

SPECTRAL REFLECTANCE CHARACTERISTICS OF MANGROVE FORESTS IN MULTISPECTRAL UNMANNED AERIAL VEHICLE IMAGERY IN CA MAU PROVINCE, VIETNAM

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ABSTRACT

Flight altitude and radiometric calibration strongly influence the usability of multispectral imagery from unmanned aerial vehicles (UAVs) for mangrove forest monitoring. This study quantifies both effects for two different forest types, planted and natural mangrove forests, through three components: spectral reflectance characteristics, the role of radiometric calibration, and the effect of flight altitude. Images were collected with a DJI Mavic 3 Multispectral over a 66 - ha plantation and a 71 - ha natural mangrove stand in Ca Mau province during two time periods in May and November 2025, at flight altitudes of 100 m and 150 m, and processed in Pix4D Mapper with and without a reflectance panel. Reflectance of the green, red, red-edge and near-infrared (NIR) bands was highly stable within each flight at both altitudes, and the NIR and red-edge bands separated mangrove canopy from water most clearly. Classification accuracy of four surface classes reached 90.0% at 100 m and 96.0% at 150 m. Without the calibration panel, reflectance over forest canopy decreased by a factor from 11.2 to 18.5, making absolute values unusable. However, 9 of the 16 vegetation indices, all purely ratio-based (containing no additive constant), maintained correlation coefficients of 0.8 or higher with the calibrated dataset at 150 m, and six did so at 100 m. In terms of acquisition efficiency, flying at 100 m required 1.75 - 1.97 times the resources of 150 m (image count, flight time, processing time, and storage), with no corresponding gain in data quality under the illumination conditions of this study. Within the scope of the flights surveyed, the study suggests flying at 150 m and using a calibration panel whenever absolute reflectance is required; where panel deployment is impossible, the screened indices remain usable for relative monitoring.

Keywords: UAV multispectral imagery, vegetation indices, flight altitude, radiometric calibration, mangrove forest.

ĐẶC TRƯNG PHẢN XẠ PHỔ RỪNG NGẬP MẶN TRÊN ẢNH MÁY BAY KHÔNG NGƯỜI LÁI ĐA PHỔ TẠI TỈNH CÀ MAU

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TÓM TẮT

Nghiên cứu xây dựng cơ sở khoa học cho việc dùng ảnh đa phổ từ máy bay không người lái (UAV) giám sát rừng ngập mặn qua ba nội dung: đặc trưng phản xạ phổ, vai trò của tấm hiệu chỉnh phản xạ và ảnh hưởng của độ cao bay. Ảnh được thu bằng thiết bị DJI Mavic 3 Multispectral trên khu rừng trồng 66 ha và khu rừng tự nhiên 71 ha tại tỉnh Cà Mau trong hai đợt tháng 5 và tháng 11 năm 2025, ở hai độ cao 100 m và 150 m, xử lý bằng Pix4D Mapper theo phương án có và không có tấm hiệu chỉnh. Phản xạ bốn kênh Green, Red, Red edge và NIR ổn định trong cùng chuyến bay ở cả hai độ cao, trong đó NIR và Red edge phân tách rừng với mặt nước rõ nhất, và độ chính xác phân loại bốn nhóm đối tượng đạt cao ở cả hai độ cao (90,0% ở 100 m và 96,0% ở 150 m). Khi xử lý không có tấm, phản xạ trên đối tượng rừng giảm 11,2 đến 18,5 lần nên không dùng được giá trị tuyệt đối; tuy vậy, 9 trong 16 chỉ số thực vật được khảo sát, đều thuộc dạng tỷ số thuần nhất, vẫn giữ hệ số tương quan từ 0,8 trở lên so với bản có hiệu chỉnh ở độ cao 150 m. Bay 100 m tiêu tốn gấp 1,75 đến 1,97 lần nguồn lực so với 150 m mà chất lượng dữ liệu không khác biệt đáng kể. Nghiên cứu khuyến nghị bay ở độ cao 150 m, dùng tấm hiệu chỉnh khi cần giá trị phản xạ tuyệt đối, và khi không đặt được tấm thì nhóm chỉ số đã sàng lọc vẫn dùng được cho giám sát tương đối.

Từ khóa: Ảnh đa phổ UAV, chỉ số thực vật, độ cao bay, hiệu chỉnh bức xạ, rừng ngập mặn.

I. INTRODUCTION

Mangrove forests protect coastlines, sustain coastal livelihoods and store large carbon stocks (Donato *et al.*, 2011). Monitoring their dynamics requires detailed, frequently updated data, whereas the muddy, tide-inundated ground makes field surveys costly and difficult to repeat (Otero *et al.*, 2018). Optical satellite imagery offers broad coverage, but its spatial resolution and revisit frequency remain insufficient for monitoring at the stand and individual-tree scales; in rehabilitated mangroves with a homogeneous canopy, regression models based on vegetation indices from Landsat 8 and Sentinel-2A imagery explained at most 3% of the variation in carbon stock (Sumarga *et al.*, 2026).

Unmanned aerial vehicles (UAVs) carrying multispectral sensors have been used increasingly for mangrove forests worldwide, from forest inventory and biomass estimation with low-cost platforms (Otero *et al.*, 2018; Li *et al.*, 2019; Navarro *et al.*, 2019) to species classification with multispectral and hyperspectral imagery (Cao *et al.*, 2021; Yang *et al.*, 2024). Two features are common across these studies. First, each study flew at a single altitude, ranging from 25 m (Otero *et al.*, 2018) to 120 m (Yang *et al.*, 2024) depending on the trade-off between spatial resolution and area coverage. Second, most did not address radiometric calibration with a reference panel, although absolute reflectance is a prerequisite for comparing data between dates. Dedicated experiments on flight parameters in temperate forests remain inconclusive on the role of altitude: Dandois *et al.* (2015) found no significant differences in canopy height error among altitudes, overlaps and lighting conditions after correcting model-fitting bias; Seifert *et al.* (2019) reported that low altitudes combined with high overlap gave the most detailed reconstructions, while Stow *et al.* (2019), who only studied reflectance rather than structure, concluded that the effect of flight height was unclear and emphasized the need to control illumination conditions. Recent work on agricultural crops has likewise found that reflectance and vegetation indices stabilise only

at altitudes of about 100 m or higher (Luo *et al.*, 2022; Wang *et al.*, 2025), while the accuracy of retrieving physiological parameters declines with altitude even on the same DJI Mavic 3 Multispectral sensor (Li *et al.*, 2025). None of these experiments were conducted in mangrove ecosystems, and no comparable evidence exists for this type of forest.

In Vietnam, up-to-date, multispectral UAV imagery has been applied in only a few initial studies, namely identifying a set of representative vegetation indices for evergreen forest at Kon Chu Rang Nature Reserve (Đinh Bá Duy *et al.*, 2022) and monitoring seasonal changes of vegetation indices in the Dong Rui mangroves (Ngo Trung Dung, 2024). In the same Dong Rui area, object-based classification of mangrove species from multispectral UAV imagery with Random Forest achieved an overall accuracy of 91.1% (Ngo *et al.*, 2024); in Ba Ria - Vung Tau, Linh and Vinh (2025) used the same DJI Mavic 3 Multispectral to estimate mangrove biomass and carbon stocks but focused on canopy structure. None of these studies used a reflectance panel or compared flight altitudes, reflecting the general situation that radiometric calibration has received little attention in UAV applications in Vietnam.

Three main gaps have been identified. First, the spectral reflectance characteristics of mangrove forests in multispectral UAV imagery have not been described systematically. Second, the effect of the calibration panel on reflectance values and on the usability of vegetation indices has not been quantified. Third, the influence of flight altitude on data quality and acquisition cost has not been verified for mangrove conditions, where deploying a reference panel and repeating flights are more difficult than in terrestrial ecosystems.

This study therefore pursues two objectives. First, it aims to characterise the four-band spectral reflectance and the vegetation index set of Ca Mau mangroves from DJI Mavic 3 Multispectral imagery at the two flight altitudes of 100 m and 150 m. It then quantifies the role of the reflectance panel and the effect of flight altitude on data quality and acquisition

efficiency, thereby recommending a suitable flight scheme for mangrove monitoring. The findings provide site-specific empirical parameters for UAV data-based mangrove classification and carbon estimation.

II. MATERIALS AND METHODS

2.1. Study area

The study was conducted in two mangrove areas of Ca Mau province: a plantation with a 66 - ha

flight area and a natural stand with a 71 - ha flight area. The plantation is dominated by monospecific *Rhizophora apiculata*; the natural stand is a mixed, naturally regenerated community. The flight area of each site was delineated in advance as a closed polygon and the flight grid was designed to cover it completely. Stand characteristics of the two sites are summarised in Table 1 and illustrated in Fig. 1.

Table 1. Stand characteristics of the two study sites.

Indicators	Natural forest	Planted forest
Tree density (stems ha ⁻¹)	1,689 ± 562 (33.3%)	2,600 ± 956 (36.8%)
Diameter at breast height (D _{1.3} ,cm)	14.0 ± 4.1 (28.9%)	9.9 ± 1.7 (17.7%)
Total tree height (H _{vn} ,m)	15.3 ± 4.0 (26.5%)	9.8 ± 2.4 (24.9%)
Maximum tree height (Hmax,m)	22.0 ± 3.2 (14.5%)	13.4 ± 2.8 (21.0%)
Basal area (m ² ha ⁻¹)	30.1 ± 12.4 (41.1%)	22.0 ± 7.0 (32.1%)
Number of species encountered plot ⁻¹	1.7 ± 0.9 (50.8%)	2.5 ± 1.2 (48.2%)
Proportion of stems belonging to the dominant species plot ⁻¹ (%)	91.0 ± 11.6 (12.7%)	75.8 ± 19.5 (25.7%)
Total overstorey species	5	9

Note: values are mean ± standard deviation; values in parentheses are coefficients of variation (%).

