and dead tree) in *Abies religiosa* trees within a complete circular plot (1000 m², radius ≈ 17.84 m), based on the visible-light orthomosaic (RGB) in the Monarch Butterfly Biosphere Reserve, México.

The trees sampled in the field were located in the RGB orthomosaic and their crowns were delineated, the delineation of the crowns for each tree sampled in the field permitted the direct extraction of the ST, NDVI, and TVDI information which allowed obtaining data at the individual tree level. For this procedure, the "Zone Statistics" tool of the QGIS software version 3.28.15 (Rosas-Chavoya et al., 2022) was used. This calculates the descriptive statistics (minimum, maximum, and average) of the set of pixels of a raster layer delineated by a vectorial layer of superimposed polygon type, in this case, the crown of the trees (Zhang et al., 2015). The aforementioned methodology, in conjunction with the field-recorded tree vitality data, enabled the association of the ST, NDVI, and TVDI values for each *A. religiosa* individual analyzed.

Statistical analysis

To summarize the information of each of the evaluated parameters (i.e., ST, NDVI, and TVDI) in each of the tree vitality categories, with the help of the statistical software R Studio version 4.3.1 (R Project for Statistical Computing, Vienna, Austria), tables were prepared with descriptive statics data values, as well as information on the first quartile, median, and third quartile. Box and whisker plots were also prepared. In these, the box represents the dispersion of the central 50% of the data (those located between 25% and 75% of the total), where the median is included. The whiskers or wires mark the limits of the data range. Outliers are represented by dots.

Using the statistical software R Studio version 4.3.1 (R Project for Statistical Computing, Vienna, Austria), Shapiro-Wilk test was applied to assess the normal distribution of data, consideranding a p-value > 0.05 as indicative of a normal distribution. Levene´s test was conducted to evaluate the homogeneity of variances. Since the data of NDVI and ST did not meet normality assumptions, the non-parametric Kruskal-Wllis test was applied. This test is used to compare unpaired groups that do not follow a normal distribution (Cleophas & Zwinderman, 2016), to detect significant differences among tree crown vitality categories (i.e., healthy, devitalized, and dead trees) for the variables ST, NDVI, and TVDI, using the mean per crown obtained from zonal statistics. Finally, the Pairwise Wilcoxon Rank Sum Test was applied as a post hoc analysis to compare mean differences between tree vitality levels. The workflow of the proposed methodology is shown in Figure 5.

