

Multi-temporal assessment of land-condition change around Shwan Refinery Iraq using Landsat observations and soil metal evidence

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ABSTRACT

This study assesses land-condition change around Shwan Refinery, Iraq, using 79 Landsat 8 Collection 2 Level-2 scenes covering fourteen summers (2013–2026) and twenty secondary soil-metal records. QA-masked summer medians were summarized on common valid support in five distance zones extending 10 km from an internal reference point. First-zone descriptive Theil–Sen slopes of annual means were +0.002066 per year for NDVI, +0.000703 for NDMI, –0.001015 for BSI and –0.009243°C per year for LST. Negative pixel-level NDVI slopes occurred in 23.29% of common first-zone cells. The four-sign screening condition—declining NDVI and NDMI with rising BSI and LST—occurred in 6.27% of first-zone cells and 9.48% of outermost-zone cells; these are not validated degraded areas. NDBI equals –NDMI and supplies no independent confirmation. Year-omission checks retained positive NDVI and negative BSI first-zone mean slopes, but their magnitudes were sensitive to 2026; NDMI and LST signs changed. Original spatial omission maps identified mixed NDVI signs in 57.20% of first-zone cells. Conditional residual block-bootstrap tests found no significant trend after Holm adjustment across 20 index–zone series at block lengths of two, three or four years. Summer NDVI covaried with antecedent rainfall (Spearman $\rho = 0.8505$). Soil associations remained exploratory, without calibrated metal prediction or repeat chemical measurements. The evidence indicates heterogeneous surface change but does not establish generalized persistent degradation caused by refinery operations, exclude an industrial contribution or demonstrate environmental safety. Short-series uncertainty, climate covariation, spatial dependence and limited soil sampling constrain interpretation.

Keywords: land-condition change; Shwan Refinery; satellite observations; soil metals; spatial screening.

INTRODUCTION

Land degradation concerns changes in the capacity of land to sustain its functions, whereas satellite indices describe selected aspects of vegetation, exposed surfaces and surface temperature. These observations can identify locations requiring investigation, but an index trend alone does not establish loss of land function. A recent review emphasizes the limitations of vegetation-based assessments and the need for complementary indicators and contextual evidence (D’Acunto et al., 2024). In an industrial

landscape, a further distinction is essential: detecting land-condition change and identifying its cause are separate tasks. Distance from a refinery is a reproducible spatial descriptor, but it is not a measurement of exposure.

Petroleum-related activities can create pressures on Iraqi soils through wastes containing hydrocarbons, salts and trace metals. Sharif (2026) evaluated potential land-degradation risks from drilling-waste disposal through a literature-based analytical framework, including uncertainty arising from limited data. Such evidence establishes a regional motivation for monitoring; it does not

demonstrate a refinery-specific effect at Shwan. Landsat-based work around Al-Dora Refinery examined land-cover and thermal changes using selected observations (Sant and Al-Ramahee, 2024). In Kirkuk, Abdulqader and Jasim (2026) developed a GIS and multi-temporal remote-sensing assessment of heavy-metal redistribution susceptibility and monitoring priorities around KAT Refinery. These studies provide relevant regional comparisons, while their findings cannot be transferred directly to another refinery.

Soil chemistry supplies evidence that cannot be inferred reliably from broad-band index values alone. Laboratory research on Pb-contaminated calcareous and gypsum soils, including soils amended with used engine oil, illustrates the importance of direct chemical measurements and soil-specific processes (Al-Robai et al., 2021). Reviews of remote sensing of soil metals likewise distinguish empirical associations from direct detection and emphasize calibration, confounding and validation (Wang et al., 2024; Lovynska et al., 2024). Thermal observations also depend on landscape setting: developed surfaces can be cooler than surrounding exposed land in dry environments (Lazzarini et al., 2013). Consequently, neither a soil-index correlation nor a radial thermal contrast identifies an industrial cause by itself.

Previous investigations provide a Shwan-specific basis for the present assessment. Al-Teay and Al-Jumaily (2023) investigated heavy metals in twenty surface-soil samples around Shwan Refinery. Ibrahim and Azeez (2024) evaluated spectral indicators across the broader Shwan–Altun Kopri area using selected years, 1997, 2014, 2020 and 2023. Geochemical work in the wider Shwan Sub-basin identified both natural and anthropogenic influences, including agricultural and industrial activities (Al-Gburi et al., 2023). These studies motivate testing the temporal persistence and spatial coherence of refinery-area signals, without assuming a single source for the observed conditions.