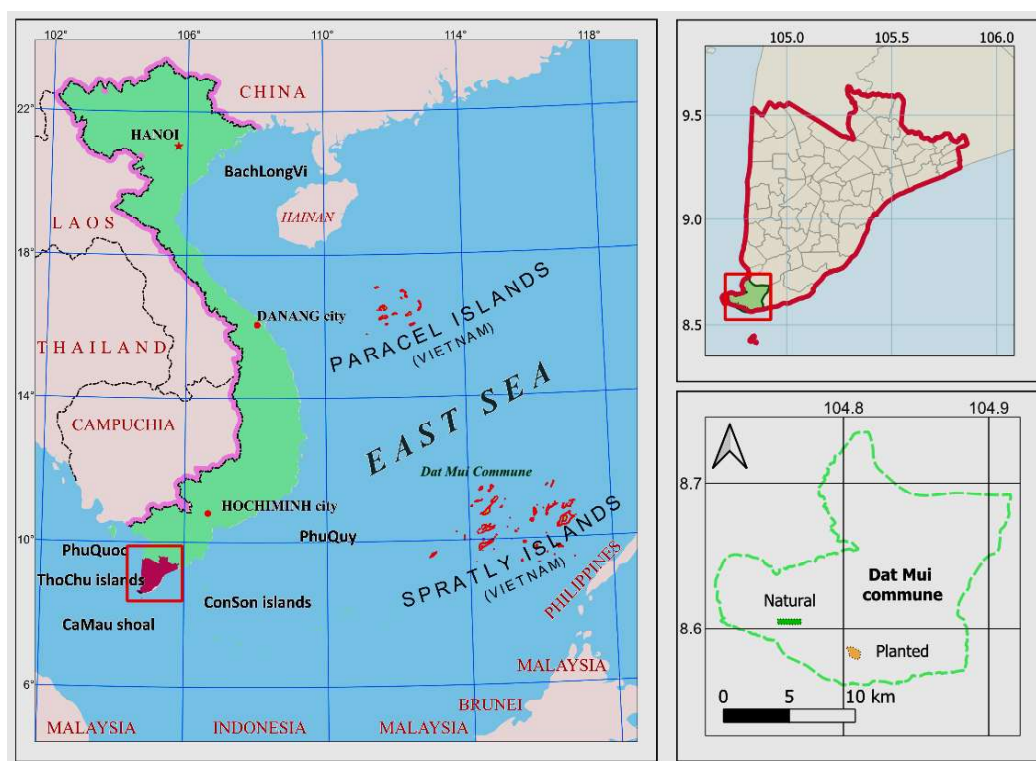


Fig. 1. Locations of the two study sites (natural and planted mangrove forests) in Ca Mau province

A total of 90 circular sample plots, each with an area of 100 m², were surveyed, 45 plots in the natural stand and 45 in the plantation. In each plot, all standing trees were identified to species and counted; diameter at breast height ($D_{1.3}$) was measured at 1.3 m above the ground with a girth tape, and tree heights (H_{vn} and H_{max}) were measured with a laser hypsometer. Basal area per hectare was derived from the measured $D_{1.3}$ values, and the stand indicators in Table 1 were computed from these plot records. The natural stand is managed by Mui Ca Mau National Park, while the plantation has been planted since 2003 and is under the management of the Dat Mui Protection Forest Management Board. *Rhizophora* dominates both sites: the natural stand is nearly monospecific, accounting for 671 of 760 stems (88.3%), with the remainder belonging to four other species. In contrast, the plantation contains nine species, primarily *Rhizophora apiculata* (59.1%), *Avicennia officinalis* (22.3%), and *Ceriops zippeliana* (11.1%). Notably, stem density is higher in the plantation than in the natural stand, consistent with the successional development of planted mangroves.

2.2. Data collection and processing

The overall workflow of data collection and processing is illustrated in Fig. 2; the following sections describe each step in detail.

Equipment and image acquisition:

UAV images were collected with a DJI Mavic 3 Multispectral, which integrates a 20 MP RGB camera and four multispectral cameras, green (560 nm), red (650 nm), red edge (730 nm) and NIR (860 nm), together with an integrated upward-facing irradiance sensor (sunlight sensor) mounted on the top surface of the aircraft, which records incident solar irradiance at approximately 1 Hz throughout each flight mission and is used by Pix4D Mapper to normalise for illumination changes during

image acquisition. The reflectance panel was a Reflectance Panel Kit 6X with reflectance factors of 0.1099 for green (550 nm), 0.1079 for red (670 nm), 0.1071 for red edge (715 nm) and 0.1050 for NIR (840 nm). The panel characterisation wavelengths do not precisely match the sensor band centres: offsets of 10 nm (green: 550 vs. 560 nm), 20 nm (red: 670 vs. 650 nm), 15 nm (red edge: 715 vs. 730 nm), and 20 nm (NIR: 840 vs. 860 nm) may introduce systematic calibration bias. The red-edge band is most susceptible due to the steep reflectance gradient across the chlorophyll absorption edge, and red-edge-derived indices (NDRE) should be interpreted with this caveat in mind. UAV flights were conducted twice at each site in May and November 2025. Each campaign included the two flight altitudes (100 m and 150 m) with 70% forward overlap, 80% side overlap, and nadir (-90°) imaging. During the November campaign, the calibration panel was photographed before and after each flight mission. In May, however, the panel could not be deployed because the ground was inundated by the tide. Geotag corrections were applied using post-processed kinematic (PPK) positioning with a base station near the study area.

Image processing and the three calibration cases:

UAV images were processed in Pix4D Mapper (version 4.9.0; Pix4D SA, Lausanne, Switzerland) in three steps, namely initial calibration and image matching, point cloud densification, and generation of per-band reflectance orthomosaics (Ref). The orthomosaics represent Pix4D-calibrated apparent reflectance values; they have not been independently validated against field spectrometer measurements or validated satellite reflectance products. Where precision absolute reflectance is required, independent field-based validation is recommended. Three processing cases were established. In Case A, the November data were calibrated using the combination of the reflectance panel, the

sunlight sensor, and the sun angle as the calibration reference. In Case B, the same November data were reprocessed without the panel, relying solely on the camera parameters, the sunlight sensor, and the sun angle. In this configuration, Pix4D Mapper applies an irradiance-based radiometric correction using the on-board sunlight sensor irradiance log and the sun angle at acquisition time, without an absolute reflectance reference; the resulting pixel values are calibrated radiance-equivalent digital numbers normalised by irradiance, not surface reflectance in the strict radiometric sense. In Case C, the May data were processed without the panel as in Case B. The no-panel

versions were created by duplicating the project and changing only the calibration option, while keeping all other parameters identical. Comparing Case A with Case B using the same flight data isolated the net effect of the calibration panel, while comparing Case B with Case C revealed the seasonal variation in the absence of the panel. Because the panel was deployed only in November, the Case B versus Case C comparison reflects seasonal differences confounded with other between-campaign factors; it is therefore not equivalent to the Case A versus Case B comparison, which isolates the panel effect within the same campaign.

Table 2. Flight information and processing cases for radiometric calibration.

Flight area	Field campaign	Altitude (m)	Date	Flights	Processing case
Planted mangrove forest	May	100	25/5/2025	2	C
		150	26/5/2025	2	C
	Nov	100	4/11/2025	2	A, B
		150	4/11/2025	2	A, B
Natural mangrove forest	May	150	26/5/2025	2	C
		100	27/5/2025	4	C
	Nov	100	5/11/2025	3	A, B
		150	5/11/2025	2	A, B

Note: all missions used 70% forward overlap, 80% side overlap and nadir imaging; the flight areas were 66 ha for the planted forest and 71 ha for the natural forest.

Sample regions, vegetation indices and data analysis:

Four target classes, comprising planted mangrove forest, natural mangrove forest, water surface and bare land, were delineated in the field using 25 - m² sample regions. A total of 150 sample regions, independent of the 90 field inventory plots described in Section 2.1, were collected: 45 in natural mangrove forest, 45 in planted mangrove forest, 30 on bare land, and 30 on water. Band reflectance was extracted using zonal statistics, treating the sample region rather than individual pixels as the unit of analysis to prevent pseudo-replication caused by

spatial autocorrelation among adjacent pixels. Following mosaicking, each mission yielded five GeoTIFF products in the WGS 84 / UTM zone 48N coordinate system: an RGB orthomosaic and individual G, R, RE and NIR band rasters. Mean values for the four spectral bands were extracted in QGIS and used to compute the vegetation indices. The four primary indices were calculated as follows:

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

$$GNDVI = \frac{NIR - G}{NIR + G} \quad (2)$$

$$CI_{green} = \frac{NIR}{G} - 1 \quad (3)$$

$$NDRE = \frac{NIR - RE}{NIR + RE} \quad (4)$$

NIR, RE, R and G are the reflectance values of the four spectral bands. NDVI was calculated following Rouse *et al.* (1974), GNDVI following

Gitelson *et al.* (1996), CIgreen following Gitelson *et al.* (2003), and NDRE based on the red-edge chlorophyll relationship described by Gitelson and Merzlyak (1994).