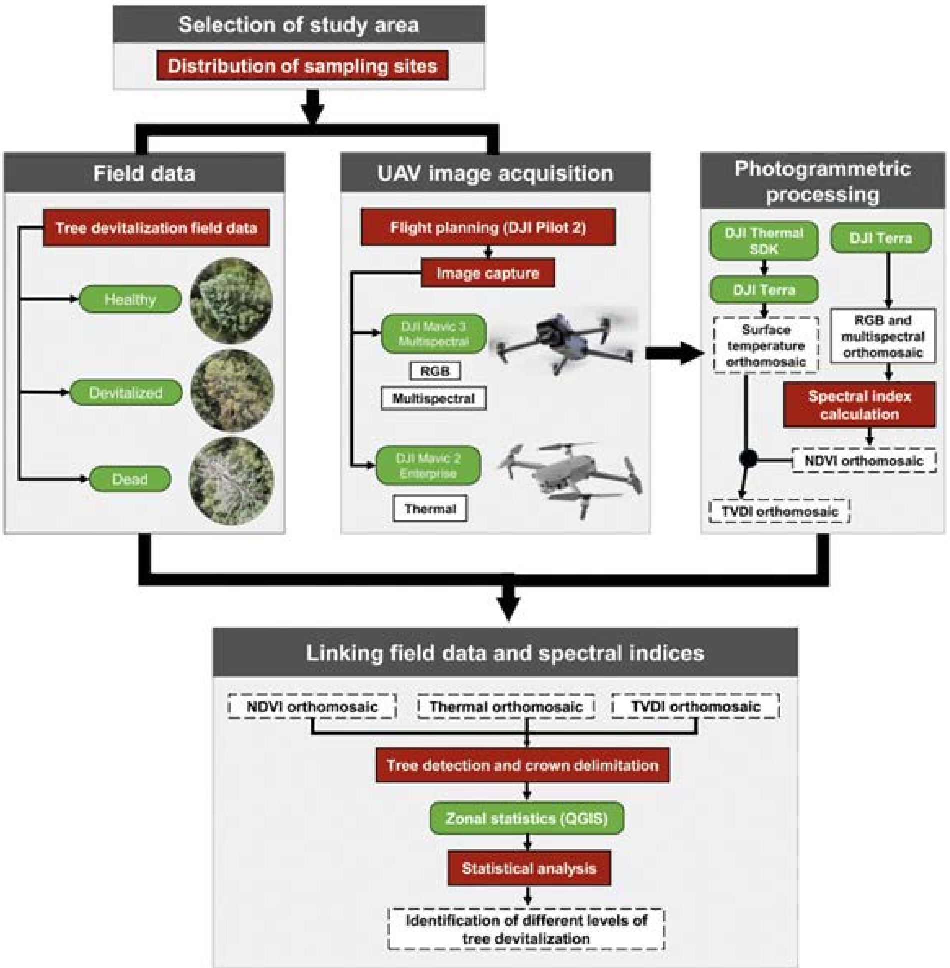

Figure 5. Diagram of the proposed methodological workflow. NDVI: normalized difference vegetation index, TVDI: temperature-vegetation dryness index.

Results

Three orthomosaics were derived from the flights conducted over the study area: RBG (Figure 6a), NDVI (Figure 6b), and ST (Figure 6c), with spatial resolutions of 2, 3, and 18 cm, respectively. In general, the NDVI values for the entire study area ranged from -0.12 to 0.92, while the ST values ranged from 4 to 63 °C.

The overall average NDVI of all trees sampled in the field was 0.62. The average NDVI values of each designated vitality category in the field (i.e. healthy, devitalized, and dead) showed a positive relationship with the decrease in vigor. Dead trees had the lowest average NDVI value (0.43), followed by devitalized trees (0.67), and healthy trees (0.74).

Regarding the ranges of values obtained by each sensor, the trees identified in the field as belonging to the Healthy category showed an NDVI of 0.67 to 0.80, ST of 17.90 to 22.90 °C, and TVDI of between 0 and 0.31. The Devitalized category showed an NDVI in the range of 0.61 to 0.73, ST of 21 to 27.10 °C, and a TVDI of 0.19 to 0.48. The Dead category obtained an NDVI of 0.38 to 0.46, ST of 26.30 to 34.80 °C, and TVDI of 0.37 to 0.73 (Table 1).

The overall ST of the canopy resulted in an average of 24.11 °C. In contrast to the trend of NDVI, ST increased as the trees were identified in conditions of lower vigor. Thus, healthy trees presented the lowest ST values, with an average of 20.13 °C, followed by devitalized trees with an average ST of 23.82 °C and, finally, dead trees with an average ST of 29.77 °C. That is, there is a difference of 9.64 °C between the trees identified in the field as healthy and those identified as dead.

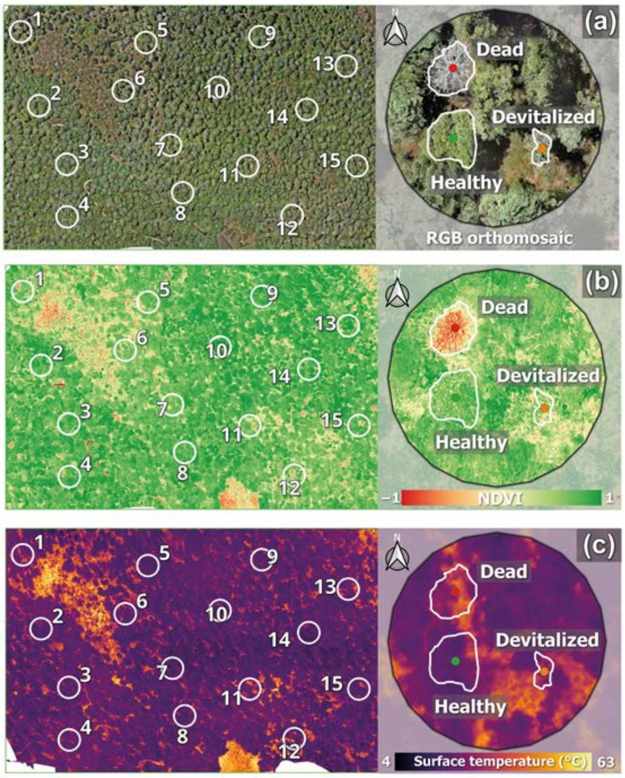

Figure 6. Examples of orthomosaics generated from different sensor type in the Monarch Butterfly Biosphere Reserve, Mexico, showing the total study area and approach to the sampling plot 1 (right column of panels): (a) RGB orthomosaic, (b) NDVI orthomosaic, and (c) thermal orthomosaic (Surface temperature). NDVI: normalized difference vegetation index, RGB: visible-light spectrum.

