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King Abdullah University of Science and Technology

Cross-Platform Analysis of Land Cover Using UAV, SkySat, and Sentinel-2 Imagery

KAUST Academy Water Sustainability Program

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Abstract

This report compares land-cover NDVI derived from UAV, SkySat, and Sentinel-2 imagery at the King Abdullah Monument site at KAUST. UAV28 and SkySat were acquired on 28 June 2021, and UAV30 and Sentinel-2 on 30 June 2021. The observations were evaluated using an overall mangrove region of interest (ROI), three equal-area mangrove-density ROIs, and land-cover ROIs representing mangroves, seawater, asphalt, and a green surface. Overall mangrove mean NDVI was 0.546 for UAV28, 0.557 for UAV30, 0.352 for SkySat, and 0.206 for Sentinel-2. All platforms preserved the dense > moderate > low mangrove ordering and physically interpretable class signs, but their absolute NDVI values were not interchangeable. Spatial support and mixed pixels are the leading expected contributors, alongside sensor characteristics and acquisition conditions. Supplementary Sentinel-2 index analyses at KAUST1 and KAUST2 and an exploratory four-band MicaSense K-means classification at HUW1 are documented separately and are not pooled with the main-site statistics. Multi-sensor monitoring should therefore use fixed ROIs, harmonized reflectance, explicit uncertainty, and independent validation.

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1 Introduction

Coastal environments contain narrow, heterogeneous land-cover features whose surface reflectance can change substantially. Mangrove crowns, intertidal water, exposed sediment, asphalt, landscaped vegetation, and engineered green surfaces may all occur within the same satellite pixel. This creates a practical challenge: because sensors differ in spatial resolution, central wavelength, and bandwidth, measurements calculated from different satellites may describe the same landscape pattern while producing different absolute reflectance values for the same land-cover class. Understanding this distinction is essential when observations from drones and satellites are compared or combined.

Several optical indices have been developed to characterize vegetation by combining different spectral bands. The Normalized Difference Vegetation Index (NDVI) was selected for this study because it contrasts near-infrared reflectance, which is commonly high for healthy foliage, with red reflectance, which is reduced by chlorophyll absorption. In mangrove research, NDVI has been used to map extent, density, condition, and biophysical properties, but it remains sensitive to canopy structure, soil and water background, tide, atmospheric effects, radiometric calibration, and sensor characteristics [1,2]. NDVI therefore supports comparative interpretation; it is not a sensor-independent measurement of vegetation condition.

A systematic review of mangrove spectral-index research confirmed NDVI as the dominant index while emphasizing sensitivity to environmental background, tide, radiometric calibration, surface reflectance, and canopy density [2]. These effects are especially important in narrow coastal zones, where vegetation and water may coexist within one pixel and small shoreline or geolocation differences can alter the observed mixture.

Multi-platform studies show that higher spatial resolution can reduce background interference and reveal within-canopy variation, but resolution alone does not guarantee more comparable biophysical estimates. Tian et al. compared UAV and WorldView-2 measurements in mangroves and found that platform performance varied with canopy composition and background effects [3]. Guo et al. compared UAV, WorldView-2, and Sentinel-2 red-edge indices for mangrove leaf area index and demonstrated that the relationships depend on both the sensor and the index formulation [4].

Outside mangrove environments, UAV-Sentinel-2 comparisons also report useful agreement in absolute vegetation-index values and local spatial variability [5]. SkySat occupies an intermediate scale: its four-band orthorectified multispectral product is sampled at 0.5 m [6], whereas Sentinel-2 bands B4 and B8 used for NDVI are provided at 10 m [7]. These differences motivate a site-specific comparison rather than a universal sensor conversion.

The primary cross-platform analysis examines the coastal King Abdullah Monument site at King Abdullah University of Science and Technology (KAUST), Saudi Arabia. UAV28 and SkySat were acquired on 28 June 2021, while UAV30 and Sentinel-2 were acquired on 30 June 2021, spanning nominal spatial resolutions of approximately 0.10, 0.5, and 10 m. The wider internship project also included supplementary Sentinel-2 index analyses at sites designated KAUST1 and KAUST2 and an exploratory four-band MicaSense K-means classification at HUW1. These components are reported separately and are not pooled with the main-site NDVI statistics.

