

Supplementary File S1 — Search protocol, screening rules and data-extraction codebook

Thermal and Multispectral UAV Remote Sensing in Archaeology: A Systematic Review of Sensors, Platforms, Acquisition Contexts, and Processing Workflows (2013–July 2026)

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S1.1 Screening rules as implemented

The automated stage applied two deterministic rules to bibliographic metadata only. No machine-learning classifier was used at any point. Rule 1 excluded a record when the term “review”, “meta-analysis” or “overview” appeared in the title. The rule was deliberately confined to the title and not extended to abstracts, because the string “peer-reviewed” occurs there frequently and would have removed eligible records. Rule 2 excluded a record when no term carrying the stem archaeolog* or archeolog*, or its equivalent in the other corpus languages, occurred in the title or in the abstract where an abstract was supplied by the source. The two rules were applied in that order, so that the 15 records removed by Rule 1 and the 65 removed by Rule 2 are disjoint sets summing to the 80 automated exclusions reported in Figure 1.

Deduplication over the merged pool of 758 records proceeded in three ordered passes: exact match on normalised digital object identifiers (251 records removed); exact match on titles normalised by case-folding, removal of diacritics and punctuation, and whitespace collapse (120 removed); and a guarded fuzzy pass on normalised titles, retaining a pair only when the token-sorted similarity reached 90 and the two titles contained the same set of numerals, so that companion volumes and numbered series parts were not merged (5 removed). Two further records carried no usable title and were set aside. A total of 376 duplicates were eliminated, leaving 380 unique records; the DOI pass alone accounts for 66.8 per cent of all duplicate removals, a direct consequence of the improved DOI coverage of these exports.

The review draws on two identification tracks. The database, register and LLM-assisted searches described below yielded the 380 unique records screened, of which 110 were included. A further 22 publications were identified through the author’s own reference library and through citation searching of the retrieved items, and were assessed against the same eligibility criteria; these are predominantly Italian-language contributions in venues that none of the six sources indexes. The two tracks are reported separately in Figure 1, following the PRISMA 2020 two-column layout, and the retrieval route of every included publication is recorded in the Retrieval_provenance column of Supplementary Table S1.

All screening and extraction were carried out by a single reviewer (GC), working non-independently. No second reviewer duplicated any stage, and inter-rater agreement could therefore not be computed.

S1.2 Assignment of excluded records to screening stages

Supplementary Table S2 records all 270 excluded records with the stage at which each was removed, so that the counts in the flow diagram can be verified without re-executing the pipeline. The assignment is deterministic and was made as follows.

Automated screening (n = 80). Records removed by Rule 1 or Rule 2 above, identified in Table S2 by the Automated_rule column, which names the rule applied. These records were never read.

Metadata screening (n = 26). Records whose exclusion is decidable from bibliographic metadata alone, namely those carrying one of four reasons in the controlled vocabulary: grey-literature report or thesis; conference abstract or communication without extractable data; editorial or aggregate record; and insufficient or unverifiable bibliographic metadata. Peer-review status was established from the publication venue and required no reading of the study itself.

Full-text eligibility (n = 164). All remaining records. Their full texts were sought, retrieved and read, and each carries an individually assigned exclusion reason drawn from the same thirteen-term vocabulary. The three commonest reasons at this stage are the absence of a thermal or multispectral sensor on the UAV (56), a review or overview without primary case data that had escaped the title rule (27) and the absence of any UAV platform (21).

The reconciliation sheet of Table S2 reproduces the flow diagram with live COUNTIF formulas over the Screening_stage column, so that $80 + 26 + 164 + 110 = 380$ can be checked directly in the workbook.

S1.3 Data-extraction codebook: operational definitions

The following definitions were applied uniformly to all 132 included publications. They are reproduced here because several are review-specific and cannot be inferred from the field names alone.

Table S1.1. Operational definitions of the coded categories.

