Evaluating Vegetation Indices Across Scales: An Integrated Analysis of PROSPECT-4 Model, Sentinel-2, and Multispectral Drone

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Abstract

The use of Vegetation Indices (VIs) is important in remote sensing for inferring biophysical parameters and monitoring environmental processes. Since VIs are derived from reflectance measurements, the scale and platform of acquisition-satellite, commercial multispectral drone, or simulation model—can potentially influence their derived values and inter-relationships. This study addresses this influence by presenting a multiscale comparison of four common indices: MPRI, NDVI, NDWI, and OSAVI. Data were sourced from three distinct platforms: Sentinel-2 satellite imagery, high-resolution data acquired via a multispectral drone, and a simulated spectral library generated using the PROSPECT-4 via ARTMO software. The core objective was to assess the consistency of the correlational structure among these VIs across the three scale measurements. Results indicate a statistically significant similarity in the overall correlational pattern of the indices, suggesting that the intrinsic mathematical relationships between these VIs are largely scale-invariant. However, the study identifies a critical need to standardize the data acquisition and processing protocol for drone measurements to match the known consistency of the Sentinel-2 mission and the rigorous parameters of the PROSPECT-4 simulation. This standardization is essential for future multi-sensor integration and calibration efforts.

1. Introduction

1.1 Background of the Study

The study of vegetation dynamics and health is significant for a wide range of applications, including agriculture, ecological monitoring, and climate science. Vegetation indices are derived from the reflectance of different wavelength combinations, serving as a powerful tool to approximate relevant vegetation parameters, such as chlorophyll content, biomass, and stress levels. The importance of these indices lies in their simplicity and ability to provide a consistent, large-scale, and non-destructive method for tracking vegetation changes over time.

Various vegetation indices (VIs) have already been developed to understand different environmental parameters. This serves as a preliminary observation to a certain event that is happening in the ground that needs to be further investigated. For example, Normalized Vegetation Index (NDVI) was used in precision agriculture to observe crop health monitoring, yield prediction, field zoning and management, and drought stress detection (Elmaguin et al., 2024). In water monitoring, the Normalized Difference Turbidity Index (NDTI) is a useful key indicator of water quality that measures the optical clarity of water, which is impaired by the presence of suspended particles like silt, algae, and pollutants. For forest monitoring, especially in a hot tropical region, Normalized Burn Ratio (NBR) were utilized to detect burned areas due to forest fires. With the use of these vegetation indices (VIs), researchers were able to gain insight from different environmental processes that utilize reflectance spectra from the sensors aboard different satellite platforms.

1.2 Monitoring Techniques and Vegetation Indices

Monitoring various vegetation indices and dynamics can be observed using remote sensing data from different satellite-based platforms, such as Sentinel-2 from the European Space Agency (ESA), which provides consistent, large-scale coverage with a medium spatial resolution. The effectiveness of Sentinel-2 satellite imagery stems from its technical specifications, which include spectral bands necessary for understanding vegetation composition (Frampton et al., 2013). This includes crucial bands in the visible region: green (band 3), red (band 4), three red-edge bands (band 5, band 6, and band 7), and the NIR region (band 8). Band 4 (red) is used to assess chlorophyll absorption, and the red edge bands (band 5, band 6, and band 7) are sensitive to detect vegetation stress and nitrogen content. Table 1 shows the summary of Sentinel 2 bands and characteristics

The Sentinel-2 satellite mission is a highly prominent and extensively utilized data source within remote sensing research, particularly for environmental monitoring. Its utility in the Philippines is well-established across diverse environmental applications. For instance, studies have successfully leveraged

Sentinel-2-derived vegetation indices to investigate various vegetative processes (Baloloy et al., 2018; Castillo et al., 2017).

Figure 1. Sentinel 2

Furthermore, its application extends to aquatic environments, demonstrating efficacy in water quality monitoring within critical Philippine water bodies, including Manila Bay (Medina et al., 2023) and Laguna Lake (Caballero & Navarro, 2021). These examples collectively underscore the versatility and proven applicability of Sentinel-2 data in supporting environmental management and research initiatives throughout the Philippines.

Band	Central wavelength (nm)	Resolution (m)
Green	560	10
Red	665	10
Red edge	740	20
NIR	865	20

Table 1. Sentinel 2 bands and characteristics

The advent of Unmanned Aerial Vehicles (drones) equipped with multispectral sensors has enabled high-resolution data acquisition at a local scale, providing an unprecedented level of detail for specific fields or plots. Different spectral cameras can be attached to these drones depending on the application.

Figure 2. DJI Mavic 3M (DJI, n.d.)