The central objective is to determine which NDVI observations are stable across sensors and which are dependent on platform scale and processing. Mangrove was selected as the primary focus because it is the

dominant and most spectrally variable vegetation class at the study site, making it the most sensitive indicator of cross-sensor NDVI consistency; other land-cover classes (water, asphalt, and a green surface) are included as reference targets in question (3) to test class separability more broadly. The analysis addresses four questions: (1) how does overall mangrove NDVI differ among UAV28, UAV30, SkySat, and Sentinel-2; (2) do dense, moderate, and low mangrove-density areas retain the same relative ordering of NDVI values across all platforms; (3) can mangroves, water, asphalt, and a green surface be separated consistently; and (4) what limitations must be considered before multi-sensor NDVI values are treated as interchangeable?

Working interpretation The report distinguishes between pattern agreement and value agreement. Different sensing platforms can preserve the same ranking among land-cover classes while reporting a different numerical NDVI scale.

2 Materials and Methods

2.1 Study area

The primary quantitative study area surrounds the King Abdullah Monument at KAUST on the eastern coast of the Red Sea, Saudi Arabia. It includes a mangrove stand, shallow coastal water, paved roads, landscaped vegetation, exposed ground, and a green artificial surface. This compact mixture provides clear spectral contrasts but also creates strong edge effects at coarser spatial resolution. The comparison used a common geographic region of interest (ROI) wherever coverage permitted, supplemented by manually defined land-cover and mangrove-density polygons (Figure 1). The supporting KAUST1 and KAUST2 sites were used only for separate Sentinel-2 NDVI/GNDVI summaries, while HUW1 was used for the exploratory K-means classification. Because their objectives, sensors, and sampling definitions differ, results from those sites are not combined with the main cross-platform comparison.