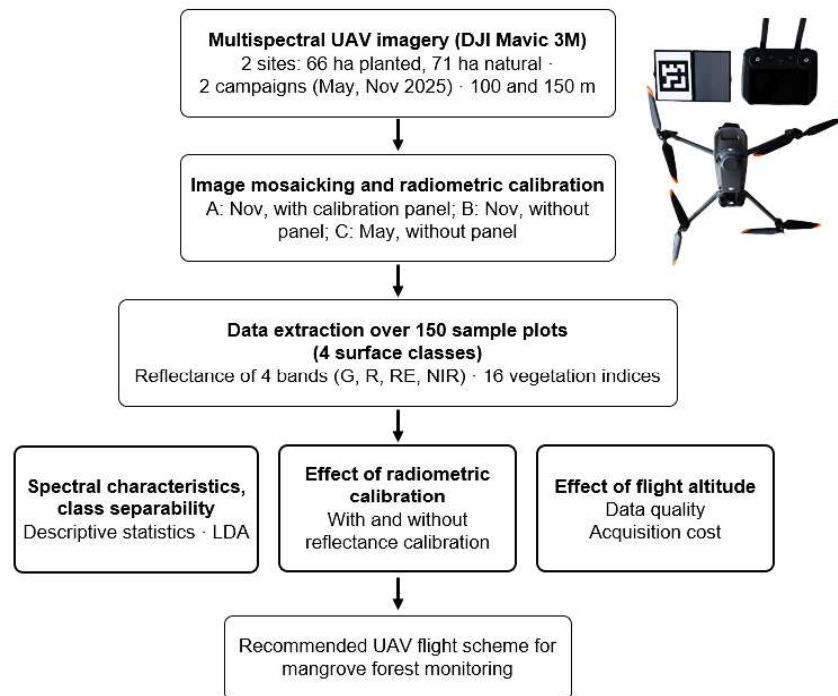


Fig. 2. Workflow of methodology used in this study.

This set of indices was selected to ensure comparability with the most recent domestic multispectral UAV study. Đinh Bá Duy *et al.* (2022) evaluated five indices, namely NDVI, GNDVI, SAVI, EVI and GCI, using a sensor equipped with a blue band. However, EVI cannot be computed from the four bands of the DJI Mavic 3 Multispectral, and GCI is identical to CIgreen. Although SAVI could be computed, it was excluded because the soil adjustment factor ($L = 0.5$) is intended for sparse vegetation over exposed soil, making it of limited relevance to dense and closed mangrove canopies. NDRE was added to incorporate a red-edge-based index, leveraging a spectral band present on the previously mentioned platform, but left unutilised in their study.

Data were analysed in R (RStudio 2026.07.1; Posit Software, PBC) across four stages. First, descriptive statistics of band reflectance, along

with the within-flight coefficient of variation, were calculated by class, flight altitude and calibration case. Second, changes between calibration cases were computed by pairing each sample region: absolute differences, ratios, and percentage changes were all calculated from the unrounded values of each pair. Paired differences were summarised with 95% confidence intervals based on the t-distribution; an interval excluding zero corresponds to a two-sided paired t-test at $p < 0.05$. Third, the usability of panel-free vegetation indices was evaluated across 16 candidates using the Pearson correlation coefficient for each of the following comparison pairs, evaluated separately at each altitude: (i) Case A vs. Case B, natural forest ($n = 45$ sample regions); (ii) Case A vs. Case B, planted forest ($n = 45$); (iii) Case B vs. Case C, natural forest ($n = 45$); and (iv) Case B vs. Case C, planted forest ($n = 45$). Each Pearson r was

computed from the sample-region-level index values; the correlation reflects how well the uncalibrated index preserves the rank order of values relative to the calibrated reference. An index was deemed suitable if it maintained a correlation of $r \geq 0.8$ across all pairs. This threshold corresponds to an R^2 of 0.64, meaning that no more than 36% of the variance in the calibrated index value remains unexplained by the uncalibrated estimate; it was selected a priori as a minimum usability criterion consistent with thresholds applied in index-substitutability studies in remote sensing (e.g., Tran *et al.*, 2022). Sensitivity to this threshold is discussed in Supplementary Table S1, which reports passing counts at $r \geq 0.7$ and $r \geq 0.9$ as well. All sixteen candidate indices, their formulas, index type (pure ratio versus formula with additive constant), and Pearson r values across each comparison pair at both altitudes are reported in Supplementary Table S1. Fourth, the separability of the four target classes was assessed using linear discriminant analysis (LDA) with leave-one-out cross-validation, implemented with the `lda` function of the MASS package in R, evaluating performance through overall accuracy and the confusion matrix. Discriminant analysis has been previously proven effective for identifying the spectral regions that differentiate mangrove species (Kumar *et al.*, 2019). The operational efficiency of the two flight altitudes was evaluated across eight identically configured missions using five metrics, namely image count, flight duration, total three-step processing time, raw image volume and output product volume. These metrics were extracted from flight logs and Pix4D Mapper log files, averaged by altitude, and normalised per hectare. Missions that failed to produce an acceptable mosaic were recorded separately. The overall workflow is illustrated in Fig. 2.

III. RESULTS AND DISCUSSION

3.1. Changes in mangrove spectral characteristics with flight altitude

Spectral reflectance of the surface classes in the mangrove area was measured across the green, red, red-edge, and NIR bands at the flight

altitudes of 100 m and 150 m. In each band, every class occupied a distinct range of values, with little variation in its mean between the two altitudes (Table 3). Mangrove forest exhibited the highest reflectance in the NIR band. Natural forest reached 0.3122 at 100 m and 0.2785 at 150 m, a difference of 0.0337 or 10.8% (Table 3), whereas the planted forest reached 0.3194 at 100 m and 0.3651 at 150 m (a difference of 0.0458 or 14.3%). For the same forest types, the red band exhibited the lowest reflectance values: 0.0141 at 100 m and 0.0146 at 150 m for the natural forest (a 3.5% difference), and 0.0242 and 0.0253 in the plantation (a 4.5% difference). These results align with the well-established optical properties of vegetation, wherein leaves absorb most red light for photosynthesis and strongly reflect near-infrared radiation, resulting in low red and high NIR reflectance values. Previous reviews on mangrove remote sensing similarly report that canopy reflectance consistently peaks in the NIR region across various sensors (Tran *et al.*, 2022).

Water exhibited the opposite spectral trend, with the highest reflectance occurring in the visible bands. At 100 m and 150 m flight altitudes, green reflectance reached 0.0465 and 0.0585 (a difference of 0.0120 or 25.8%), while red reflectance reached 0.0584 and 0.0792 (0.0208 or 35.6%). In contrast, NIR reflectance dropped to 0.0336 at 100 m and 0.0457 at 150 m (0.0121 or 36.0%). This pattern aligns with the strong absorption of infrared radiation by water bodies, where reflectance decreases steadily from the red band towards longer wavelengths (Jia *et al.*, 2019). Bare land exhibited the highest red reflectance among the four classes, with values of 0.0608 at 100 m and 0.0713 at 150 m (a difference of 0.0105 or 17.3%), corresponding to the exposed dyke and pond banks in the study area. Its NIR reflectance values reached 0.0950 and 0.1175 (a difference of 0.0225 or 23.7%). Overall, the percentage differences across flight altitudes were substantially larger for the background classes than for the forest types.

In the NIR band, the lowest mean reflectance for mangrove forest (0.2785 in the natural forest at 150 m) remained substantially higher than the peak values of bare land (0.1175) and water (0.0457), both recorded at 150 m. Consequently,

the NIR band provided the clearest separation between mangrove forest and non-forest cover across both flight altitudes. This strong infrared contrast between mangroves and adjacent covers also forms the physical basis for satellite

indices designed to discriminate mangroves from water and tidal flats (Zhang *et al.*, 2023). Detailed statistics, including means, standard deviations and coefficients of variation, are provided in Table 3.

Table 3. Band reflectance of the four classes at the two flight altitudes

Altitude	Class	n	Green 560 nm	Red 650 nm	Red edge 730 nm	NIR 860 nm
100 m	Natural forest	45	0.0225 ± 0.0045 (19.8)	0.0141 ± 0.0032 (22.6)	0.0914 ± 0.0090 (9.8)	0.3122 ± 0.0291 (9.3)
	Planted forest	45	0.0405 ± 0.0109 (26.9)	0.0242 ± 0.0087 (35.9)	0.1212 ± 0.0201 (16.6)	0.3194 ± 0.0617 (19.3)
	Bare land	30	0.0439 ± 0.0109 (24.8)	0.0608 ± 0.0200 (32.9)	0.0601 ± 0.0132 (22.0)	0.0950 ± 0.0264 (27.8)
	Water surface	30	0.0465 ± 0.0126 (27.2)	0.0584 ± 0.0139 (23.8)	0.0319 ± 0.0059 (18.7)	0.0336 ± 0.0110 (32.7)
150 m	Natural forest	45	0.0233 ± 0.0041 (17.4)	0.0146 ± 0.0031 (21.5)	0.0916 ± 0.0086 (9.4)	0.2785 ± 0.0222 (8.0)
	Planted forest	45	0.0397 ± 0.0080 (20.1)	0.0253 ± 0.0080 (31.5)	0.1412 ± 0.0119 (8.4)	0.3651 ± 0.0346 (9.5)
	Bare land	30	0.0499 ± 0.0132 (26.5)	0.0713 ± 0.0244 (34.2)	0.0773 ± 0.0220 (28.4)	0.1175 ± 0.0323 (27.5)
	Water surface	30	0.0585 ± 0.0155 (26.4)	0.0792 ± 0.0223 (28.1)	0.0469 ± 0.0087 (18.6)	0.0457 ± 0.0062 (13.5)

Note: mean ± standard deviation; values in parentheses are coefficients of variation (%). CV is not reported for classes where the mean value is negative or where $|mean| < 0.01$, as a ratio of standard deviation to near-zero mean is not interpretable; affected cells are marked '- '.