For agriculture and environmental applications, common spectral bands that are attached to these drones are green, red, red-edge, and NIR. These bands are used to imitate the capabilities of satellite data to observe vegetation parameters at very high resolution (typically ranging from 3 cm to 10 cm), depending on the flight configuration.

Band	Central wavelength (nm)
Green	560 ± 16
Red	650 ± 16
Red edge	730 ± 16
NIR	860 ± 26

Table 2. DJI Mavic 3M bands and characteristics

Another approach to understanding vegetation dynamics is through the use of mathematical modeling and simulation. One model that is already established for observing spectral reflectance at the leaf level is the PROSPECT-4 leaf model, which provides a robust framework for simulating the spectral signatures of vegetation under controlled conditions. This model is based on the radiative transfer model (RTM) that focuses on how the electromagnetic spectrum is absorbed, reflected, and transmitted. It uses the equation that describes how light is absorbed or scattered when it interacts with a material. The model requires vegetation parameters, such as leaf structure, chlorophyll content, water thickness, and dry matter content, to accurately represent the vegetation's spectral reflectance. These radiative transfer models (RTMs) were utilized by Verrelst and Rivera (2016) in studying reflectance, fluorescence, and radiance to gain insight into vegetation–light interactions and RTM input–output functioning.

1.3 Objectives

The primary challenge lies in reconciling these disparate data sources. The scale-dependent nature of VIs means that an index value calculated from a low-resolution satellite pixel may not directly correspond to an average of the same index derived from thousands of high-resolution drone pixels within that same area. This discrepancy is further complicated by the fact that model simulations, while valuable for understanding underlying processes, must be validated against real-world observations.

This research aims to address this critical gap by performing an integrated analysis to evaluate and compare a suite of vegetation indices across these three distinct scales: model simulations (PROSPECT 4 model), broad-scale satellite data (Sentinel-2), and high-resolution drone-derived imagery (DJI Mavic 3 multispectral). By systematically assessing the consistency and performance of VIs across these scales, this study seeks to enhance our understanding of their applicability and limitations, thereby paving the way for more robust and reliable multi-scale vegetation monitoring.

2. Assessment of Vegetation Indices

The study focused on *Oryza sativa* (rice) to investigate the behaviour of various vegetation indices across different spatial scales. The research was conducted in the Municipality of Victoria, Tarlac, Philippines (latitude:15.60524, longitude: 120.65137), specifically during the reproductive phase of the rice plant. Data was collected on January 18, 2025, which corresponds to approximately 70-80 days after germination. Figure 3 shows the research location that covers approximately 2 hectares of rice farm.

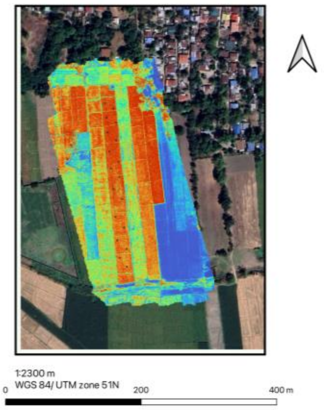

Figure 3. Research area located in Tarlac, Philippines

To address the study's objective, which involves the comparative analysis of vegetation indices derived from distinct spatial scales, a systematic protocol was implemented shown in Figure 4. This methodology was specifically designed to ensure the co-registration and inter-comparison of indices calculated from the multispectral drone imagery and the Sentinel-2 satellite data, thereby establishing a rigorous framework for multiscale evaluation.

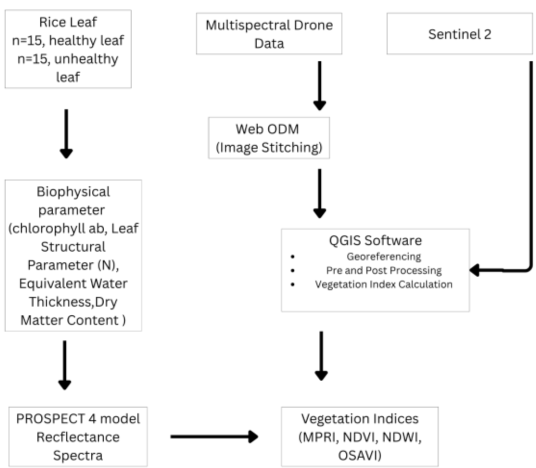

Figure 4. Research Framework

To facilitate the simulation, rice leaf samples were collected, and the concentration of chlorophyll ab (Cab) was empirically determined using the standard methanol extraction and subsequent analysis, following the established protocol of Ngcobo et al. (2023). This measured Cab value, along with other essential PROSPECT-4 model input parameters—specifically the Leaf Structural Parameter (N), Equivalent Water Thickness (Cw), and Dry Matter Content (Cm)—was then input into the model. The PROSPECT-4 radiative transfer model, executed within the Automated Radiative Transfer Model Operator (ARTMO) software package, was used to generate synthetic leaf hemispherical reflectance spectra spanning the 400 nm to 900 nm range. The resulting spectral output is graphically presented in Figure 5.