Coded category	Operational definition as applied
Distinct research project	A body of fieldwork addressing one research question at one study area by one team. Two or more publications were assigned to the same project when they report the same acquisitions over the same target, irrespective of the analytical treatment applied to them.
Substantially the same research	A publication was flagged as reporting substantially the same research as another in the corpus when it presents no new acquisition and no new analytical result relative to the earlier or fuller item. The typical cases are a preliminary conference paper later expanded into a journal article, and a thematic re-presentation of a single long-running field project. Flagged publications were retained in all publication-level analyses and removed only from the project-level series.
Multisensor study	A study deploying both a thermal-infrared and a multispectral sensor over the same target, whether in a single flight or in successive flights. RGB photogrammetry, LiDAR and microtopographic survey accompanying TIR or MS do not by themselves make a study multisensor within this taxonomy, which is defined on the TIR/MS axis only.
Multitemporal acquisition	Acquisition over the same target on two or more occasions separated by at least one calendar month, one season or one crop growth stage. Repeated passes within a single flight session were not counted as multitemporal. A campaign described only as systematic or year-round, without named months, was coded as an unspecified multi-month programme and is excluded from the month-resolution counts.
Sensor classes	Thermal-only; multispectral-only; thermal and multispectral. Hyperspectral acquisitions are assimilated to the multispectral family when accompanying TIR or MS. Additional modalities carried alongside the TIR/MS payload are recorded separately in the Additional_modalities column.
Vegetation classes	Wetland, coastal and submerged; tundra and Arctic vegetation; bare soil and excavation contexts; desert and arid surfaces; cultivated fields (any sown crop, overwhelmingly cereals); grassland and pasture (managed or unmanaged herbaceous cover, including moorland and meadow); Mediterranean shrub and woodland (including any closed arboreal canopy); steppe; mixed or otherwise unclassifiable. Where a publication reported more than one context, the dominant context of the reported acquisitions was coded; the rule set applies the classes in the order listed, so that a description such as “crops / grassland” resolves to cultivated fields.
Factory-integrated system	A commercial platform whose TIR and/or MS payload is supplied, embedded and co-registered by the manufacturer, and supported by the manufacturer’s own processing chain. Examples in the corpus: senseFly eBee with thermoMAP or multiSPEC payloads, DJI P4 Multispectral, Mavic 2 Enterprise Advanced, Mavic 3M and 3T, Matrice with Zenmuse gimbals, Parrot Anafi Thermal, and Parrot Disco Pro AG with Sequoia.
User-adapted commercial platform	A commercial ready-to-fly platform carrying a third-party sensor mounted by the research team, whether or not the sensor itself was modified. Examples in the corpus: Asctec Falcon 8 with FLIR Tau 640, DJI Phantom 4 with Parrot Sequoia or Sentera 6X, 3DR Solo with FLIR Vue Pro R.
Custom-built platform	An aircraft assembled by the research team, or an off-the-shelf airframe substantially rebuilt for the purpose. Commercial airframe kits flown without structural modification, such as Tarot or Mikrokopter frames, were coded as user-adapted commercial platforms.
Documented processing workflow	A publication was coded as documenting its processing chain when it names at least one operation applied after orthomosaicking and beyond the computation of a standard vegetation index. Generic statements such as “standard processing” or “the images were processed in [software]” without further specification were coded as not reported.
Identifiable research group	A set of authors linked by recurrent co-authorship and shared institutional affiliation, contributing two or more publications to the corpus. Individual authors may belong to more than one group; publications were assigned to a single group on the basis of the affiliation of the corresponding author and the study area.
Document type	Journal article; conference paper; book chapter. Where the publication venue recorded in the source metadata is absent or uninformative, the type is coded as not established rather than inferred; this applies to 14 records.
Language	Language of the publication as issued, not of its title or abstract alone. Two Russian-language contributions carry transliterated titles and are coded from the publication itself.
Retrieval provenance	The identification track through which the publication entered the corpus: the named database, register or LLM system, or “other methods” for items identified through the author’s reference library and citation searching.

S1.4 Reporting-completeness appraisal: fields and coding

Four fields were coded for every included publication, chosen because they could be assessed consistently across the whole 2013–2026 record: presence of the platform and sensor model; presence of an acquisition date at month resolution or finer; presence of a vegetation or surface context; and presence of a documented processing chain as defined above. Each field was coded reported or not reported, giving a score from 0 to 4. Per-publication results are given in Supplementary Table S1, columns RC1 to RC4 and RC_score_0_4.

Table S1.2. Aggregate results of the four-field reporting-completeness appraisal ($n = 132$).

Field	Reported	%	Not reported
Platform and sensor model	122	92.4	10
Acquisition month or finer	53	40.2	79
Vegetation or surface context	106	80.3	26
Documented processing chain	30	22.7	102

Table S1.3. Distribution of the completeness score across the corpus.

Fields reported (of 4)	Publications	% of corpus
0	5	3.8
1	18	13.6
2	47	35.6
3	49	37.1
4	13	9.8
Mean score	2.36 / 4	—

Thirteen publications (9.8%) report all four fields and five (3.8%) report none. The modal publication reports two or three, almost always the platform and the surface context, and omits the processing chain. Reporting completeness and internal validity are distinct properties, and these scores should not be read as an appraisal of study quality; the appraisal is not a risk-of-bias assessment and is not offered as one.

