

Supplementary Information

Manuscript title: Traceable acquisition and processing workflow for multispectral drone monitoring of orchards

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Table S1. Operational QA/QC review and disposition criteria for multispectral orchard surveys.

QA/QC domain	Minimum check	Record to retain	Action where requirement is not met
Coverage	Complete coverage of the intended survey area without material gaps	Coverage review and affected locations	Reacquire where possible or flag affected area
Image quality	No severe blur, exposure failure or unusable image sequences	Rejected image count and reason	Exclude affected images or repeat acquisition
Illumination and weather	Record rainfall, cloud variation, major shadow change, wind and canopy wetness	Field-condition notes and available illumination records	Flag restricted comparability or repeat where severe
Positioning	RTK status and ground-control information retained	RTK status, GCP role and coordinate reference system	Report positional limitation if records are incomplete
Multispectral alignment	No obvious band misregistration, seam-line failure or missing coverage	Visual review and available diagnostic metrics	Reprocess or flag affected products
Radiometric documentation	Illumination records, radiometric processing mode and available calibration information retained	DLS status, panel status, correction settings and numerical scaling	Treat products as relative outputs where evidence is incomplete
Processing provenance	Software, version, processing role and essential settings retained	Processing record and export parameters	State limits on exact reproducibility
Output integrity	CRS, resolution, units, file format and no-data treatment verified	Output manifest	Correct or re-export affected product

Note: Criteria synthesise platform documentation and current guidance on UAV mapping, reproducibility and positional quality control¹⁻⁶. No universal numerical rejection thresholds are prescribed. Where project specific thresholds are used, they should be defined before analysis and retained in the QA/QC record. QA/QC, quality assurance and quality control.

Table S2. Software roles and minimum provenance information for the demonstration workflow.

Software	Role in workflow	Minimum provenance information to retain	Principal output or record
DJI Terra v4.3.0 ⁷	Multispectral reconstruction, band alignment, radiometric processing using available illumination information and generation of band orthomosaics	Software version, project settings, radiometric option, illumination input, output data type, raster resolution, CRS and any numerical scaling	Band specific orthomosaics and reconstruction records
Agisoft Metashape Professional v2.2.0 ⁸	Review of spatial consistency, image alignment and overall processing quality	Software version, CRS, inspection settings and any retained diagnostic metrics	Spatial and alignment QA/QC record
Global Mapper Pro v24.1 ^{9,10}	Vegetation index calculation using predefined or custom raster formulas, raster review and GeoTIFF export	Software version, vegetation index formula, band assignment, output data type, numerical scaling, no data value, raster resolution and CRS	NDVI, GNDVI, NDRE and LCI raster products

Note: Software roles describe the processing sequence used in this study. Recording software versions, processing parameters and output characteristics is important because photogrammetric outputs can vary with processing environment and workflow settings^{8,11}. CRS, coordinate reference system; QA/QC, quality assurance and quality control.

Table S3. Radiometric documentation, correction and calibration approaches relevant to multispectral UAV workflows.

Radiometric control level	Required inputs	Best use	Main caution	Recommended reporting
DLS metadata retention ²	Onboard downwelling light records	Operational documentation and relative workflow traceability	Does not by itself validate absolute reflectance	DLS status, acquisition timing and illumination notes
DLS assisted radiometric correction or numerical scaling ^{2,12,13}	DLS metadata and software correction settings	Relative within flight or same day index generation under sufficiently stable illumination	Sensitive to changing illumination, sensor geometry and processing assumptions	Software version, correction mode, radiometric correction settings and any numerical scaling applied
Single panel calibration ^{14,15}	One characterised panel imaged before and/or after flight	Quantitative workflows under relatively stable illumination	Accuracy can degrade when illumination varies materially during acquisition	Panel model, characterised reflectance values, panel image timing and correction method
Multi panel empirical line calibration ^{15,16}	Two or more targets with known reflectance values	Quantitative reflectance workflows spanning a wider reflectance range	Requires careful target handling, exposure control and complete field documentation	Target reflectance values, target images, exposure settings and calibration equation
Integrated panel and DLS workflow ^{13,17}	Reflectance panel images and DLS metadata	Repeated or multi-date surveys requiring stronger radiometric consistency	Performance may remain affected by rapid illumination changes or poor panel acquisition	Panel and DLS status, acquisition timing, software settings and QA/QC flags
Advanced radiometric adjustment ¹⁸	Multi image radiometric modelling or block adjustment	Research workflows under spatially or temporally variable illumination	Greater methodological complexity and stronger validation requirements	Model assumptions, correction parameters and independent validation data