Drone data were acquired using a multispectral sensor. The raw aerial imagery was processed using OpenDroneMap (ODM) photogrammetry software to generate a high-resolution, orthorectified mosaic. The ODM output inherently provided the initial set of vegetation indices (VIs) for analysis. To enable direct multi-scale comparison, the Sentinel-2 satellite data were precisely co-registered to the established geometric reference of the orthomosaic images from the drone. All subsequent spatial analyses, including the calculation of scale-specific parameters and the inter-comparison of the derived indices, were conducted within the QGIS Software (version 3.40) environment.

Vegetation Index	Formula	Uses
Modified Photochemical Reflectance Index (MPRI)	MPRI = GREEN-RED/GREEN + RED	sensitive to changes in plant pigments (specifically the xanthophyll cycle) that indicate photosynthetic light use efficiency and physiological stress in live foliage
Normalized Vegetation Index (NDVI)	NDVI = (NIR – RED) / (NIR + RED)	used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health
Normalized Difference Water Index (NDWI)	NDWI = (GREEN – NIR) / (GREEN + NIR)	primarily used in plant dynamics to estimate the liquid water content of vegetation canopies. It serves as a crucial indicator of plant water stress and overall moisture status
Optimized Soil-Adjusted Vegetation Index (OSAVI)	OSAVI= (1.5)(NIR)-RED/ (NIR+RED+0.16)	designed to estimate green biomass and vegetation cover while minimizing the interference from soil background reflectance

Table 3. Vegetation Indices used in the study

Four key vegetation indices were selected for analysis indicated in Table 3: the Modified Photochemical Reflectance Index (MPRI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Optimized Soil-Adjusted Vegetation Index (OSAVI). These specific indices were chosen due to their common wavelength bands, which enabled a direct and consistent comparison between the data acquired from the multispectral drone and the Sentinel-2 satellite platforms.

This study investigated the correlation coefficients between four key vegetation indices—Modified Pigment and Reflectance Index (MPRI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Optimized Soil Adjusted Vegetation Index (OSAVI)—across three distinct platforms: the ARTMO-PROSPECT 4 model, a multispectral drone, and the Sentinel-2 satellite. The goal was to assess if there was a consistent pattern of correlation across these different measurement scales.

3. Results and Discussion

To utilize the simulation model, input parameters were defined based on both measured data and established constraints derived from the literature. These parameters were subsequently used in the PROSPECT-4 radiative transfer model, executed via the ARTMO software package, to generate a synthetic reflectance spectral library. Table 4 details the specific range of values sampled for each input parameter. The chlorophyll a+b concentration range was derived empirically from in situ standard methanol extraction and subsequent UV-VIS absorption spectroscopy, following the methodology detailed by Ngcobo et al. (2023). The remaining input parameters (specifically Leaf Structural Parameter, Equivalent Water Thickness, Dry Matter Content) were constrained based on typical literature values for the target vegetation type and defined using a uniform random sampling within the ranges specified in Table 4. This approach ensures the simulated spectra represent a realistic and statistically diverse distribution of biophysical characteristics.

Parameter	Minimum	Maximum	Step
Chlorophyll ab	1.65	29.95	50
Leaf Structural Parameter	1.08	1.38	5
Equivalent Water Thickness	0.0144	0.0618	5
Dry Matter Content	0.0031	0.0389	10

Table 4. Input Parameters in PROSPECT 4 Model

Following the determination of the requisite input parameters, the PROSPECT-4 radiative transfer model was executed within the Automated Radiative Transfer Model Operator (ARTMO) framework. This modelling process generated a library of synthetic leaf hemispherical reflectance spectra spanning the visible and near-infrared (NIR) domains, specifically from 400 nm to 900 nm. These simulated spectra, visually represented in Figure 5, served as the foundation for the subsequent extraction of several key indices: the Modified Photochemical Reflectance Index (MPRI), the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Optimized Soil Adjusted Vegetation Index (OSAVI).