The present study assesses land-condition change around Shwan Refinery through a fourteen-summer Landsat record for 2013–2026, descriptive robust trends, year-omission sensitivity, regional climate covariation, spatial screening and localized soil-metal evidence. Its contribution is the integration of these complementary assessments, rather than a claim to be the first remote-sensing study in Shwan. The objectives are to characterize annual and spatial variation, examine the sensitivity of trend directions and

magnitudes to individual summers, identify cells meeting a clearly defined four-sign screening condition, and evaluate the scope and stability of exploratory soil–satellite associations. The analysis distinguishes these observational results from validated degradation and causal attribution. An additional conditional block-bootstrap assessment and original pixel-level omission-stability maps extend the quantitative and spatial evaluation. This is an observational monitoring contribution, not a new index or estimator. No benchmark establishes general superiority over alternative land-change methods. Its purpose is to show which spatial patterns and temporal directions remain interpretable after the stated sensitivity checks, and which claims the available evidence cannot support.

MATERIALS AND METHODS

The study covered a circular area extending 10 km from an internal reference location at Shwan Refinery. This location was calculated as the mean of the four sampling coordinates Sh1–Sh4 reported in Al-Taey (2022): 35.4470638889° N, 44.5700958333° E. It provides a reproducible origin for measuring distance, rather than a surveyed geometric center. A circular framework was adopted because the available imagery did not allow the entire refinery perimeter to be identified confidently.

Five distance zones were defined at 0–1, 1–2, 2–3, 3–5, and 5–10 km. The first zone included the reference location, refinery facilities, and their immediate surroundings. Distances were measured from raster-cell centers in UTM zone 38N. The thesis coordinates were provisionally interpreted as WGS84 because their datum could not be independently confirmed. The study setting and sampling geometry are shown in Figures 1 and 2, respectively.

The primary temporal analysis used 79 Landsat 8 Collection 2 Tier 1 Level-2 L2SP scenes from path 169/row 035, acquired between 1 June and 31 August in each year from 2013 to 2026. The originally selected July scenes—17 July 2013, 28 July 2017, 23 July 2021, and 21 July 2026—were retained for supplementary date-specific comparisons. A Landsat 5 TM scene from 17 July 2007 was reviewed separately as a historical baseline, without assigning it a pre-operation status. Matching an acquisition month does not

ensure equivalent surface or atmospheric conditions. The primary dataset is documented by the Earth Resources Observation and Science (EROS) Center (2020). The index composites, trend maps, omission summaries and spatial screening products were derived within the present analysis; the public datasets are their inputs, not previously published study maps.

QA_PIXEL was used to exclude fill, clouds, dilated clouds, cloud shadows, and snow; cirrus was also excluded for Landsat 8. QA_RADSAT removed sensor-defined saturated pixels, along with dropped pixels for Landsat 5 and terrain occlusion for Landsat 8. Water was retained. Exclusion counts were calculated as unions, so a pixel

carrying several flags was counted once. The annual-composite processing applied a shared source-band non-fill mask before index-specific denominator checks. It did not apply additional thresholds to SR_QA_AEROSOL or ST_QA; the retained observations therefore remain subject to residual atmospheric and temperature-retrieval uncertainty.

Reflectance was converted as $DN \times 0.0000275 - 0.2$, and surface temperature as $DN \times 0.00341802 + 149.0 - 273.15^{\circ}\text{C}$. The coefficients were verified against each scene's metadata. The delivered Level-2 temperature product was used without introducing an assumed emissivity. These conversions and flag definitions follow the USGS