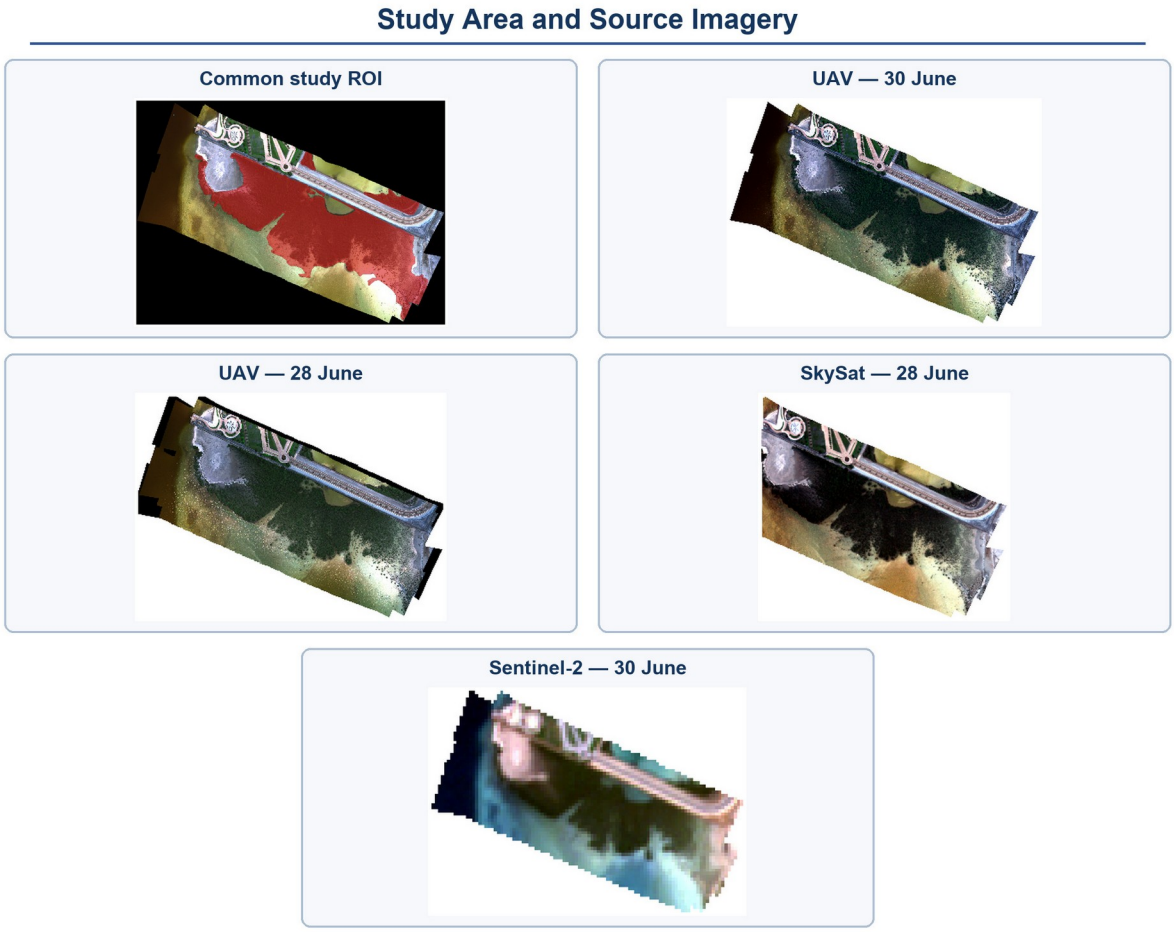


Figure 1. Common study ROI and source imagery. The different visible levels of detail illustrate the scale transition from UAV to SkySat to Sentinel-2.

2.2 Datasets and acquisition conditions

Four observations were used. UAV28 and SkySat were acquired on 28 June 2021, while UAV30 and Sentinel-2 were acquired on 30 June 2021 (Table 1).

Dataset	Date	UTC time	Local time	Nominal pixel size	Role
UAV28	28 Jun 2021	07:23:07–07:43:46	10:23:07–10:43:46	~0.106 m	Very-high-resolution repeat
SkySat	28 Jun 2021	07:41:59.5	10:41:59.5	0.5 m	High-resolution satellite
UAV30	30 Jun 2021	06:58:29–07:19:31	09:58:29–10:19:31	~0.108 m	Primary UAV analysis
Sentinel-2	30 Jun 2021	08:03:54.9	11:03:54.9	10 m	Moderate-resolution satellite

Table 1. Acquisition summary. Times are reported exactly where available; ranges represent UAV flight intervals.

The UAV imagery was collected with a MicaSense RedEdge-M five-band multispectral camera. The flight altitude was 165 m, yielding a ground sampling distance of 10.8 cm per pixel. The mapped area was 0.397 km². The photogrammetric solution used 1,242,143 tie points and 6,736,598 projections, with a mean reprojection error of 0.58 pixel. The output orthomosaic contained five 16-bit bands and was referenced to WGS 84 / UTM zone 37N (EPSG:32637) [8]. Most observations were close to nadir, with a mean view zenith angle of 5.871°.

2.3 NDVI calculation

NDVI was calculated from red and near-infrared reflectance using the standard normalized difference expression:

$$NDVI = (NIR - Red) / (NIR + Red)$$

Positive values generally identify surfaces with stronger near-infrared than red reflectance, including green vegetation. Water is commonly negative, while asphalt and other low-reflectance non-vegetated surfaces tend to remain near zero. These interpretations are class-level expectations rather than universal thresholds.

2.4 ROI design and land-cover sampling

Three related but distinct ROI analyses were retained. First, an overall mangrove ROI provided one mean NDVI for each of the four observations. Second, three mangrove-density zones—dense, moderate, and low—were represented by polygons of approximately 3,996.8 m² each. Third, a separate land-cover experiment sampled mangroves, water, asphalt, and a green artificial surface and recorded the mean and observed range for UAV, SkySat, and Sentinel-2.

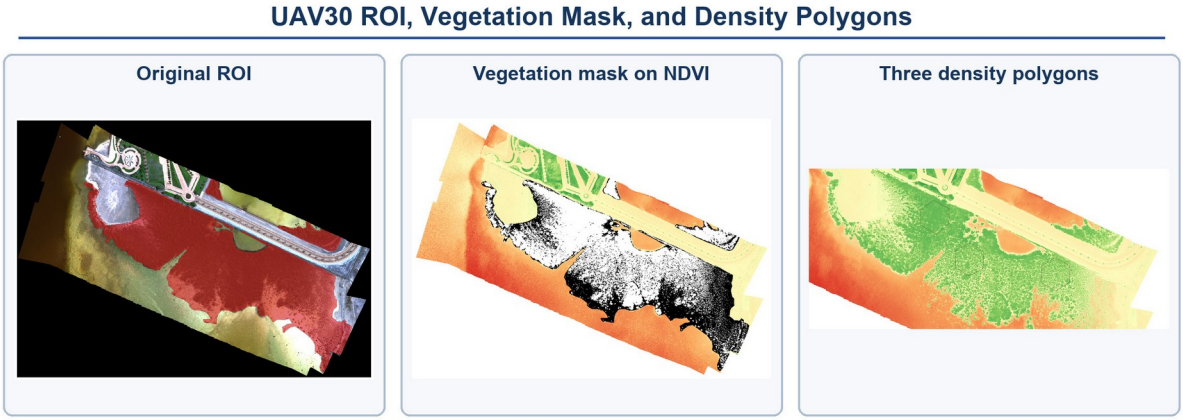


Figure 2. UAV30 analysis layers showing the original ROI, vegetation mask, and the three density-class polygons on the NDVI layer.