S1.5 Search strings as executed

The strings below are reproduced verbatim, without editorial normalisation of quotation marks or spacing. Machine-readable copies, together with the deduplication and automated-filtering code, are released as Supplementary File S3. The 22 publications identified through other methods did not derive from these strings and are flagged accordingly in Table S1.

Platform	String as executed on 27 July 2026
Scopus	TITLE-ABS-KEY (("archaeology" OR "archaeological prospection" OR "archaeological survey" OR "landscape archaeology") AND ("thermal" OR "thermography" OR "multispectral") AND ("UAV" OR "UAVs" OR "UAS" OR "RPAS" OR "drone" OR "drones"))
OpenAlex	"landscape archaeology" OR "archaeological survey" OR "archaeological prospection" OR archaeology OR archaeological OR archeology OR archeological) AND (UAV OR UAS OR RPAS OR drone OR "unmanned aerial vehicle" OR "unmanned aerial system") AND (thermal OR thermography OR multispectral) - submitted through the OpenAlex search API
Semantic Scholar	+(archaeolog* archeolog*) +(thermal* thermograph* multispectral) +(UAV UAVs UAS RPAS drone*)
Google Scholar (Publish or Perish v8)	archaeology OR "archaeological prospection" OR "archaeological survey" OR "landscape archaeology" thermal OR thermography OR multispectral UAV OR UAS OR drone OR drones — entered in the “The words” field of the General Citation Search. Google Scholar applies implicit AND between space-separated terms and does not support nested parentheses, so the three concept blocks were entered sequentially. The complete returned set was exported without truncation, in the citation-ranked order returned by the service; 197 records were returned and exported.
LLM track	Identical natural-language prompt issued to Claude (Anthropic, Opus 5) and ChatGPT (OpenAI, GPT-5.5): “Conduct an online search of everything published on the use of drones with thermal and multispectral sensors in archaeology, in all languages and in any journal, book or digital archive.” Complete outputs, verification status and exclusion reasons are released as

Platform	String as executed on 27 July 2026
	Supplementary File S2.

S1.6 Minimum reporting standard: complete specification

Table 7 of the main text is reproduced here in full, including the field definitions and rationales abridged there for reasons of space. Status values are mandatory or recommended; the “applies to” column indicates whether a field is required of thermal acquisitions, of multispectral acquisitions, or of both.

Table S1.4. Minimum reporting standard for UAV-based thermal and multispectral archaeological prospection.

Field	Definition	Unit / format	Status	Applies to	Rationale
Platform and sensor					
Platform	Make and model of the unmanned aircraft	Free text	Mandatory	TIR + MS	Determines stability, endurance and achievable positional accuracy
Sensor	Make and model of every imaging sensor carried	Free text	Mandatory	TIR + MS	Fixes band configuration and detector class
Radiometric status	Whether the TIR sensor returns calibrated apparent temperature or uncalibrated relative contrast; whether MS bands were referenced to an irradiance sensor or reflectance panel	Categorical: radiometric / non-radiometric; calibrated / uncalibrated	Mandatory	TIR + MS	Required to determine whether measurements can be compared across flights or studies.
Spectral bands	Centre wavelength and bandwidth of each band	nm	Mandatory	MS	Indices computed on different band definitions are not the same index
Acquisition geometry					
Flight altitude	Height above ground level	m AGL	Mandatory	TIR + MS	Together with focal length determines resolution and atmospheric path
Ground sampling distance	Nominal pixel size on the ground	cm / pixel	Mandatory	TIR + MS	Sets the minimum resolvable feature width
Image overlap	Forward and side overlap of the flight plan	%	Recommended	TIR + MS	Governs mosaic geometry and radiometric homogenisation
Timing					
Flight date	Calendar date of every flight, not only of the campaign	YYYY-MM-DD	Mandatory	TIR + MS	The signal is transient; a campaign-level year is not usable
Time of day	Local clock time and UTC offset of every flight	HH:MM ± UTC	Mandatory	TIR + MS	Thermal contrast reaches a maximum and reverses sign within the diurnal cycle
Multitemporal design	Number and spacing of repeat flights over the same target	Count + dates	Recommended	TIR + MS	Distinguishes a single opportunistic acquisition from a sampled series
Atmospheric and illumination conditions					
Air temperature	Mean air temperature during the flight, together with the minimum and maximum values when conditions varied appreciably.	°C; mean and range	Mandatory for TIR; recommended for MS	TIR + MS	Influences surface–atmosphere thermal exchange, canopy stress, apparent temperature, and thermal-camera correction.
Relative humidity	Mean relative humidity during acquisition and, where available, its range over the flight period.	%; mean and range	Mandatory for TIR; recommended for MS	TIR + MS	Affects atmospheric transmission in the thermal infrared and provides contextual information on evapotranspiration and vegetation stress.