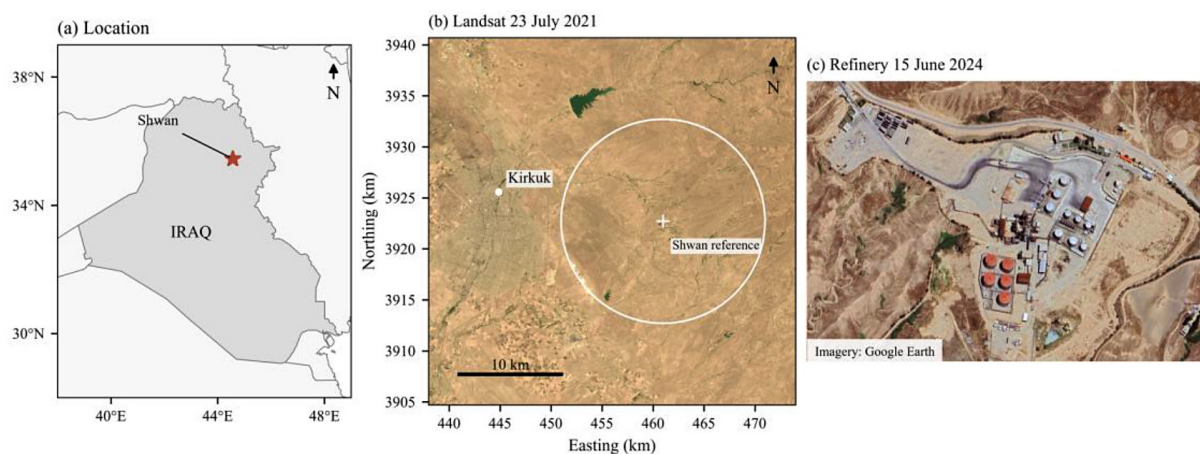


Figure 1. Study location and refinery context: (a) Iraq and neighboring countries; (b) Landsat natural-color imagery, 23 July 2021, with the 10 km study extent and Kirkuk; (c) supplied Google Earth imagery displayed as 15 June 2024. Natural Earth supplies boundaries and Kirkuk location. The reference is the mean of Sh1–Sh4, not a surveyed centroid. Panel (c) provides visual context only

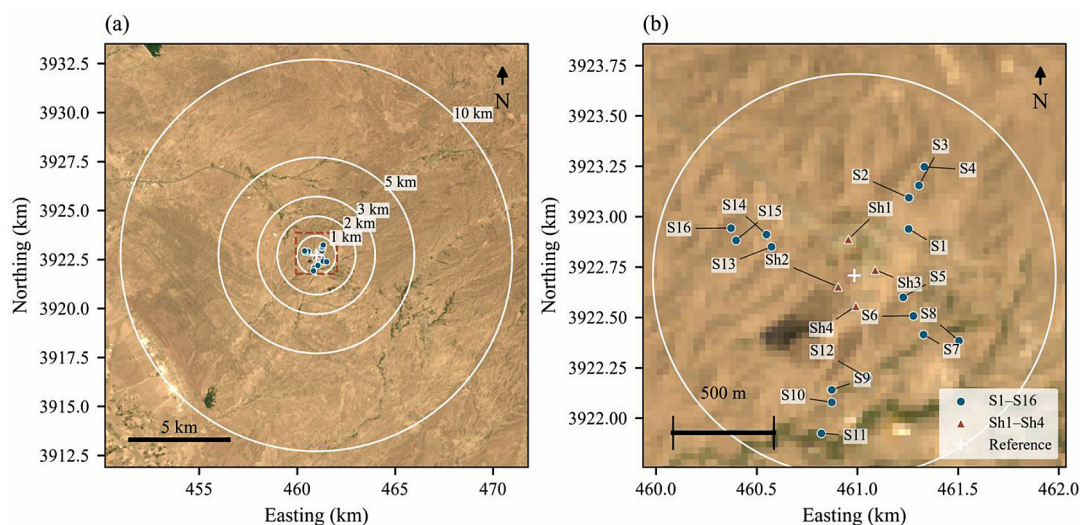


Figure 2. Distance zones and twenty January 2021 soil locations: (a) 10 km extent with rings at 1, 2, 3, 5 and 10 km; (b) enlarged sampling cluster. Blue circles denote S1–S16 and orange triangles Sh1–Sh4; all lie within 1 km. Background: QA-masked Landsat natural color, 23 July 2021. Axes use UTM 38N; soil coordinates are provisionally WGS84. The image postdates sampling and is not a quantitative exposure map

scaling guidance and QA documentation. Scaling coefficients follow USGS (n.d.-d), and the QA bit definitions follow USGS (n.d.-a).

Natural-color context was prepared from Landsat 8 surface-reflectance bands 4, 3 and 2 using the same QA exclusions. A fixed display stretch of 0.015–0.350 reflectance and gamma 1.5 was applied across the four selected scenes; it does not alter the quantitative index rasters. The detailed Google Earth view supplied by the author, displayed imagery date 15 June 2024, illustrates refinery facilities only and was not used for coordinate overlays or numerical change measurements.