Data separation rule The overall mangrove-ROI means and the separate land-cover mangrove means use different sampling definitions. They are reported in different subsections and are not averaged or merged.

Earlier exploratory workflows used platform-specific vegetation-mask thresholds (approximately 0.20 for UAV, 0.10 for SkySat, and 0.05 for Sentinel-2). This choice helped isolate vegetation within each image but can also bias cross-platform mean values because the included pixel population changes by sensor. Consequently, the report treats the masked results as descriptive and identifies threshold harmonization as a required next step.

2.5 Cross-platform evaluation

Cross-platform evaluation used mean NDVI calculated within predefined ROIs; no pixel-to-pixel comparison or pixel-level significance testing was performed. Evidence included differences in mean NDVI among platforms, the ordering of the three mangrove-density ROIs, class sign and separation, observed within-ROI ranges, and the two-date UAV comparison. Because pixel support differs by platform, the statistics are descriptive and do not define a universal conversion.

3 Results

3.1 Overall mangrove ROI

The two UAV acquisitions produced similar overall mangrove mean NDVI values: 0.546 on 28 June and 0.557 on 30 June. The absolute difference was 0.011, equivalent to approximately 2.0% of the UAV28 value. SkySat reported 0.352 for the 28 June acquisition, while Sentinel-2 reported 0.206 on 30 June. The satellite values were therefore lower than the same-date/near-date UAV values, with the largest separation observed for Sentinel-2 (Table 2 and Figure 3).

Dataset	Mean NDVI	Difference from paired-date UAV	Interpretation
UAV28	0.546	Reference for 28 Jun	Fine-scale canopy and gaps resolved
SkySat	0.352	−0.194	Intermediate scale; lower absolute mean
UAV30	0.557	Reference for 30 Jun	Repeat UAV mean close to UAV28
Sentinel-2	0.206	−0.351	Strongest mixed-pixel influence expected

Table 2. Overall mangrove ROI means. These values belong to the overall-ROI analysis only.

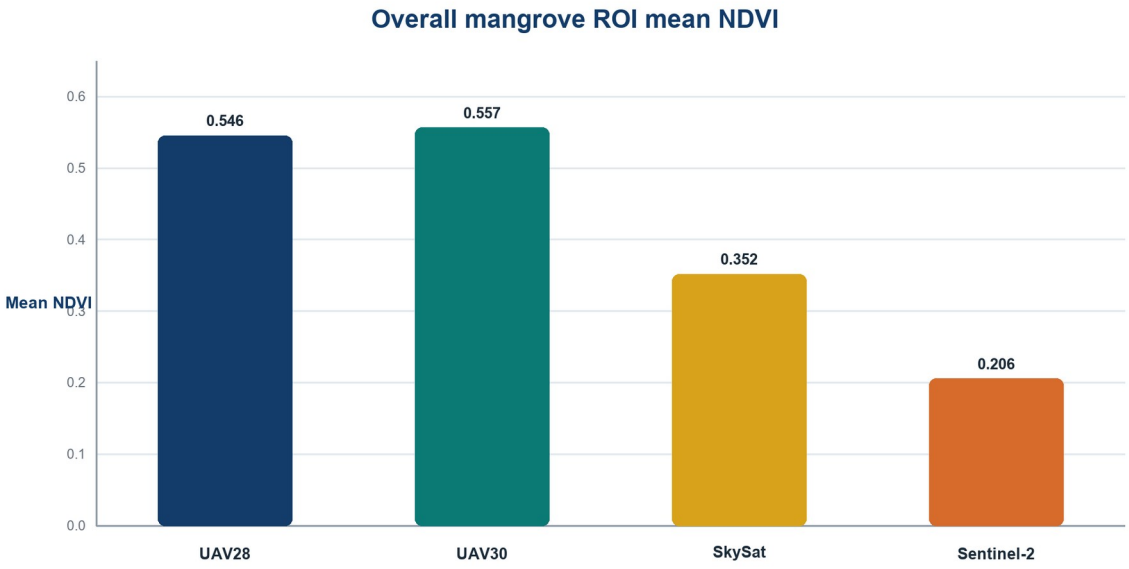


Figure 3. Overall mangrove ROI mean NDVI for the four observations.