Field	Definition	Unit / format	Status	Applies to	Rationale
Wind speed and direction	Mean wind speed, maximum gust speed, and prevailing wind direction during acquisition.	m s ⁻¹ ; degrees from north or cardinal direction	Mandatory for TIR; recommended for MS	TIR + MS	Wind modifies convective surface cooling and canopy temperature and may reduce or spatially redistribute thermal contrasts.
Cloud cover	Fraction of the sky covered by clouds during acquisition, including whether illumination remained stable or changed during the flight.	% or oktas (0–8); clear / few / scattered / broken / overcast; stable / variable	Mandatory	TIR + MS	Cloud cover modifies incoming solar radiation, surface heating, shadows, and multispectral reflectance, potentially generating inconsistencies within a single mosaic.
Solar irradiance	Incoming shortwave irradiance during acquisition, measured or modelled	W m ⁻² ; instantaneous and range	Mandatory for MS; recommended for TIR	TIR + MS	Reflectance is normalised against incident radiation; without it index values are not transferable between flights
Solar geometry	Solar elevation and azimuth at the midpoint of each flight	Degrees	Recommended	TIR + MS	Governs shadowing, bidirectional reflectance and the diurnal position of the thermal signal
Time relative to sunrise or sunset	Elapsed time between sunrise or sunset and the beginning and end of the flight.	Hours and minutes; before/after sunrise or sunset	Recommended	TIR	Provides a physically comparable temporal reference for warming, cooling, and thermal-crossover conditions across seasons and latitudes.
Precipitation during acquisition	Occurrence and intensity of precipitation during the flight, including drizzle or intermittent rainfall.	None / drizzle / rain / snow; mm h ⁻¹ where measured	Mandatory	TIR + MS	Precipitation changes surface moisture, temperature, reflectance, and emissivity and may invalidate comparisons between images acquired under different conditions.
Antecedent precipitation	Rainfall preceding each flight, and the interval since the last measurable rainfall event	mm over 24 h, 7 days, 14 days and 30 days; hours or days since last rainfall	Mandatory	TIR + MS	Soil moisture is the proximate driver of both thermal and reflectance contrast; the decay interval matters as much as the total
Weather stability	Overall stability of atmospheric and illumination conditions during acquisition. Any rapid change should be documented with its approximate time.	Stable / gradually changing / rapidly variable; free-text note and timestamp	Mandatory	TIR + MS	Rapid changes in wind, cloud cover, temperature, or irradiance can introduce radiometric discontinuities and artificial spatial patterns into orthomosaics.
Meteorological data source	Provenance of the reported meteorological values	On-board sensor / field station / named public station with distance and elevation / reanalysis product with version	Mandatory	TIR + MS	A value read from a station tens of kilometres away is not equivalent to an on-site measurement, and the difference must be assessable
Surface and agronomy					
Land cover	Vegetation or surface context at the time of flight	Controlled vocabulary	Mandatory	TIR + MS	Determines which detection mechanism is operative
Crop and growth stage	Species and phenological stage where a crop is present	Species + BBCH / Zadoks code	Mandatory where a crop is present	TIR + MS	The stage, not the month, is the physical variable; the month is only a proxy for it
Surface wetness	Presence of dew, standing water, irrigation residue or surface film at acquisition	Absent / dew / partially wet / saturated; time of observation	Mandatory	TIR + MS	Evaporative cooling and reflectance changes from a wet surface can dominate the thermal signal and mimic or mask an archaeological

Field	Definition	Unit / format	Status	Applies to	Rationale
					anomaly
Row spacing and orientation	Sowing geometry of the crop	cm; degrees from north	Recommended	TIR + MS	Sets the spatial frequency of the canopy and can alias with feature width
Agronomic management	Dates and quantities of irrigation and fertilisation	Dates; mm; kg ha ⁻¹	Recommended	TIR + MS	Can suppress an archaeological signal or generate a spurious one
Soil	Soil type and texture in a stated classification	WRB or national system	Recommended	TIR + MS	Governs thermal inertia and water retention
Processing chain					
Radiometric correction	Method and reference target used to convert raw values to reflectance or temperature	Free text + citation	Mandatory	TIR + MS	Determines whether values are transferable beyond the single flight
Mosaicking	Software and version used for alignment and orthomosaic generation	Name + version	Mandatory	TIR + MS	Version-dependent defaults alter radiometry, not only geometry
Index definitions	Explicit formula for every index computed	Equation	Mandatory	MS	Named indices exist in incompatible variants
Enhancement or classification	Every operation applied after mosaicking, with its parameters	Named method + parameters	Mandatory	TIR + MS	“Standard processing” is not a reproducible description