Table 3 also shows which altitude yielded the more stable reflectance, as measured by the coefficient of variation (CV). For the two forest types, all eight CV values decreased at the 150 m altitude. This stabilization was most pronounced in the planted forest, where the NIR CV declined from 19.3% to 9.5% and the red-edge CV from 16.6% to 8.4%. Similarly, in the natural forest, the NIR CV dropped from 9.3% to 8.0%. These differences in CV were not formally tested for statistical significance; the apparent reduction in CV at 150 m may partly reflect the coarser spatial resolution (larger GSD), which averages more pixels per sample region, or differences in illumination between the two acquisitions. In contrast, the two background classes exhibited no consistent trend: bare land CV increased slightly across three bands, whereas water CV values decreased sharply in the NIR band but increased in the red band. In this study, for both natural and planted mangrove forest types, the 150 m dataset yielded lower CV values than the 100 m dataset;

however, because each altitude was acquired at a different time of day within the same site-campaign combination, this pattern cannot be attributed solely to flight altitude. The spatial distribution of the four bands over the two sites is shown in Fig. 3. The forest canopy is dark in the green and red bands and bright in the NIR band, while channels and exposed banks display the opposite pattern.

Differences between the two flight altitudes were assessed for each sample region using the paired comparison described in Section 2.2, with the results represented in Fig. 4. For the red-edge band in the natural forest and the green band in the plantation, these differences were not statistically significant, as their 95% confidence intervals spanned zero. For the remaining green and red band comparisons across both forest types, differences ranged from only 0.0005 to 0.0011, negligible relative to the magnitude of reflectance values. Instead, altitude-related differences were concentrated in the plantation red-edge band (+0.0200; 95% CI:

[0.0152, 0.0248]) and in the NIR band, reaching -0.0337 [-0.0382, -0.0291] in the natural forest and +0.0458 [0.0315, 0.0600] in the plantation. The two sites shifted in opposite directions, indicating that this response is not a systematic effect of flight altitude, but rather is tied to mission-specific factors. This outcome aligns with the acquisition timing of the four November missions: the plantation was surveyed in the late afternoon, whereas the natural forest was flown in the morning. Furthermore, within each site, the two altitudes were flown at different times, resulting in distinct illumination conditions for each mission. Illumination geometry is well recognised as a major factor influencing surface reflectance in multispectral UAV imagery (Stow *et al.*, 2019). The absolute NIR differences between altitudes observed in this study therefore reflect contributions from factors other than altitude alone. Crucially for class

separability, these shifts did not obscure class boundaries: in the NIR band, the spectral distance between mangrove forest and bare land reached 0.2172 at 100 m and 0.1610 at 150 m, three and a half to nearly five times the largest altitude-related difference. Consequently, within the flights surveyed, altering flight altitude in the 100 to 150 m range shifted absolute NIR values but did not substantially compromise the separability between forest cover and non-forest background classes.

Multispectral UAV imagery thus provides detailed spectral characteristics of the surface classes in mangrove ecosystems and effectively supports discriminating mangrove forest from the other land cover classes. The NIR band differentiates mangrove forest from bare land and water most clearly across flight altitudes, while the 150 m dataset was associated with lower within-class CV under the illumination conditions of this study.

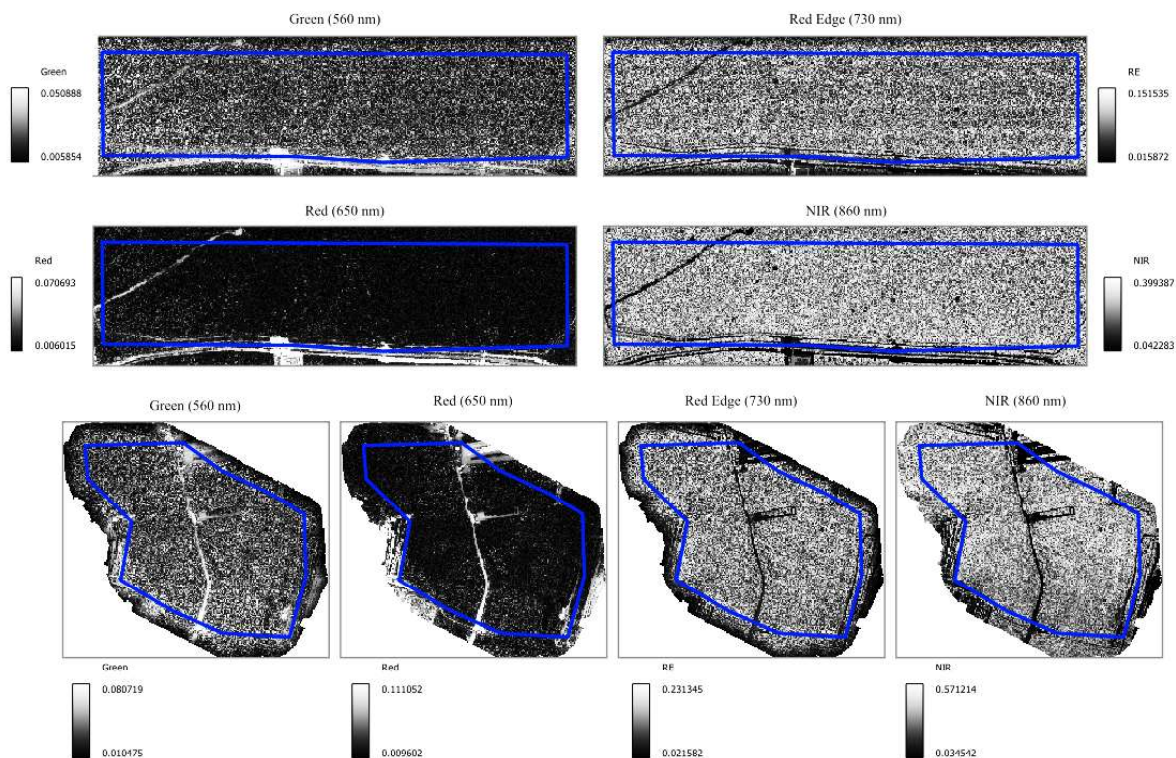


Fig. 3. Spatial distribution of spectral reflectance across the green, red, red-edge, and NIR bands for the natural forest (upper) and the plantation (lower) at a flight altitude of 150 m (November 2025), processed using Case A (panel + sunlight sensor calibration). Blue polygons delineate the analysis boundaries.

Fig. 4 presents these values as spectral curves. Panels (a) and (b) display each flight altitude separately, with one line per class connecting the four band values along with standard deviation bars. Panel (c) overlays both altitudes on the same axes (solid lines for 100 m, dashed

lines for 150 m); class curves nearly coincide in the green and red bands, diverging distinctly only in the red-edge and NIR bands for the plantation. Panel (d) illustrates the paired difference between the two altitudes for each band and class.

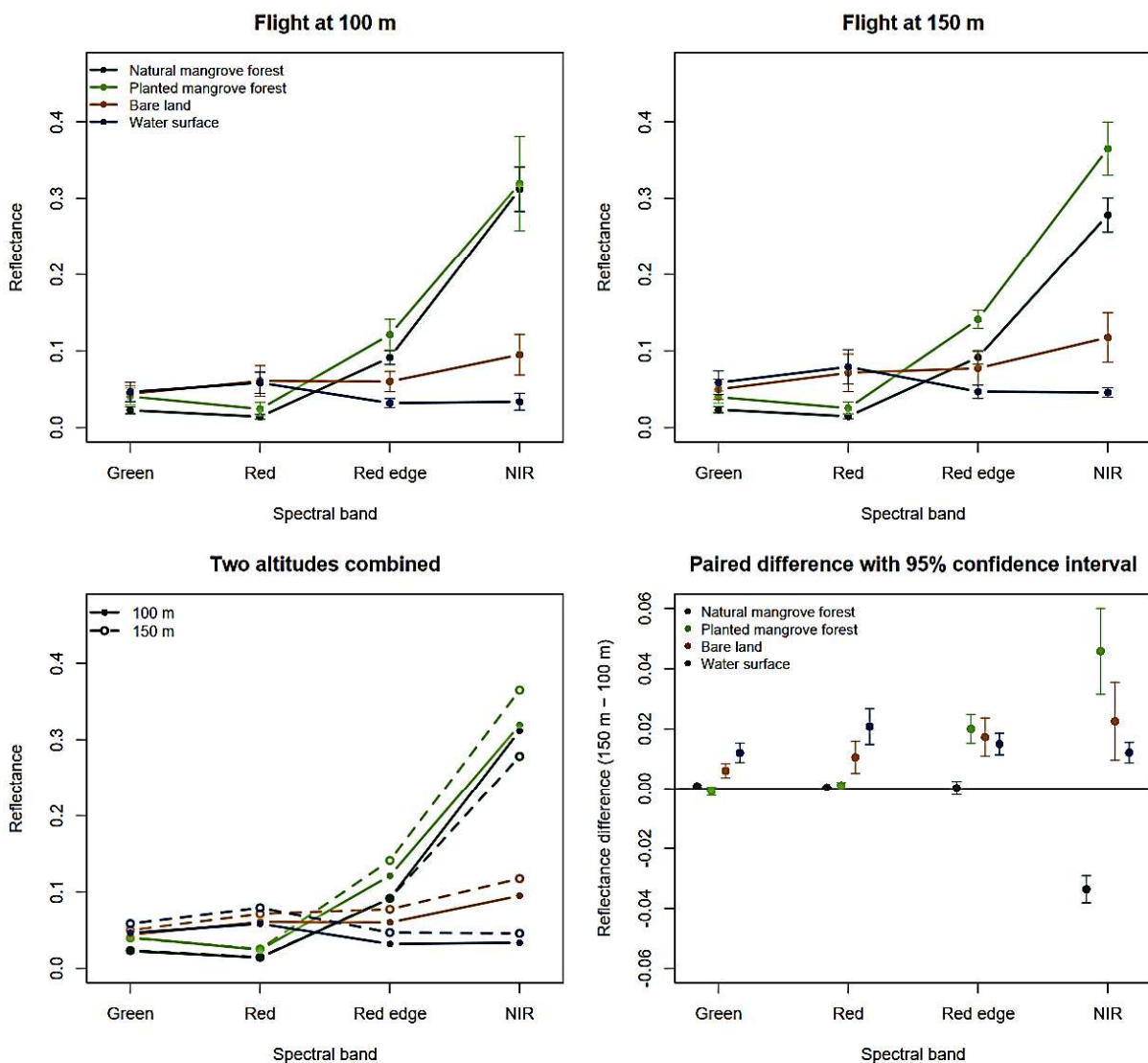


Fig. 4. Spectral reflectance curves of the four land covers: (a) 100 m flight altitude; (b) 150 m flight altitude; (c) both comparison of both altitudes (solid lines for 100 m and dashed lines for 150 m); (d) paired differences between the two altitudes with 95% confidence intervals. Error bars in (a) and (b) represent standard deviations