3.2 Mangrove density classes

All datasets preserved the expected density ordering: dense mangroves had the highest NDVI, moderate mangroves were intermediate, and low-density mangroves had the lowest values. This ordering is the strongest cross-platform agreement in the study because it is unchanged despite substantial differences in absolute scale (Table 3).

Platform	Dense	Moderate	Low	Dense – Low
UAV28	0.6670	0.4837	0.4387	0.2283
UAV30	0.6790	0.5210	0.4720	0.2070
SkySat	0.5110	0.4047	0.3618	0.1492
Sentinel-2	0.3370	0.2387	0.2056	0.1314

Table 3. Mean NDVI by mangrove-density class. Each density polygon was approximately 3,996.8 m².

The dense-to-low contrast decreased from 0.2283 for UAV28 and 0.2070 for UAV30 to 0.1492 for SkySat and 0.1314 for Sentinel-2. This compression is consistent with spatial averaging: coarse pixels combine canopy, water, soil, shadow, and gaps, reducing the separation between the ends of the density gradient (Figure 4).

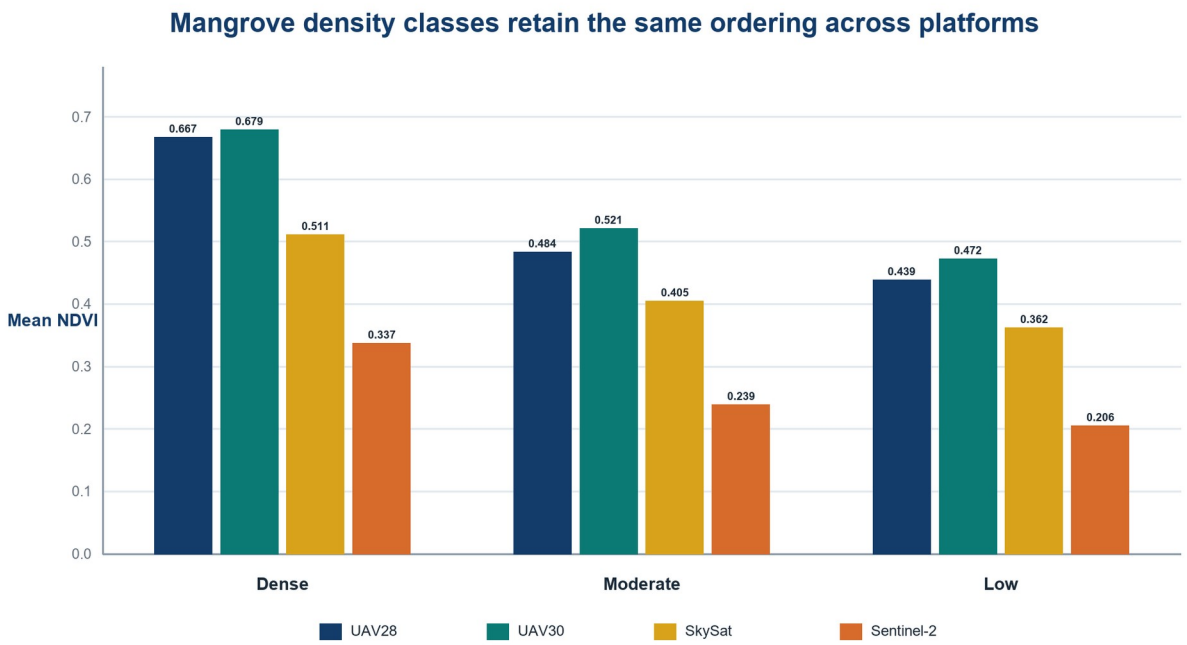


Figure 4. Mean NDVI for dense, moderate, and low mangrove-density zones across the four datasets.

3.3 Land-cover classes

The separate land-cover experiment retained physically interpretable class signatures. Mangroves and the green surface were positive in all platforms; water was negative; asphalt remained near zero, although SkySat produced a small positive mean of 0.063. The green surface had the highest mean for all three platforms in this analysis, followed by mangroves.