Table 1. Descriptive statistics for the NDVI, ST, and TVDI for *Abies religiosa* trees with different vitality categories (healthy, devitalized, dead) in the Monarch Butterfly Biosphere Reserve, Mexico.

Index	Descriptive measure	General	Healthy	Devitalized	Dead
NDVI	1st Qu.	0.46	0.71	0.64	0.42
	Mean	0.62	0.74	0.67	0.43
	3rd Qu.	0.73	0.76	0.72	0.45
ST (°C)	1st Qu.	20.30	18.95	21.90	27.15
	Mean	24.11	20.13	23.82	29.77
	3rd Qu.	27.00	21.05	25.40	31.90
TVDI	1st Qu.	0.15	0.07	0.23	0.41
	Mean	0.31	0.14	0.33	0.53
	3rd Qu.	0.43	0.19	0.40	0.62

NDVI: Normalized Difference Vegetation Index, ST: surface temperature, TVDI: Temperature Vegetation Dryness Index.

Regarding the TVDI, the average value of all the sampled trees was 0.31. A trend similar to that of the ST was observed: as trees were identified in the field with better vigor conditions, the values were lower. The resulting average TVDI values were 0.14, 0.33, and 0.53 for the healthy, devitalized, and dead categories, respectively. The behavior of NDVI, ST, and TVDI in each of the three vitality categories is shown in Figure 7.

Statistically significant differences were identified in the three vitality categories [chi-squared (X^2) = 25.66; Degrees of freedom (DF) = 2, 32; $p < 0.0001$, $X^2 = 26.99$; DF = 2, 32; $p < 0.0001$ and $X^2 = 25.46$; DF = 2, 32; $p < 0.0001$]. The comparison of means between each of the vitality categories (healthy, devitalized, and dead) in terms of their ST, NDVI, and TVDI values was performed using Pairwise Wilcoxon Rank Sum Tests. It was found that, for each index evaluated, there were statistically significant differences in nine of the nine possible combinations of vitality categories identified in the field (Table 2 and Figure 7).

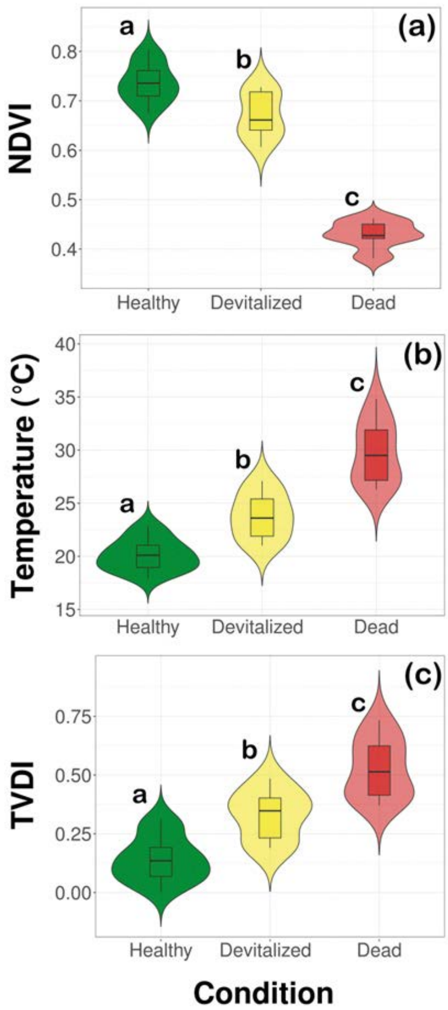

Figure 7. Boxplot summarizing the canopy values of *Abies religiosa* trees in the Monarch Butterfly Biosphere, México, for each vitality category: (a) normalized difference vegetation index (NDVI); (b) surface temperature and (c) temperature-vegetation dryness index (TVDI). The line across the box corresponds to the median and the rectangle corresponds to the interquartile range. Boxes with different letters differ significantly (multiple comparisons of means Pairwise Wilcoxon Rank Sum Tests' post hoc test, $p \leq 0.05$).

Table 2. Statistical tests applied to NDVI, ST, and TVDI in *Abies religiosa* trees from the Monarch Butterfly Biosphere Reserve, Mexico.