3.2. Separability of the observed classes by flight altitude

Class separability across the four classes was evaluated using Linear Discriminant Analysis

(LDA) on each sample region. A leave-one-out cross-validation approach was applied. The model was trained on 149 labelled sample regions to classify the remaining one, repeating

this process for all 150 sample regions separately at each altitude. Predicted labels were then compared with ground-truth classes to evaluate classification accuracy (Table 4). LDA assumes multivariate normality within classes and homogeneity of within-class covariance matrices. These assumptions were not formally tested in this study due to the small within-class sample size relative to the predictor dimensionality; this is acknowledged as a methodological limitation. Authors should consider testing these assumptions using Mardia's multivariate normality test and Box's M test in subsequent analyses.

At a flight altitude of 100 m, the model correctly classified 135 of the 150 regions, achieving an overall accuracy (OA) of 90.0% with a Cohen's Kappa coefficient of 0.865. At 150 m, performance improved to 144 correctly classified regions out of 150, corresponding to

an OA of 96.0% with a Kappa of 0.946 (Table 4). McNemar's test (Fody, 2004) comparing the paired classification outcomes at the two altitudes yielded $\chi^2(1)=7.11$, $p = 0.008$ with continuity correction (exact binomial $p = 0.004$): of the 15 regions misclassified at 100 m, nine were correctly classified at 150 m, whereas no region was classified correctly at 100 m but incorrectly at 150 m. This indicates a statistically significant difference in classification accuracy between altitudes under the illumination conditions of this study. High classification performance was achieved at both altitudes. The higher accuracy observed at 150 m is consistent with the lower CV reported in Section 3.1, under the illumination conditions of these missions; a causal attribution to altitude alone would require replication with matched illumination.

Table 4. Classification accuracy of the four classes at the two flight altitudes

Flight altitude	n	Correctly assigned	Misassigned	OA (%)	Kappa
100 m	150	135	15	90.0	0.865
150 m	150	144	6	96.0	0.946

In this study, 90 sample plots were established to investigate mangrove structure and to conduct spectral analysis. Additionally, 60 sample regions were designated for water, bare land, and wet land areas (Table 5). These

regions were clearly delineated based on UAV RGB imagery and field surveys at each flight altitude (100 m and 150m) to construct the confusion matrix for the LDA classification with leave-one-out cross-validation (Table 5).

Table 5. Confusion matrix of the LDA classification with leave-one-out cross-validation

Altitude	Reference\Predicted	Natural forest	Planted forest	Bare land	Water surface	Total
100 m	Natural forest	43	2	0	0	45
	Planted forest	5	40	0	0	45
	Bare land	1	0	29	0	30
	Water surface	0	0	7	23	30
150 m	Natural forest	44	1	0	0	45
	Planted forest	0	45	0	0	45
	Bare land	1	0	29	0	30
	Water surface	0	0	4	26	30

As indicated in Table 5, at a 100 m flight altitude, five planted-forest sample plots were misclassified as natural forest and two natural-forest sample plots as planted forest. At 150 m, only a single misclassification remained (a natural forest plot assigned to planted forest). Regarding the non-forest categories, seven and four water sample regions were misclassified as bare land at 100 m and 150 m, respectively. Aside from these two main sources of confusion, each altitude contained only one additional error, in which a bare-land sample region was misclassified as natural forest.

Assessments of class accuracies, expressed as producer's accuracy (PA) and user's accuracy (UA), were derived directly from the confusion matrix (Table 5). Water recorded the lowest PA (76.7% at 100 m and 86.7% at 150 m) but a UA of 100% at both altitudes. In other words, the model omitted part of the water surface, yet every sample region assigned to water was indeed water, producing no commission errors. Bare land exhibited the inverse pattern, achieving a high PA of 96.7% at both altitudes, but lower UA of 80.6% (100 m) and 87.9% (150 m) due to commission errors from misassigned

water regions. Notably, both forest types achieved high accuracy, with PA and UA exceeding 87.8% at 100 m and reaching at least 97.8% at 150 m.

Both points of confusion can be explained by specific site characteristics. The spectral confusion between the two forest types aligns with the stand descriptions in Table 1: *Rhizophora* dominates both sites, resulting in similar foliar optical properties. Consequently, the primary distinction lies in canopy structure, which appeared to be captured more clearly in the 150 m imagery of this study. The confusion of water with bare land most likely originates from transitional surfaces, such as shallow water over mud at the forest edge and moist accreting flats; all such errors run in one direction, from water to bare land, consistent with shallow water having higher NIR reflectance than deep water and approaching that of moist soil. Fig. 5 shows the 150 sample regions in the red-NIR reflectance plane: the two forest clusters lie well separated at the top, while the water and bare-land clusters lie close together at the bottom, matching where the classification errors occur.

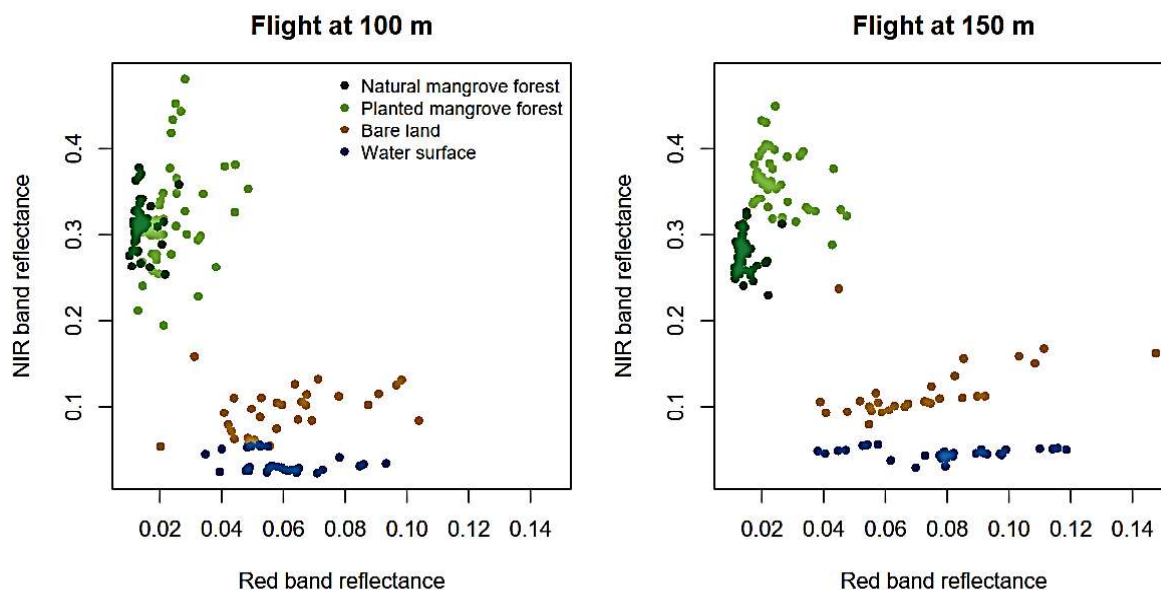


Fig. 5. Distribution of the 150 sample regions in the red-NIR reflectance plane at the two flight altitudes

The four-class accuracy of this study is comparable to published UAV mangrove classifications: species classification reached an overall accuracy of about 81.0% with multispectral and above 97% with hyperspectral imagery (Yang *et al.*, 2024), 89.9% when combining spectral, structural and textural features from five-band multispectral imagery (Chen *et al.*, 2026), 91.1% with object-based analysis at Dong Rui (Ngo *et al.*, 2024), and higher when hyperspectral data were combined with LiDAR (Cao *et al.*, 2021). It should be noted, however, that those studies addressed species-level classification, a considerably more demanding task than the separation of four basic land-cover classes performed here; direct comparison of accuracy figures should therefore be made with caution. Within this simpler task, the four bands of this platform met the requirement of distinguishing mangrove forest from the adjacent classes, and the 150 m results were somewhat better across all four classes.