Class	UAV mean (range)	SkySat mean (range)	Sentinel-2 mean (range)
Mangroves	0.682 (0.614–0.783)	0.466 (0.348–0.547)	0.268 (0.158–0.311)
Water	−0.480 (−0.629–−0.051)	−0.228 (−0.328–−0.120)	−0.223 (−0.304–−0.161)
Asphalt	−0.035 (−0.082–−0.002)	0.063 (0.045–0.085)	−0.010 (−0.025–−0.001)
Green surface	0.737 (0.709–0.778)	0.625 (0.601–0.682)	0.382 (0.322–0.442)

Table 4. Land-cover ROI mean NDVI and observed within-ROI range. This is a separate sampling experiment from Table 2.

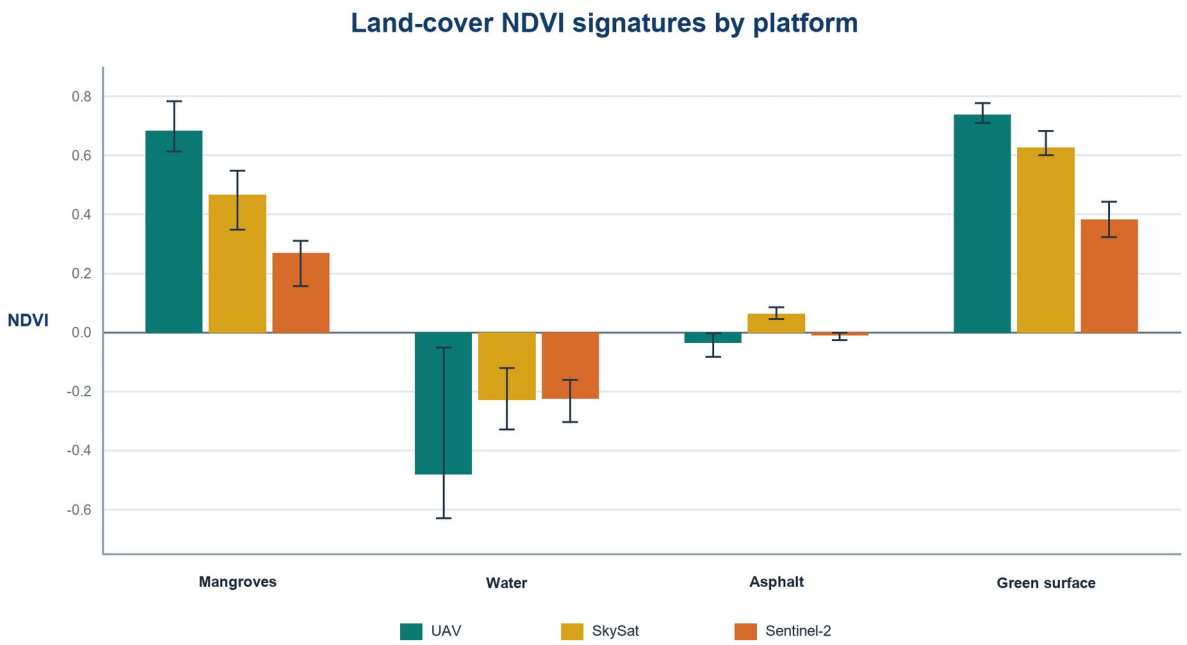


Figure 5. Land-cover class means and observed ranges for UAV, SkySat, and Sentinel-2.

The absolute platform gap was class dependent. For mangroves, the UAV–Sentinel-2 difference was 0.414; for the green surface it was 0.355. Water remained negative across platforms, but the UAV mean was more negative than either satellite mean. Asphalt showed the greatest sign sensitivity because all values were close to zero: a small shift in reflectance, shadow, adjacency, or ROI position was sufficient to change the sign.

3.4 UAV repeatability

The two UAV flights were separated by two days, over which no change in mangrove condition would be expected, and produced closely matched overall mangrove means (Table 5). Density-class differences between UAV30 and UAV28 were +0.012 for dense, +0.0373 for moderate, and +0.0333 for low-density polygons. The ordering was identical on both dates. These observations indicate good short-term qualitative repeatability within the UAV workflow, while the small numerical shifts may reflect illumination, tide, radiometric calibration, view geometry, real surface change, or polygon-level sampling.