Shapiro-Wilk Test			
Index	**W**		**p-value**
NDVI	0.84466		0.0001749
ST (°C)	0.92601		0.02132
TVDI	0.96336		0.2876
Levene Test			
Index	**Df**	**F value**	**p-value**
NDVI	2, 32	1.9732	0.1556
ST (°C)	2, 32	4.2699	0.02271
TVDI	2, 32	1.0157	0.3735
Kruskal-Wallis Test			
Index	**Chi-squared**	**df**	**p-value**
NDVI	25.661	2	0.00000268
ST (°C)	26.994	2	0.00000138
TVDI	25.46	2	0.00000296
Significance levels for Pairwise Wilcoxon Tests			
Index		**Dead**	**Devitalized**
NDVI	Devitalized	2.4×10^{-5}	---
	Healthy	7.8×10^{-7}	4.4×10^{-3}
ST (°C)	Devitalized	1.1×10^{-3}	---
	Healthy	6.2×10^{-5}	1.1×10^{-3}
TVDI	Devitalized	1.64×10^{-3}	---
	Healthy	7.8×10^{-7}	5.9×10^{-4}

NDVI: Normalized Difference Vegetation Index, ST: surface temperature, TVDI: Temperature Vegetation Dryness Index.

Discussion

This study is particularly relevant in the context of devitalization caused by extreme climatic events associated with climate change. Increasingly prolonged droughts with higher temperatures induce stress in trees, making them more vulnerable to pests, diseases, and irreversible physiological damage (Gómez-Pineda et al., 2022; Li et al., 2022). Gómez-Pineda et al. (2022), in a study on bark beetle outbreak notifications in the Transmexican Volcanic Belt, reports of *Abies religiosa* bark beetle infestations have significantly increased in years of extreme drought. Additionally, predictive models suggest that by 2090, the climatic habitat of *Abies religiosa* within the Monarch Butterfly Biosphere Reserve (MBBR) will be drastically reduced (Sáenz-Romero et al., 2012; Sáenz-Romero et al., 2024). The three levels of *A. religiosa* vitality identified in the field were clearly distinguished using three indicators generated with the UAV images. These were NDVI, ST, and TVDI (Figure 6 and Figure 7). The most significant outcome of this research was to demonstrate that it is feasible to associate the vitality information obtained in field sampling with information captured using UAV flights, which was statistically reliable in all the comparisons made (Figure 7). The ranges of NDVI, ST, and TVDI values for the vitality categories of *A. religiosa* can be utilized in future research and to extrapolate the information generated with UAVs to larger areas (Munawar et al., 2022) in order to conduct forest health monitoring in a more timely and efficient manner in the forests of the MBBR.

NDVI, a widely applied and studied indicator (Huang et al., 2021), was shown to be reliable for evaluating physiological stress in vegetation at the individual *A. religiosa* tree level in the MBBR in central Mexico. The mean NDVI values found in the present study (0.62) are consistent with those reported for other conifers

(*Pinus arizonica*) in northern Mexico (0.7) (Gallardo-Salazar et al., 2022), using a similar multispectral sensor. This also supports the findings of Pádua et al. (2019), who report that areas with NDVI values lower than 0.5 correspond to sites with dead trees or sites devoid of vegetation, which coincides with NDVI values of between 0.38 and 0.46 where we found trees of *A. religiosa* categorized in the field as dead (Figure 2e). Similarly, Gallardo-Salazar et. al (2023a) describe the most stressed zone of *Pinus hartwegii* (xeric limit; drier and warmer) as presenting NDVI values lower than 0.4, in the low altitude zone of the Nevado de Toluca Protected Natural Area, which is also in central Mexico. However, studies conducted at other latitudes report wider NDVI ranges to describe vigorous vegetation (Abdollahnejad & Panagiotidis, 2020). Such discrepancies may be due to ecosystem type, the species under study, the causal agents of devitalization, or the season of evaluation. In this context, it is recommended that future research should incorporate multi-temporal flights of the same study site. This would permit the description of the fluctuation of NDVI and other vegetation indices throughout the year and the determination of the physiological response of the vegetation to different humidity and temperature conditions (Gallardo-Salazar, 2023b).

Another important finding was the ability to distinguish the vitality levels of *A. religiosa* based on canopy surface temperature. Although thermal sensors have been employed less frequently than multispectral sensors in forest health monitoring studies (Ecke et al., 2022), the present study found that the thermal sensor exhibited comparable sensitivity to the multispectral sensor in terms of distinguishing the vitality of *A. religiosa* (Figure 7b). We observed that trees identified as having higher vigor presented lower crown temperatures while trees with lower vigor were associated with higher temperatures. This suggests an active defense mechanism employed by the trees against drought in order to reduce transpiration (stomata closure) (Martin-StPaul et al., 2017), leading to an increase in leaf and overall canopy temperatures (Maes et al., 2018). Nevertheless, the results indicate that these mechanisms appear to be insufficient to ameliorate the negative impacts of accelerated climate change (Park-Willams et al., 2013).