3.3. Vegetation index characteristics of the mangrove forest

The four vegetation indices, NDVI, GNDVI, C_{Igreen} and NDRE, were computed from the reflectance of each sample region separately for each altitude, following Section 2.2. The results are presented in Table 6 and Fig. 6. For all four indices, the two forest types separated clearly

from the two background classes, and a consistent trend emerged: the natural forest showed higher index values than the planted forest for all four indices at both altitudes, while between-altitude differences within each forest type remained small relative to the differences between classes. NDVI for the natural forest reached 0.913 at 100 m and 0.900 at 150 m (a 1.4% difference), while the plantation reached 0.859 and 0.869 (a 1.2% difference). Bare land reached only 0.220 and 0.249, whereas water remained negative at -0.270 and -0.247. GNDVI and NDRE exhibited a similar trend, with between-altitude differences for the forest types not exceeding 0.042; the largest variation was 7.6% for NDRE in the natural forest. C_{Igreen} varied most with altitude, reaching 13.261 and 11.192 in the natural forest (a 15.6% difference) and 7.239 and 8.566 in the plantation (an 18.3% difference). This may occur because C_{Igreen} is a non-normalised ratio that propagates nearly all of the NIR variation noted in Section 3.1 directly into the index, whereas the normalised indices cancel much of it. The NDVI coefficient of variation for the natural and planted forest was only 2.2% and 5.3%, respectively, at 100 m, compared to 69.8% for bare land and 71.7% for water, demonstrating that index values over mangrove canopy are far more homogeneous than over the background surfaces.

Table 6. Vegetation indices of the four land cover classes at the two flight altitudes

Altitude	Class	n	NDVI	GNDVI	C _{Igreen}	NDRE
100 m	Natural forest	45	0.913 ± 0.020 (2.2)	0.865 ± 0.026 (3.0)	13.261 ± 2.280 (17.2)	0.547 ± 0.031 (5.6)
	Planted forest	45	0.859 ± 0.045 (5.3)	0.773 ± 0.055 (7.1)	7.239 ± 1.927 (26.6)	0.447 ± 0.051 (11.4)
	Bare land	30	0.220 ± 0.154 (69.8)	0.358 ± 0.125 (34.9)	1.235 ± 0.668 (54.1)	0.217 ± 0.086 (39.5)
	Water surface	30	-0.270 ± 0.193 (71.7)	-0.158 ± 0.249	-0.146 ± 0.649	0.012 ± 0.129
150 m	Natural forest	45	0.900 ± 0.022 (2.5)	0.845 ± 0.026 (3.1)	11.192 ± 1.759 (15.7)	0.505 ± 0.027 (5.4)
	Planted forest	45	0.869 ± 0.046 (5.3)	0.802 ± 0.045 (5.6)	8.566 ± 2.048 (23.9)	0.441 ± 0.037 (8.4)
	Bare land	30	0.249 ± 0.123 (49.5)	0.401 ± 0.083 (20.8)	1.420 ± 0.636 (44.8)	0.208 ± 0.051 (24.5)
	Water surface	30	-0.247 ± 0.166 (67.5)	-0.107 ± 0.170	-0.143 ± 0.339	-0.009 ± 0.085

Note: mean ± standard deviation; values in parentheses are coefficients of variation (%). CV is not reported for classes where the mean value is negative or where $|mean| < 0.01$, as a ratio of standard deviation to near-zero mean is not interpretable; affected cells are marked '-'.

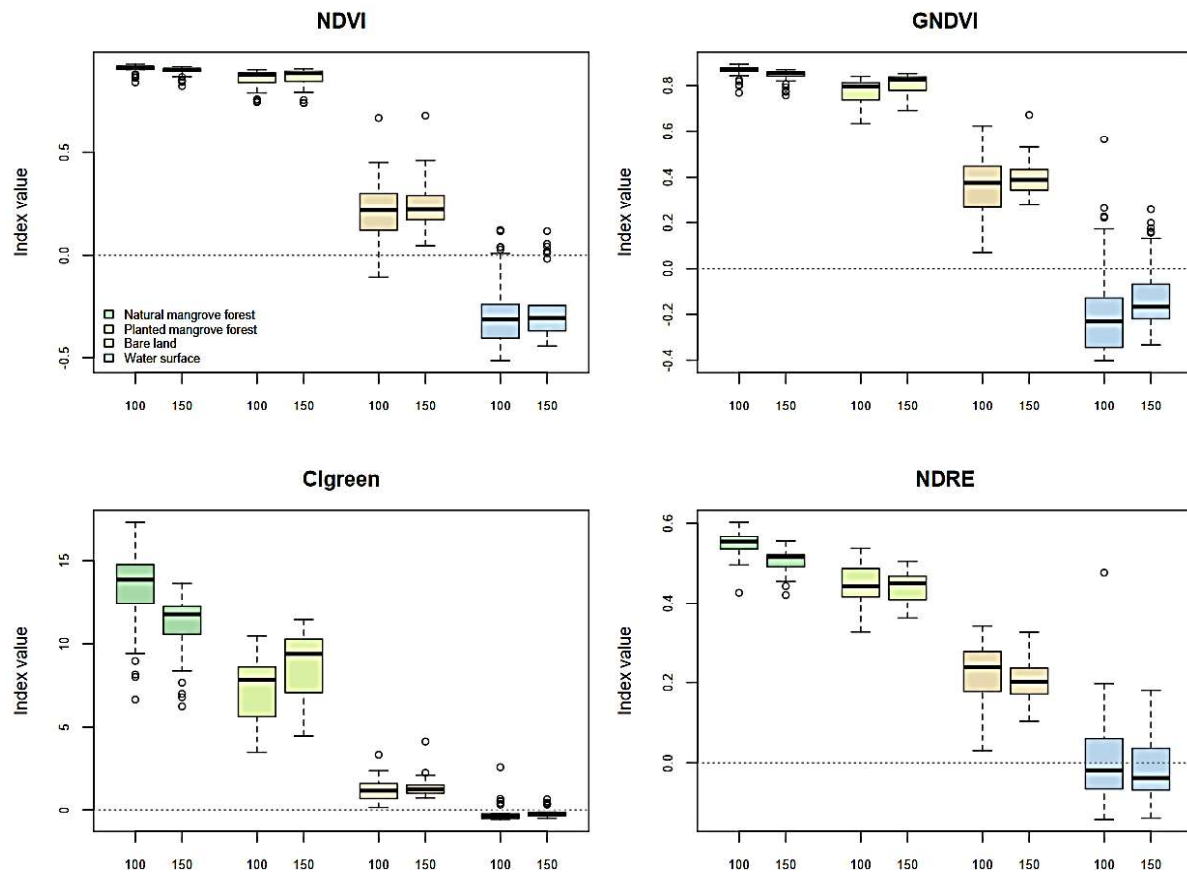


Fig. 6. Distribution of the four vegetation indices of the four land-cover classes at the two flight altitudes

Compared with the two domestic multispectral UAV studies, the index values of the *Rhizophora*-dominated canopies of both forest types in Ca Mau are notably high. In the estuarine Dong Rui mangroves of Quang Ninh province, where mangrove tree height ranges from 1.0 to 5.3 m (Ngo *et al.*, 2023), Ngô Trung Dũng (2024) reported a mean summer NDVI of 0.77, winter NDVI of 0.684, GNDVI of 0.62 and 0.59, and a mean GCI of 3.53 across 50 sample points. The corresponding Ca Mau values are consistently higher (NDVI: 0.859 to 0.913, GNDVI: 0.773 to 0.865, and CIgreen: 7.239 to 13.261), which aligns with the taller (9.8 to 15.3 m) and almost continuously closed *Rhizophora* stands of this study area. In the closed evergreen forest of Kon Chu Rang Nature Reserve in the Central Highlands, Đinh Bá Duy *et al.* (2022) observed that 80.99% of the area had an NDVI between 0.8 and 1.0, while 58.91% had a GCI

between 5 and 10. The NDVI values for both Ca Mau forest types fall within this same NDVI range. Similarly, the CIgreen of the Ca Mau plantation lies within 5 to 10, whereas that of the natural forest is higher at 13.261.

Information overlap among the four indices was evaluated using the Pearson correlation coefficients computed within each forest class, ensuring that the coefficients were not inflated by between-class distances (Table 7). The three visible-band indices were strongly correlated (ranging from 0.911 to 0.982), indicating significant information overlap. Within this group, the NDVI-CIgreen pair showed the lowest correlation, at 0.961 in the natural forest and 0.911 in the plantation. In contrast, NDRE showed a remarkably lower correlation with NDVI, yielding values of 0.821 and 0.769, respectively. The direction of these relationships agrees with the two domestic studies, where the

NDVI-GCI pair was also among the weakest ($r = 0.74$ at Kon Chu Rang, and 0.670 to 0.686 at Dong Rui). Because both studies computed correlations over points scattered across the entire flight area, their values are not directly comparable with the within-class figures reported here; nevertheless, the general direction of the relationships remains consistent. Đinh Bá Duy *et al.* (2022) suggested that for UAV imagery over dense forest cover, NDVI alone may suffice. The Ca Mau data support this within the visible-band group. However, NDRE, which utilises the red-edge band, provides complementary information not captured by NDVI and is therefore retained for characterising mangrove canopy (noting the 15 nm offset between panel characterisation and sensor band centre in the red-edge calibration). This aligns with the recognised role of the red-edge spectral region reported in mangrove monitoring: in high-biomass stands, NDVI typically saturates around 0.86, whereas red-edge indices still resolve variations in canopy conditions (Karang, Basheer Ahammed, 2026). The NDVI values observed over the Ca Mau *Rhizophora* canopy (0.859 to 0.913) lie squarely within this saturation zone.

Table 7. Pearson correlation coefficients among the four vegetation indices within each forest class at an altitude of 100 m. The upper triangle represents natural forest, and the lower triangle represents plantation).