Metric	UAV28	UAV30	UAV30 – UAV28
Overall mangrove ROI	0.546	0.557	+0.011
Dense mangroves	0.6670	0.6790	+0.0120
Moderate mangroves	0.4837	0.5210	+0.0373
Low-density mangroves	0.4387	0.4720	+0.0333

Table 5. Two-day UAV comparison. Values are descriptive and are not corrected for all acquisition-condition differences.

4 Discussion

4.1 Platform scale and mixed pixels

The primary cross-platform result is a combination of qualitative agreement and quantitative offset. UAV, SkySat, and Sentinel-2 identify vegetation as positive, water as negative, and asphalt as close to zero; they also preserve the mangrove-density ranking. Nevertheless, the satellite-derived mangrove means are lower, and the density contrast is compressed as pixel size increases. The strongest expected explanation is the increasing contribution of mixed pixels.

At 0.1 m, UAV pixels can resolve individual canopy patches, crown gaps, narrow road edges, and small water channels. At 0.5 m, SkySat retains much of the landscape structure but integrates more sub-meter variation. At 10 m, a Sentinel-2 pixel may cover 100 m^2 and combine several materials. If mangrove foliage shares a pixel with water, exposed substrate, shadow, or non-vegetated ground, the resulting red and near-infrared mixture moves the NDVI toward the background value. This explains why spatial detail and class contrast decline together.

However, the data do not isolate resolution as the only cause. The sensors have different bandpasses, signal-to-noise characteristics, calibration chains, atmospheric corrections, acquisition geometries, and observation times. Differences in tide and shoreline position may be particularly important at this coastal site. The appropriate conclusion is therefore that spatial resolution and mixed pixels are the leading expected contributors within a broader set of platform and acquisition effects.

4.2 Class-specific behavior

Mangroves and the green surface remained well separated from water and asphalt on every platform, supporting NDVI for broad class interpretation. The green surface consistently had a higher mean NDVI than mangroves in the land-cover experiment. Its dense, uniform, and regularly maintained cover likely reduced gaps and background mixing, whereas mangrove canopies included structural gaps, shadow, water, and sediment. This difference does not necessarily indicate greater biological vigor: a managed green surface can produce a strong red/NIR contrast without being directly comparable to a natural mangrove canopy. NDVI must therefore be interpreted in its land-cover context.

Water showed the expected negative NDVI, while the UAV values were more negative and had a wider range. Fine spatial resolution can resolve deep water, shallow water, sunglint, sediment, and vegetation-edge conditions that satellites average together. Asphalt values clustered around zero. Because the means are small, the sign difference in SkySat should not be interpreted as a class change; it is more appropriately viewed as sensitivity to ROI placement, spectral response, surface brightness, adjacency, and geometric alignment.

4.3 Mangrove density and repeatability

The stable dense–moderate–low ordering is ecologically meaningful and more transferable than the absolute means. Dense canopies present a larger fraction of photosynthetically active foliage and less visible background; low-density zones expose more water, soil, and shadow. Every platform detected that gradient. Even Sentinel-2, despite its compressed numerical range, retained the expected ordering.

The small difference between the UAV28 and UAV30 overall mangrove means suggests that the UAV workflow is repeatable over short intervals at the landscape level. Class-level differences were somewhat larger for moderate- and low-density polygons, which are also the areas most affected by exposed background and boundary placement. Repeated flights under matched illumination, tide, calibration, and flight geometry would be needed to convert this descriptive repeatability into a formal uncertainty estimate.

4.4 Implications for multi-sensor monitoring

The results support a tiered monitoring strategy. UAV imagery is best suited to local calibration, detailed habitat boundaries, crown gaps, and fine-scale change. SkySat provides a useful intermediate product when sub-meter mapping is required over larger areas. Sentinel-2 offers broad coverage and frequent revisit but requires careful interpretation in narrow or fragmented coastal features. Rather than selecting one platform for every task, the sensors can be used together if the analysis distinguishes their measurement support and uncertainty.

For trend analysis, absolute NDVI values from different platforms should not be placed on one time series without harmonization. A defensible approach is to define stable geographic polygons, use reflectance products with documented calibration, aggregate high-resolution red and near-infrared bands to the coarsest common grid before computing NDVI, and derive platform-specific uncertainty or conversion relationships using independent reference data.