Note: These approaches represent different levels of radiometric documentation, correction and validation. DLS metadata retention, DLS assisted correction, panel-based calibration and independent reflectance validation should not be interpreted as equivalent levels of evidence. DLS, downwelling light sensor; QA/QC, quality assurance and quality control.

Table S4. Minimum and conditional metadata fields for multispectral orchard surveys.

Metadata domain	Minimum record for all surveys	Additional record where relevant or for quantitative claims	Purpose
Site and survey context	Site identifier; crop type; surveyed area; general location or privacy note; terrain condition; relevant canopy or orchard characteristics ^{3,5}	Approximate coordinates; orchard age; phenological or canopy stage; canopy height or row spacing where relevant	Defines the spatial and biological context needed to interpret the survey
Mission geometry	Acquisition date; start and end time; time zone; flight height and height reference; achieved or expected GSD; forward and side overlap; ground speed; gimbal angle; flight line direction; flight duration; image count ^{4,5}	Terrain following settings; boundary buffer; repeat flight path identifier; deviations from the planned mission	Documents acquisition geometry and supports reconstruction and repeatability
Weather and illumination	Rainfall status; cloud condition; illumination stability; wind condition; canopy wetness; major shadow changes during acquisition ^{4,13}	Measured wind speed; air temperature; relative humidity; solar elevation or azimuth; irradiance or downwelling light summary	Helps distinguish acquisition related variation from genuine canopy or spectral variation
Positioning and georeferencing	RTK source and status; GCP number and role; GCP survey method where used; processing CRS; export CRS ^{5,6}	Independent checkpoint number and distribution; checkpoint survey method and accuracy; horizontal and vertical residuals; RMSE or other reported positional accuracy statistics ⁶	Provides spatial traceability and separates georeferencing support from independent product accuracy validation
Radiometric control	DLS status; panel availability; exposure mode where retained; radiometric correction method; correction settings; any numerical scaling applied ^{3,13,15,16}	Panel model; characterised reflectance values; panel image timing; exposure information; independent spectral or reflectance measurements; band level radiometric error statistics ^{13,15,16}	Defines whether outputs are relative workflow products or quantitatively validated reflectance products
Processing and outputs	Software name and version; software role; principal processing settings; input and output data type or bit depth; processing CRS; export CRS; raster resolution; output units; no data treatment; vegetation index formula and band assignment where applicable; file format; naming convention ^{3,5}	Quantitative alignment or registration diagnostics; rejected image counts; reprocessing records; processing diagnostics; validation metrics ^{3,5}	Supports auditing, reprocessing, reproducibility and interpretation of generated products

Note: Fields in the third column should be retained where relevant and are required when quantitative radiometric or positional performance is reported. Independent checkpoints should be separated from control used for georeferencing. DLS, downwelling light sensor; GCP, ground control point; GSD, ground sampling distance; CRS, coordinate reference system; RTK, real time kinematic; RMSE, root mean square error.

Table S5. Vegetation index formulas generated from DJI Mavic 3 Multispectral imagery.