NDVI, NDMI, BSI, and NDBI were calculated from scaled reflectance using the appropriate sensor bands. For Landsat 5, blue, red, NIR, and SWIR1 were B1, B3, B4, and B5; the corresponding Landsat 8 bands were B2, B4, B5, and B6. Source-band fill and near-zero denominators were excluded. The scenes shared an aligned 30 m grid and were cropped without interpolation. Calculated values were not forced into a predetermined range. The equations and complete band mapping are retained in the technical processing record. Here NDVI denotes the normalized difference vegetation index, NDMI the normalized difference moisture index, BSI the bare soil index, NDBI the normalized difference built-up index, and LST land surface temperature. Landsat NDMI follows the NIR–SWIR formulation documented by USGS (n.d.-b). Gao (1996) provides the broader vegetation-water-index basis, although its original SWIR wavelength differs from Landsat SWIR1. NDBI follows Zha et al. (2003).

Using scaled blue (B), red (R), near-infrared (N) and shortwave-infrared (S) reflectance, the indices were calculated as follows:

$$\text{NDVI} = (N - R)/(N + R) \quad (1)$$

$$\text{NDMI} = (N - S)/(N + S) \quad (2)$$

$$\text{BSI} = [(S + R) - (N + B)]/[(S + R) + (N + B)] \quad (3)$$

$$\text{NDBI} = (S - N)/(S + N) \quad (4)$$

Denominators with absolute values $\leq 10^{-12}$ were excluded. The temperature bands were ST_B6 for Landsat 5 and ST_B10 for Landsat 8. The delivered product incorporates emissivity inputs, so no additional emissivity correction was applied. Equations (2) and (4) imply $\text{NDBI} = -\text{NDMI}$ for identical NIR and SWIR1 inputs.

NDBI is retained only for presentation and excluded as additional evidence.

Descriptive statistics were calculated for each date and distance zone. Temporal comparisons additionally used the intersection of valid pixels. Eight directional sectors were examined within each zone to determine whether the circular means concealed spatial variation. Sectors were defined relative to UTM grid north and were not interpreted as wind directions.

Standard deviations describe pixel populations (ddof = 0); Spearman coefficients use average ranks for ties. Circular and directional comparisons used common valid support, with 2007 excluded from endpoint differences. Supplementary Material S1 details the sector geometry and retained masks. Raster counts describe coverage rather than independent replicates; spatial dependence and coarser native thermal information preclude inference based on nominal cell counts.

The soil dataset comprised 20 samples collected in January 2021 at 0–20 cm depth. The present authors did not collect these samples or perform their chemical analyses. Eleven metal concentrations were transcribed from Al-Taey (2022). A fresh transcription confirmed all 220 entries against the analysis input without changing any source concentration. The present contribution is secondary-data analysis and integration with satellite observations. Records were linked by sample identifier to July 2021 imagery; this is a same-year spatial association, not simultaneous sampling. The study by Al-Taey and Al-Jumaily (2023) supplies published context for the same sampling investigation, rather than an independent validation dataset.

The thesis describes drying, grinding and 200-mesh sieving, with 20 g of prepared material sent to the geology laboratories in the Faculty of Engineering, Ankara University. Its ICP-MS section describes a 2 g aliquot, Teflon vessels and an $\text{HClO}_4\text{--HNO}_3\text{--HF--H}_2\text{O}$ digestion mixture. An acid ratio previously introduced through PDF text extraction has been removed because it did not match the source-page image. These are source-reported procedures, not analyses performed or a laboratory SOP independently verified by the present authors. Supplementary Material (Tables S1–S6) reports detection limits, reference-material comparisons, the S5 repeat and source discrepancies. The primary concentration table remains unchanged; campaign-linked certificates and metal-analysis blank results were not verified.

A separate author-side recalculation from the verified concentrations and saved July 2021 extractions reproduced all 198 exploratory Spearman coefficients and their leave-one-sample-out bounds without numerical differences. A discrepancy sensitivity check substituted the repeatable S5 value for Co or Cd separately, without changing the retained input table. Among 18 all-sample coefficients, one near-zero Co–LST neighborhood association changed sign (+0.0090 to −0.0120); the largest absolute coefficient difference was 0.1882 for Cd–NDMI neighborhood means. This quantifies source-table sensitivity, not a correction or laboratory validation (Supplementary Material – Table S9).