Our findings align with those reported by several other authors, who found temperature differences between healthy vegetation and vegetation exhibiting some level of stress (Maes et al., 2018; Yuan et al., 2019). Nevertheless, the observed differences between tree vitality conditions did not exceed 3 °C (ranges from 0.41 °C to 2.67 °C in variation within each vitality category). The present study revealed a difference in tree crown temperature of 3.69 °C between healthy and devitalized trees; 5.95 °C between devitalized and dead trees, and 9.64 °C between healthy and dead trees, which is a much higher value than initially anticipated, and we consider this an important finding (Figure 7b). Tree canopies play a crucial role in the interaction between the Earth's surface and the atmosphere. Tree temperature largely depends on canopy structure in combination with leaf characteristics (Leuzinger & Körner, 2007; Abdullah et al., 2025). Canopy transparency is a key attribute that refers to the amount of electromagnetic radiation that can pass through the canopy. A canopy with a higher transparency percentage may lead to an increase in temperature values captured by drones due to the inclusion of ground surface data (Olson et al., 2025).

The considerable disparity in temperature between the vitality categories lends greater reliability to the detection of devitalized trees and, to a greater extent, dead trees. Such a diagnostic tool can be of great utility in informed decision-making for the management of monarch butterfly overwintering sites. In particular, this study can help to address the management dilemmas that arise from tree mortality associated with the rapid increase of bark beetle outbreaks in *A. religiosa* forests, caused by the physiological vulnerability of trees after an abnormal drought event (Del-Val & Sáenz-Romero, 2017; Sáenz-Romero et al., 2020; Gómez-Pineda et al., 2022). Similarly, the timely monitoring of the accumulation of dead trees will allow assessment of the quantities of available fuel as a risk factor for extreme forest fires (Gaboriau et al., 2020).

TVDI has been employed primarily with regionally focused satellite imagery for the analysis of soil moisture and its correlation with vegetation cover (Holzman et al., 2014; Chen et al., 2015). To our knowledge, this study represents the first investigation of TVDI derived from high-resolution imagery for the analysis of stress conditions at the individual tree level (Ecke et al., 2022). Although the analysis of variance revealed significant differences in TVDI among the three vitality categories, the results suggest no advantage over NDVI and ST (Figure 7). In a study by Shi et al. (2020), in which the authors evaluated the responsiveness of TVDI estimated from MODIS images for monitoring drought conditions in Eurasian forests, it was observed that TVDI adequately identifies high and moderate hydric stress conditions, but not for mild drought conditions. The aforementioned study also demonstrated differences between forests with different plant compositions. It is therefore recommended to explore the potential of this index in different tree species and under different hydric stress conditions.

Conclusions

The methodology developed here enabled the association of the devitalization information of *A. religiosa* individuals recorded in the field with information captured using UAVs. The NDVI, ST, and the combination of these two indicators in the TVDI, were demonstrated to be reliable parameters for differentiating the three vitality levels of the trees (healthy, devitalized, and dead). The ranges of NDVI, ST, and TVDI values, identified in the present investigation for the vitality categories of *A. religiosa*, could be extrapolated to larger areas in order to conduct forest health monitoring in a more timely and efficient manner in the forests of the Monarch Butterfly Biosphere Reserve. However, an essential next step is to develop a statistical model that can accurately determine tree devitalization categories. We recommend this as a crucial avenue for future research.

In future research, it will be important to consider the dynamics of NDVI, ST, and TVDI throughout the year to determine whether there are differences in these indices between seasons. While this study represents progress in identifying devitalized trees by linking field data with information obtained from drones, it is essential to consider that identifying the causes of devitalization, such as forest pests, would require focusing efforts on field identification of trees infected by causal agents and relating this information to data obtained from UAV flights.

The present study establishes a foundation for future research focused on analyzing the causal agents (biotic and abiotic) of devitalization in *A. religiosa* and its association with high-resolution information generated by UAVs. Climate change is causing a significant increase in the incidence of bark insect attacks, so the development of a methodology using UAVs for early warning and identification of devitalized trees attacked by bark insects is vital for better-informed decision-making by forest managers.

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

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