Vegetation index	Formula	Spectral bands used	Typical spectral sensitivity or use
Normalised Difference Vegetation Index (NDVI) ^{19,20}	$(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$	Red, NIR	General contrast between red absorption and NIR canopy reflectance
Green Normalised Difference Vegetation Index (GNDVI) ^{19,20}	$(\text{NIR} - \text{Green}) / (\text{NIR} + \text{Green})$	Green, NIR	Green and NIR responses are commonly used in chlorophyll sensitive vegetation assessment
Normalised Difference Red Edge Index (NDRE) ^{20,21}	$(\text{NIR} - \text{Red Edge}) / (\text{NIR} + \text{Red Edge})$	Red edge, NIR	Red edge and NIR response commonly used where dense vegetation reduces NDVI sensitivity
Leaf Chlorophyll Index (LCI) ^{20,21}	$(\text{NIR} - \text{Red Edge}) / (\text{NIR} + \text{Red})$	Red, red edge, NIR	Chlorophyll sensitive combination of NIR, red edge and red reflectance

Note: The equations define the exact vegetation index formulations used in this workflow because index nomenclature and implementation can vary among studies. The resulting indices were treated as workflow derived outputs and were not used to make independently validated agronomic claims. NIR, near infrared.

Table S6. Selected acquisition, radiometric, positioning and processing settings reported in DJI Mavic 3 Multispectral and comparable multispectral UAV studies.

Platform and sensor	Flight height and forward/side overlap where reported	Radiometric approach	Positioning or validation approach	Processing software
DJI Mavic 3M ²²	65 m; 70%/80%	Calibration cloth used for radiometric correction	RTK used to geolocate field sampling points; independent image product positional validation not reported	DJI Terra
DJI Mavic 3M ²³	65 m; 70%/80%	Onboard sunshine sensor and a 0.5 x 1 m standard grey panel imaged before and after each flight	Independent positional validation procedure not reported	DJI Terra v4.2.5; ArcMap
DJI Mavic 3M ²⁴	65, 80, 100, 120, 140, 160, 180 and 200 m; 70%/80% for the 65 m reference acquisition	Two 0.5 x 1 m grey reference panels used for reflectance calibration	Differential GPS used for field sampling points; independent image product positional validation not reported	DJI Terra; ArcGIS Desktop 10.8
Multispectral UAV system ¹⁴	30, 60 and 90 m	Camera only, camera plus sun irradiance, camera plus sun irradiance and sun angle, and an independent irradiance sensor based correction method were compared	Independent positional validation was not a study objective	Pix4Dmapper; R for the independent irradiance sensor method
DJI Mavic 3M ²⁵	65 m; 70%/80%	Grey and white reference boards; gain and offset correction followed by Z score normalisation	RTK/GCP assisted georeferencing	DJI Terra
DJI Mavic 3M ²¹	30 m; 80%/70%	Grey reference board used for radiometric calibration	Independent positional validation procedure not reported	DJI Terra
DJI Mavic 3M ²⁶	15 m; 80%/70%	Calibrated reflectance panel used before flight to convert digital numbers to reflectance	RTK GPS ground control points used for geometric correction	DJI Terra v4.2.5
DJI Mavic 3M and comparator sensors ²⁷	30 m; 90%/85%	Four reflectance cloths supported by reference measurements from an ASD spectroradiometer	RTK supported spatial information and relative geometric correction	DJI Terra v4.3.0; DJI GS Pro for mission planning
DJI Phantom 4 Multispectral RTK ⁸	80.1 m; 75%/75%	Characterised reflectance panels and incident light sensor based correction strategies were evaluated	RTK acquisition; multiple GCP configurations and independent validation points used to calculate positional error	Agisoft Metashape
eBee Plus with Parrot Sequoia ¹⁶	120 m	Five radiometric calibration strategies, including reference target, sunshine sensor and empirical line approaches	Six GCPs distributed across the survey area	Pix4D

Note: The studies were selected to illustrate variation in acquisition geometry, radiometric control, positioning and processing practice rather than to provide a systematic review or performance ranking. Forward/side overlap is included where verified from the cited study. ASD, Analytical Spectral Devices; GCP, ground control point; GPS, Global Positioning System; RTK, real time kinematic.

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