Containing-pixel values and 3×3-cell neighborhood means were extracted for each sample. Spearman correlations were examined for all 20 samples and for S1–S16 separately. NDBI was excluded from the association matrix because it is the negative of NDMI under the adopted equations. Sensitivity was assessed by omitting one sample at a time and by applying hypothetical shared shifts to the sampling locations: 30 m along either coordinate axis and approximately 42.4 m along the diagonals (30 m in each axis). The same offset was applied to every sample in each scenario. These tests describe dependence on individual observations and extraction position; their ranges were not treated as confidence intervals or measured GPS errors. No causal interpretation or inferential significance claim was assigned to the coefficients.

First-zone and outer-zone 2021 cells were compared within shared ESA WorldCover 2021 v200 classes (Zanaga et al., 2022) and elevation–surface-slope strata. Outer stratum means were standardized to retained first-zone cell proportions. Four exploratory grouping schemes, detailed in Supplementary Material S1, tested landscape composition without establishing exposure matching or an unaffected control.

A supplementary 23-scene comparison used all catalogued summer scenes for 2013, 2017, 2021 and 2026, respectively 5, 6, 6 and 6 scenes. QA rules, scaling and the source grid were unchanged. Seasonal medians required at least two valid observations, and comparisons used common support; Supplementary Material S1 reports monthly balancing and further seasonal checks. Catalogue access followed Microsoft Planetary Computer (n.d.).

The primary fourteen-year analysis included all 79 catalogued Landsat 8 Tier 1 L2SP summer scenes for 2013–2026, retaining the same processing and minimum two-observation rule. Per-index common support was recalculated across all fourteen annual summer composites. Descriptive Theil–Sen slopes (Sen, 1968) were computed as the median of 91 pairwise slopes. Pixel-level slopes and slopes of annual zone means were retained separately; they are different summaries. The original pixel slope maps remain descriptive, without significance labels or independent-pixel inference. Conditional uncertainty for slopes of annual zone means is assessed separately below; no causal interpretation is assigned.

For sensitivity to individual summers, each zone-mean trend was recomputed after omitting one year at a time. This produced fourteen omission scenarios for each of four nonredundant indices and five zones. The original fourteen-year common pixel support was held fixed; the masks and composites were not rebuilt. Omission ranges describe sensitivity of the saved annual summaries, not confidence intervals or a test of statistical significance.

Regional climate context was extended to all fourteen years using daily ERA5 (Hersbach et al., 2020) precipitation and 2 m air temperature, with UTC dates and elevation adjustment disabled. January–May precipitation represented an antecedent window; June–August rainfall and mean air temperature represented summer context. Spearman associations were examined for all four nonredundant indices and five zones, with leave-one-year-out sensitivity. The 60 retained relationships are exploratory annual associations and do not constitute a weather-adjusted causal model. Reanalysis data were retrieved through the Open-Meteo historical API (Open-Meteo, n.d.); they provide regional context rather than separate climate measurements for each distance zone.

The four-sign screening condition was defined as the co-occurrence of negative pixel-level NDVI and NDMI slopes with positive BSI and LST slopes, on common support across all fourteen summers. All sixteen possible sign combinations were retained. NDBI was not counted as a separate confirmation because it is the negative of NDMI under the adopted equations. The four retained indices also share spectral inputs and are not independent measurements. Zero was used only to identify sign, without a validated minimum effect or uncertainty threshold; sign agreement was

not interpreted as degradation severity. Figure 7 presents the mapped screening result.

A supplementary soil-location follow-up compared 2021 and 2026 summer composites at the twenty sampling locations. Containing-cell values and 3×3 means were retained; neighborhood endpoint differences used cells valid in both summers. Associations between January 2021 metal concentrations and subsequent index differences were exploratory, with all-sample and external-sample groups and leave-one-sample-out sensitivity. No 2026 metal measurements were inferred. Separately, expanding-origin hindcasts used at least eight annual observations and one-, two- and four-year horizons, comparing Theil–Sen extrapolation with persistence and the available historical mean. Future target values were excluded from fitting; cases were not treated as independent samples.