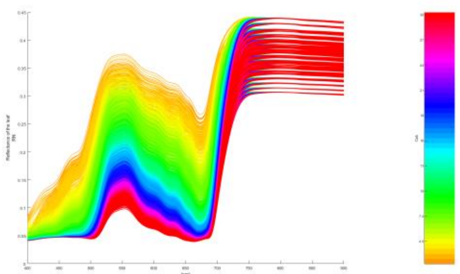

Figure 5. Reflectance Spectra generated using the PROSPECT-4 model through ARTMO Software

The raw aerial imagery acquired from the multispectral drone was processed using the OpenDroneMap (ODM) photogrammetry software suite. This provides an orthomosaic image file that will be compared to Sentinel 2 satellite images. From this orthomosaic, several key vegetation indices (VIs) and a water index were quantitatively derived shown in Figure 6. Specifically, the Modified Photochemical Reflectance Index (MPRI), the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Optimized Soil Adjusted Vegetation Index (OSAVI) were extracted to facilitate subsequent analysis using QGIS software (version 3.40).

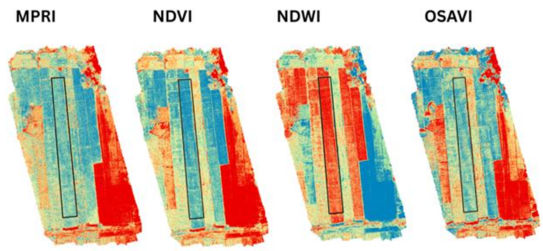

Figure 6. Derived vegetation indices from multispectral drone data

Sentinel-2 Level-2A surface reflectance data were acquired via the Copernicus Open Access Hub (Copernicus Browser). The specific acquisition date for the satellite imagery was January 21, 2025, which was intentionally selected to maintain temporal proximity, occurring three days after the drone data collection. Individual spectral bands—specifically the Green (B3), Red (B4), Red Edge (B6), and Near-Infrared (NIR, B8)—were downloaded. Subsequently, these bands were processed using QGIS software to calculate the following four indices for comparative analysis, as shown in Figure 7.

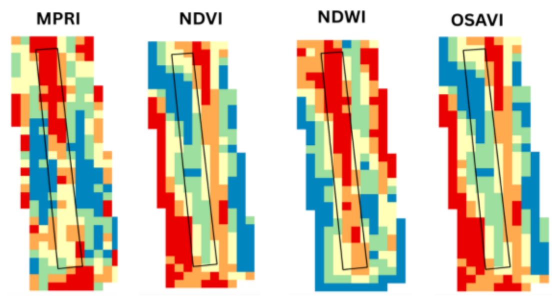

Figure 7. Derived vegetation indices from the Sentinel-2 satellite

As depicted in Figure 8, a correlation heatmap was generated for each platform. The indices were arranged identically on each heatmap to facilitate a direct comparison of their intercorrelations. The results reveal a remarkable similarity in the overall pattern of correlations across all three platforms, suggesting that the relationships between these vegetation indices remain largely consistent regardless of the scale of measurement—from the controlled simulation of PROSPECT 4 to the broad-area coverage of Sentinel-2.

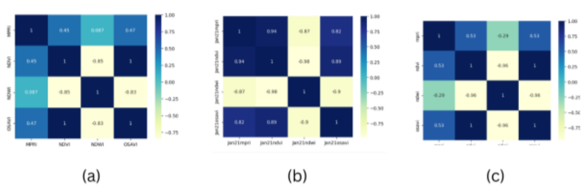

Figure 8. Correlation Heat Map derived from (a)Prospect 4 model, (b) Multispectral drone, and (c) Sentinel-2

While the overall patterns are similar, a notable slight variation is observed in the heatmap derived from the multispectral drone data (Figure 8b). This minor discrepancy can likely be attributed to the unique characteristics of drone-based data acquisition and processing. Unlike the standardized, top-of-atmosphere reflectance provided by satellite platforms like Sentinel-2, drone data often requires specific and sometimes less consistent reflectance calibration procedures. Factors such as atmospheric conditions at the time of flight, inconsistencies in the ground calibration targets, and variations in sensor-to-target geometry can introduce minor inaccuracies that manifest as slight deviations in the calculated correlation coefficients.

4. Conclusion

This study investigated the consistency of several vegetation indices (VIs) derived from multi-scale remote sensing data, specifically comparing Sentinel-2 satellite imagery, high-resolution multispectral drone data, and PROSPECT-4 model simulations. The findings confirm that a significant intercorrelation exists between the various vegetation indices across these three distinct measurement scales. This observed consistency suggests that, despite differences in spatial resolution and acquisition platform, the fundamental biophysical signals captured by the indices remain coherent. Therefore, the data support the notion that multi-scale monitoring approaches can be integrated to provide robust observational data for environmental analysis. The results, however, also emphasize the necessity of systematic scaling protocols to improve data agreement and minimize variability. Future research should prioritize the development and application of standardized up-scaling and down-scaling methodologies to enhance the utility and reliability of fused multi-platform datasets in precise environmental monitoring and modeling.

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