	NDVI	GNDVI	Cgreen	NDRE
NDVI	1.0	0.982	0.961	0.821
GNDVI	0.948	1.0	0.976	0.886
Cgreen	0.911	0.979	1.0	0.887
NDRE	0.769	0.898	0.901	1.0

The four indices thus reflect two distinct information groups regarding the forest canopy: the visible-band group (NDVI, GNDVI and Cgreen), and the red-edge-based group represented by NDRE. The index values of the Ca Mau *Rhizophora* canopy are high relative to published domestic values for estuarine mangroves, reaching a magnitude comparable to the values reported for the closed evergreen forest at Kon Chu Rang Nature Reserve (Đinh Bá Duy *et al.*, 2022).

The spatial patterns of the four indices across the two sites are shown in Fig. 7. Index values are high and homogeneous over the closed canopy, whereas channels, roads and canopy gaps appear as sharply lower values.

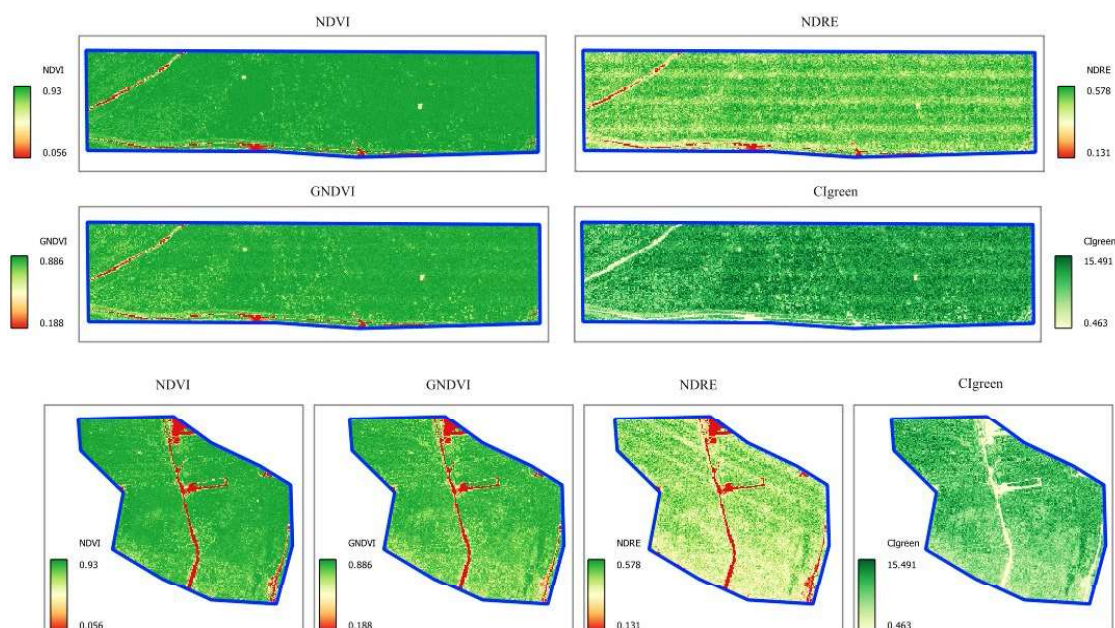


Fig. 7. Spatial distribution of the four vegetation indices (NDVI, GNDVI, NDRE and Cgreen) across the natural forest (top) and the plantation (bottom) at an altitude of 150 m, November 2025. All index values are derived from Case A (panel-calibrated) reflectance orthomosaics.

3.4. Role of the reflectance panel and flight efficiency

When the November imagery was reprocessed without the reflectance panel (Case B of Section 2.2), reflectance over forest canopy decreased by factors of 11.2 to 18.5 relative to the panel-calibrated dataset (the minimum reduction of $11.2\times$ was recorded in the red-edge band for the natural forest at 100 m; the maximum of $18.5\times$ was recorded in the green band for the plantation at 150 m; see Supplementary Table S2). Consequently, absolute reflectance values processed without the panel cannot be compared across campaigns. Screening the sixteen vegetation indices by the criterion of Section 2.2 showed that nine indices, all purely ratio-based without an additive constant, retained Pearson correlations of at least 0.8 across all four comparison pairs at 150 m (see Methods, Section 2.2), compared to six indices at 100 m. The full per-index r values and the pass/fail classification at both altitudes are presented in

Supplementary Table S1. All nine indices passing at 150 m are pure ratios (no additive constant), confirming that ratio form is the primary determinant of index stability across calibration cases. Among the four spectral bands, the red band varied the most between seasons, whereas the red-edge band was the most stable.

Across the eight missions of identical configuration, flying at 100 m consumed 1.75 to 1.97 times the resources of 150 m across all five metrics defined in Section 2.2 (the number of images, flight time, three-step processing time, raw image volume, and product volume; Table 8). However, the spectral stability and classification results of Sections 3.1 and 3.2 show no evidence of a data-quality advantage at 100 m under the illumination conditions of this study. Furthermore, operating at 150 m allows each site to be surveyed in fewer missions within a narrower time window, maintaining more homogeneous illumination across the image block.

Table 8. Mean acquisition and processing resources per mission at the two flight altitudes.

Metric (mean per mission)	100 m	150 m	Ratio 100 m/150 m
Number of raw images	5,377	2,800	1.92
Flight time (min)	36.8	18.7	1.97
Three-step processing time (min)	338.2	193.5	1.75
Raw image volume (GB)	49.7	25.6	1.94
Output product volume (GB)	15.5	8.8	1.78

Note: means across the eight identically configured missions; processing time and output product volume are averaged over missions that passed mosaic quality control (three at 100 m, four at 150 m).

IV. CONCLUSION

Four-band reflectance in the green, red, red-edge and NIR bands derived from DJI Mavic 3 Multispectral imagery was highly stable within each flight at both altitudes (100 m and 150 m). The NIR and red-edge bands provided the clearest separation between mangrove forest and water, and the four-class classification reached overall accuracies of 90.0% at 100 m and 96.0% at 150 m. Furthermore, the four vegetation indices (NDVI, GNDVI, NDRE and CIgreen) consistently captured the differences between

the planted and natural forest, aligning with previous studies using similar UAV platforms in Vietnam (Đinh Bá Duy *et al.*, 2022).

The reflectance panel determines the absolute scale of the radiometric data: reprocessing without the panel caused canopy reflectance to decrease by factors of 11.2 to 18.5, making absolute comparisons between campaigns impossible. Nevertheless, nine purely ratio-based indices retained correlations of at least 0.8 with the calibrated dataset at 150 m, and six at 100 m. Among the bands, the red band varied most

between seasons, whereas the red-edge band was the most stable. Given that many domestic UAV studies omit radiometric calibration panels (Ngo Trung Dung, 2024), this screening offers a provisional, site-specific guide to index selection in uncalibrated scenarios.

In terms of efficiency, flying at 150 m consumed roughly half the resources of 100 m across every stage, from image count and flight time to processing duration and storage, with 100 m requiring 1.75 to 1.97 times the resources of 150 m (Table 8). Crucially, spectral quality metrics and classification performance at 150 m were not lower than at 100 m under the conditions of this study. Operating at higher altitudes also allows the same area to be covered in fewer flights within a tighter time window, resulting in more homogeneous illumination across the image block. This aligns with the finding by Dandois *et al.* (2015), who demonstrated that within typical altitude ranges, flight altitude is less decisive for data quality than image overlap and illumination conditions. A trade-off should nevertheless be noted: the coarser ground sampling distance at 150 m may limit the detection of fine-scale features such as small canopy gaps or individual crowns, so the choice of flight altitude should also reflect the level of spatial detail required.

UAV imagery provides high-resolution, reliable data when processed with proper radiometric calibration. In mangrove forests, however, the muddy tidal flats and boat-based logistics make deploying and photographing a calibration panel before and after each mission exceptionally challenging. Consequently, most UAV mangrove studies, particularly in Vietnam, do not utilize or report the use of radiometric calibration panels. This study has several limitations. First, the May campaign lacked calibrated data, preventing a direct inter-seasonal comparison. Additionally, LDA assumptions of multivariate normality and covariance homogeneity were not formally verified; results should be interpreted as descriptive classification performance metrics rather than outputs of a validated statistical model. Second, each site-altitude combination

was surveyed in only a single mission, limiting replication at the mission level. Furthermore, the leave-one-out cross-validation procedure does not account for spatial autocorrelation among adjacent sample regions within a site; accuracy estimates may therefore be optimistic. A spatial block cross-validation, in which all sample regions from one site are withheld simultaneously, would provide a more conservative estimate of classification accuracy. The CV-based assessment of spectral homogeneity in Section 3.1 was not validated by formal variance-equality tests; the reported differences may partly reflect resolution-related pixel averaging or illumination differences rather than an altitude effect per se. The panel characterisation wavelengths did not precisely match the sensor band centres; potential systematic biases in the red-edge band in particular were not quantified. Finally, flights were not repeated across different times of day to more thoroughly evaluate illumination effects. Because the eight missions spanned different times of day (from early morning to late afternoon), absolute comparisons between flight altitudes are tied to specific mission pairs and require verification through repeated flights under matched illumination conditions. The study also lacked ground spectrometer measurements to serve as an independent reference. Consequently, it was not possible to determine which processing configuration produced greater absolute radiometric accuracy. This distinction is critical because low-cost multispectral sensors are prone to saturation in the visible bands and can deviate in the red-edge indices compared to hyperspectral data (Cottrell *et al.*, 2024). Based on the single-mission design of this study, the study recommends operating at 150 m with a radiometric calibration panel when absolute reflectance or accurate vegetation indices are required; this recommendation should be verified through replicated flights under matched illumination conditions before wider adoption. Where panel deployment is unfeasible, relative monitoring should rely on the screened set of purely ratio-based indices. Future work should apply this index set as predictor variables for estimating mangrove biomass and carbon

stocks as well as validating the workflow across other relevant mangrove ecosystems.