5 Limitations and Future Work

This study is an applied comparison based on a small number of acquisitions at one coastal site. Its main limitations are:

- The comparison does not include field measurements of canopy condition, leaf area index, species composition, or surface reflectance; therefore, no platform can be designated as absolute ground truth.
- Acquisitions were near-date rather than perfectly simultaneous. Illumination, atmosphere, tide, water level, wind, and surface state may differ among observations.
- Sensor-specific red and near-infrared bandpasses and processing levels were not converted to a common spectral response.
- Residual geolocation differences between independently georeferenced products can alter mixed coastal pixels and narrow road ROIs, especially for Sentinel-2.
- Vegetation masks used different exploratory NDVI thresholds by platform, so threshold selection may contribute to the reported mean differences.
- ROI ranges describe observed pixels but do not provide confidence intervals. Pixels are spatially autocorrelated and cannot be treated as independent samples.
- The number of Sentinel-2 pixels is small for narrow features; in the separate road analysis, the road ROI contained only 34 Sentinel-2 pixels, limiting the stability of that summary.

The next phase should prioritize the following actions:

1) Use one fixed set of geographic polygons for every platform and document polygon area, pixel count, nodata handling, and edge exclusions.

2) Harmonize reflectance before NDVI calculation: match radiometric level, approximate spectral response where possible, aggregate red and NIR separately to a common grid, and then compute NDVI.

3) Acquire field or proximal-sensing reference measurements and calibrated reflectance targets during UAV flights.

4) Collect repeated images under matched tide, sun angle, and viewing geometry to quantify temporal and acquisition uncertainty.

5) Use block bootstrap, spatial cross-validation, or polygon-level replication instead of pixel-level significance tests.

6) Evaluate additional indices, including red-edge and mangrove-specific indices, where equivalent bands are available.

7) Treat the existing K-means classification as a separate extension until its cluster labels are independently validated and connected to the same study polygons.

Recommended minimum standard Before combining platforms in one monitoring series, keep the ROI fixed, harmonize red/NIR inputs, report pixel support and acquisition conditions, and validate the resulting relationship with independent observations.

6 Conclusion

UAV, SkySat, and Sentinel-2 imagery provided a coherent qualitative description of land cover at the KAUST King Abdullah Monument site. Vegetated surfaces were positive in NDVI, water was negative, asphalt was close to zero, and dense mangroves consistently exceeded moderate and low-density zones. The two UAV acquisitions also produced closely matched overall mangrove means, supporting short-term repeatability of the fine-resolution workflow.

The platforms did not provide interchangeable absolute NDVI values. Overall mangrove means decreased from approximately 0.55 in the UAV data to 0.352 in SkySat and 0.206 in Sentinel-2, and the density-class contrast narrowed as spatial support became coarser. These differences are most plausibly associated with spatial averaging and mixed pixels, together with sensor bandpass and radiometric-processing differences, residual geolocation differences, tide, and other acquisition conditions.

The most reliable cross-platform conclusion is therefore the preservation of relative land-cover and mangrove-density patterns, not equality of numerical NDVI. Multi-sensor monitoring at this site is feasible, but it should use fixed ROIs, harmonized reflectance, common spatial support, explicit uncertainty, and independent validation. With those safeguards, UAV detail, SkySat intermediate scale, and Sentinel-2 coverage can become complementary components of a single coastal monitoring strategy.

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8 Appendix A — Result-set data dictionary

The project contains several valid summaries that use different ROIs. This appendix records their intended use so later edits, poster preparation, and figure revisions do not combine incompatible values.

Result set	Platforms	Classes / ROI	Use in report	Do not combine with
Overall mangrove ROI	UAV28, UAV30, SkySat, Sentinel-2	One common mangrove mask/ROI	Section 3.1; values 0.546, 0.557, 0.352, 0.206	Land-cover mangrove means
Mangrove density	UAV28, UAV30, SkySat, Sentinel-2	Dense, moderate, low polygons (~3,996.8 m² each)	Section 3.2	Whole-ROI and road summaries
Land-cover experiment	UAV, SkySat, Sentinel-2	Mangroves, water, asphalt, green surface	Section 3.3; means and observed ranges	Overall mangrove ROI
Separate road check	UAV28, UAV30, SkySat, Sentinel-2	Narrow road ROI	Limitation context only	Land-cover asphalt row without ROI reconciliation
K-means extension	UAV multispectral mosaic	Four unsupervised clusters	Future extension only	Validated land-cover classes

Table A1. Data-lineage guide for the main and supporting project analyses.