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REFERENCES

1. Cao, J., Leng, W., Liu, K., Liu, L., He, Z. and Zhu, Y., 2021. Combining UAV-based hyperspectral and LiDAR data for mangrove species classification using the rotation forest algorithm. *International Journal of Applied Earth Observation and Geoinformation* 102: 102414. DOI: 10.1016/j.jag.2021.102414.
2. Chen, Y., Shen, X., Yan, C., Jiang, B., Li, R. and Chai, M., 2026. Triple-feature fusion from UAV multispectral imagery enhances species-level mangrove carbon assessment. *Scientific Reports* 16: 11494. DOI: 10.1038/s41598 - 026 - 40303 - 1.
3. Cottrell, B., Kalacska, M., Arroyo-Mora, J.-P., Lucanus, O., Inamdar, D., Løke, T. and Soffer, R.J., 2024. Limitations of a multispectral UAV sensor for satellite validation and mapping complex vegetation. *Remote Sensing* 16(13): 2463. DOI: 10.3390/rs16132463.
4. Dandois, J.P., Olano, M. and Ellis, E.C., 2015. Optimal altitude, overlap, and weather conditions for computer vision UAV estimates of forest structure. *Remote Sensing* 7(10): 13895 - 13920. DOI: 10.3390/rs71013895.
5. Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience* 4(5): 293 - 297. DOI: 10.1038/ngeo1123.
6. Đinh Bá Duy, Ngô Trung Dũng, Nguyễn Quốc Khánh, Trần Thị Nhân, Nguyễn Hữu Việt Hiểu, Đặng Thị Ngọc, 2022. Xác định một số chỉ số thực vật đặc trưng cho hệ sinh thái rừng tại Khu Bảo tồn thiên nhiên Kon Chư Răng bằng dữ liệu ảnh UAV đa phổ. *Tạp chí Khoa học và Công nghệ nhiệt đới* 29: 23 - 31. DOI: 10.58334/vrtc.jst.n29.03.
7. Foody, G.M., 2004. Thematic map comparison: evaluating the statistical significance of differences in classification accuracy. *Photogrammetric Engineering & Remote Sensing* 70(5): 627 - 633. DOI: 10.14358/PERS.70.5.627.
8. Gitelson, A.A. and Merzlyak, M.N., 1994. Spectral reflectance changes associated with autumn senescence of *Aesculus hippocastanum* L. and *Acer platanoides* L. leaves. *Journal of Plant Physiology* 143(3): 286 - 292. DOI: 10.1016/S0176 - 1617(11)81633 - 0.
9. Gitelson, A.A., Kaufman, Y.J. and Merzlyak, M.N., 1996. Use of a green channel in remote sensing of global vegetation from EOS-MODIS. *Remote Sensing of Environment* 58(3): 289 - 298. DOI: 10.1016/S0034 - 4257(96)00072 - 7.
10. Gitelson, A.A., Gritz, Y. and Merzlyak, M.N., 2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *Journal of Plant Physiology* 160(3): 271 - 282. DOI: 10.1078/0176 - 1617 - 00887.
11. Jia, M., Wang, Z., Mao, D., Ren, C., Wang, C. and Wang, Y., 2019. A new vegetation index to detect periodically submerged mangrove forest using single-tide Sentinel-2 imagery. *Remote Sensing* 11(17): 2043. DOI: 10.3390/rs11172043.
12. Karang, I.W.G.A. and Basheer Ahammed, K.K., 2026. Narrowband red-edge indices effectively monitor species-level mangrove health in multisensor time series. *ICES Journal of Marine Science* 83(6): fsag093. DOI: 10.1093/icesjms/fsag093.
13. Kumar, T., Dutta, D., Chatterjee, D., Chandrasekar, K., Rao, G.S. and Raj, U., 2019. Different statistical methods for the discrimination of tropical mangrove species using in-situ hyperspectral data. *Journal of Hyperspectral Remote Sensing* 9(2): 49 - 67. DOI: 10.29150/jhrs.v9.2.p49 - 67.
14. Li, Y., Guo, S., Jia, S., Yan, Y., Jia, H. and Zhang, W., 2025. Quantifying the effects of UAV flight altitude on the multispectral monitoring accuracy of soil moisture and maize phenotypic parameters. *Agronomy* 15(9): 2137. DOI: 10.3390/agronomy15092137.
15. Li, Z., Zan, Q., Yang, Q., Zhu, D., Chen, Y. and Yu, S., 2019. Remote estimation of mangrove aboveground carbon stock at the species level using a low-cost unmanned aerial vehicle system. *Remote Sensing* 11(9): 1018. DOI: 10.3390/rs11091018.

16. Linh, T.V.K. and Vinh, T.V., 2025. Estimating biomass and above-ground carbon stocks of mangrove forests by using unmanned aerial systems (Southern Vietnam). IOP Conference Series: Earth and Environmental Science 1465: 012009. DOI: 10.1088/1755 - 1315/1465/1/012009.
17. Luo, S., Jiang, X., Yang, K., Li, Y. and Fang, S., 2022. Multispectral remote sensing for accurate acquisition of rice phenotypes: impacts of radiometric calibration and unmanned aerial vehicle flight altitudes. *Frontiers in Plant Science* 13: 958106. DOI: 10.3389/fpls.2022.958106.
18. Navarro, J.A., Algeet, N., Fernández-Landa, A., Esteban, J., Rodríguez-Noriega, P. and Guillén-Climent, M.L., 2019. Integration of UAV, Sentinel-1, and Sentinel-2 data for mangrove plantation aboveground biomass monitoring in Senegal. *Remote Sensing* 11(1): 77. DOI: 10.3390/rs11010077.
19. Ngo, D.T., Nguyen, H.D., Nguyen, K.Q., Dang, C.H., Nguyen, H.H.V., Dang, N.T. and Pham, T.V., 2023. Application of multispectral UAV to estimate mangrove biomass in Vietnam: A case study in Dong Rui commune, Quang Ninh Province. *One Ecosystem* 8: e103760. DOI: 10.3897/oneeco.8.e103760.
20. Ngo, D.T., Nguyen, H.H.V., Nguyen, B.T.T. and Dang, N.T., 2024. Protocol for establishing a map of mangrove species distribution using multispectral unmanned aerial vehicle data. *STAR Protocols* 5(4): 103425. DOI: 10.1016/j.xpro.2024.103425.
21. Ngo Trung Dung, 2024. Assessing the characteristics and seasonal changes of mangrove forest in Dong Rui commune, Quang Ninh province, Vietnam based on multispectral UAV data. *Landscape and Ecological Engineering* 20(2): 223 - 235. DOI: 10.1007/s11355 - 024 - 00595 - 9.
22. Otero, V., Van De Kerchove, R., Satyanarayana, B., Martínez-Espinosa, C., Fisol, M.A.B., Ibrahim, M.R.B., Sulong, I., Mohd-Lokman, H., Lucas, R. and Dahdouh-Guebas, F., 2018. Managing mangrove forests from the sky: forest inventory using field data and Unmanned Aerial Vehicle (UAV) imagery in the Matang Mangrove Forest Reserve, peninsular Malaysia. *Forest Ecology and Management* 411: 35 - 45. DOI: 10.1016/j.foreco.2017.12.049.
23. Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W., 1974. Monitoring vegetation systems in the Great Plains with ERTS. *NASA Special Publication* 351: 309 - 317.
24. Seifert, E., Seifert, S., Vogt, H., Drew, D., van Aardt, J., Kunneke, A. and Seifert, T., 2019. Influence of drone altitude, image overlap, and optical sensor resolution on multi-view reconstruction of forest images. *Remote Sensing* 11(10): 1252. DOI: 10.3390/rs11101252.
25. Stow, D., Nichol, C.J., Wade, T., Assmann, J.J., Simpson, G. and Helfter, C., 2019. Illumination geometry and glying height influence surface reflectance and NDVI derived from multispectral UAS imagery. *Drones* 3(3): 55. DOI: 10.3390/drones3030055.
26. Sumarga, E., Syamsudin, T.S., Sarah, S., Qalbi, M.P., Tansy, B.C., Basyuni, M. and Larekeng, S.H., 2026. Mapping aboveground carbon in rehabilitated mangrove: evaluating the performance of regression modelling with satellite-derived vegetation indices and kriging interpolation. *Journal of Multidisciplinary Applied Natural Science* 6(1): 108 - 120. DOI: 10.47352/jmans.2774 - 3047.311.
27. Tran, T.V., Reef, R. and Zhu, X., 2022. A review of spectral indices for mangrove remote sensing. *Remote Sensing* 14(19): 4868. DOI: 10.3390/rs14194868.
28. Wang, T., Guan, T., Qiu, F., Liu, L., Zhang, X., Zeng, H. and Zhang, Q., 2025. Evaluation of scale effects on UAV-based hyperspectral imaging for remote sensing of vegetation. *Remote Sensing* 17(6): 1080. DOI: 10.3390/rs17061080.
29. Yang, Y., Meng, Z., Zu, J., Cai, W., Wang, J., Su, H. and Yang, J., 2024. Fine-scale mangrove species classification based on UAV multispectral and hyperspectral remote sensing using machine learning. *Remote Sensing* 16(16): 3093. DOI: 10.3390/rs16163093.
30. Zhang, H., Xia, Q., Dai, S., Zheng, Q., Zhang, Y. and Deng, X., 2023. Mangrove forest mapping from object-oriented multi-feature ensemble classification using Sentinel-2 images. *Frontiers in Marine Science* 10: 1243116. DOI: 10.3389/fmars.2023.1243116.

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