Additional uncertainty assessment and spatial omission stability

An exploratory uncertainty assessment used the fourteen annual zone means for NDVI, NDMI, BSI and LST in five zones (20 series); NDBI was excluded because it equals $-NDMI$. The original Theil–Sen estimates were reproduced without altering the underlying observations. A robust intercept was the median of the annual value minus the fitted slope times year. Mean-centered residuals were resampled in circular contiguous blocks, following the block-bootstrap principle for dependent observations (Künsch, 1989). Each replicate concatenated randomly selected blocks, wrapping at the end of the series, and retained the first fourteen residuals. There were 19,999 replicates with seed 20261008; block length three years was primary, with two and four years as sensitivity settings. Resampling positions were shared across series at each setting. Adding resampled residuals to the fitted line yielded bootstrap slopes and unadjusted 95% percentile intervals. Under a zero-trend null, slopes of the resampled residuals supplied two-sided exceedance probabilities, computed as $(1 + \text{number with absolute slope at least the observed absolute slope}) / (19,999 + 1)$. Holm adjustment was applied to the 20 probabilities separately at each block length (Holm, 1979).

These are approximate, conditional uncertainty estimates, requiring sufficiently weak dependence and approximately stationary detrended residuals. Fourteen summers do not support

strong validation of those assumptions. Zones and indices are correlated; pixels were not treated as independent replicates, and no pixel-level significance was inferred. The analysis is exploratory and was added after inspection of descriptive trends. It is neither a climate-adjusted attribution model nor a calibration of degradation thresholds. Separately, each cell slope was recomputed for all fourteen single-year omissions on the unchanged full-series valid support. A stable negative or positive category required that sign in both the full series and every omission. A separate category, assigned before interpreting mixed signs, flagged any zero omission slope; remaining mixed cells contained both positive and negative signs across the full and omission fits. Original year spacing was retained. These categories summarize temporal direction sensitivity, not confidence levels.

Computational traceability was checked separately from measurement validity and environmental interpretation. A fresh extraction of the base archive supplied the complete seven raster inputs used for every one of the 79 scenes: 553 aligned source-band and QA rasters spanning the study-area grid. The offline numerical runner and bootstrap/omission extension reproduced values exactly in 395 scene-level index rasters, 144 annual/composite-count/trend rasters and 24 spatial stability arrays. All 51 compared output tables and both extension tables agreed within recorded tolerances. A separate recalculation reproduced all 198 soil-association coefficients and leave-one-sample-out bounds. The paired 2007 replay reproduced all 30 saved mean/count comparisons. These checks were performed by the manuscript preparation team using existing dependencies; they are not external independent replication or a fresh dependency installation. The aligned raster inputs cover the complete study-area grid used by the analysis.

RESULTS

Primary annual patterns and climate context

The primary annual series included 79 scenes and retained 3,491 common first-zone cells. Mean summer-median NDVI in that zone ranged from 0.12643 in 2022 to 0.20425 in 2026, with intervening declines and rebounds. The Theil–Sen slope of its annual zone means was $+0.002066$

NDVI units per year; corresponding slopes were $+0.000703$ for NDMI, -0.001015 for BSI, and $-0.009243^{\circ}\text{C}$ per year for LST. Negative pixel-level NDVI slopes occurred in 23.29% of common first-zone cells. These sign counts include changes of any magnitude and are not a degradation classification. Counts differ slightly from the earlier four-summer analysis because the complete annual comparison uses a stricter common support. Figure 3 and Table 1 summarize annual variation and zone-mean slopes.

Slopes of annual zone means differ from the mean or median of pixel slopes. This table reports descriptive estimates; conditional zone-level uncertainty is assessed separately in Table 6. No causal interpretation is assigned. NDBI slopes are the negatives of NDMI slopes.

Across the fourteen annual first-zone summaries, summer NDVI was positively associated

with January–May precipitation (Spearman $\rho = 0.8505$), with leave-one-year-out values of 0.8187 – 0.9066 . Corresponding antecedent-rainfall associations were $+0.5077$ for NDMI and -0.5736 for BSI. Summer LST was positively associated with mean summer air temperature ($\rho = 0.4286$). These relationships identify regional climatic covariation requiring consideration, without isolating rainfall effects, accounting for all temporal dependence, or excluding industrial influences.

First-zone NDVI slopes remained positive in all fourteen year-omission scenarios, ranging from $+0.000112$ to $+0.003092$ per year. Omitting 2026 reduced the slope to $+0.000112$, compared with $+0.002066$ for the full series, showing substantial sensitivity of its magnitude to the final summer. First-zone BSI slopes remained negative in all scenarios, whereas NDMI ranged from -0.000229

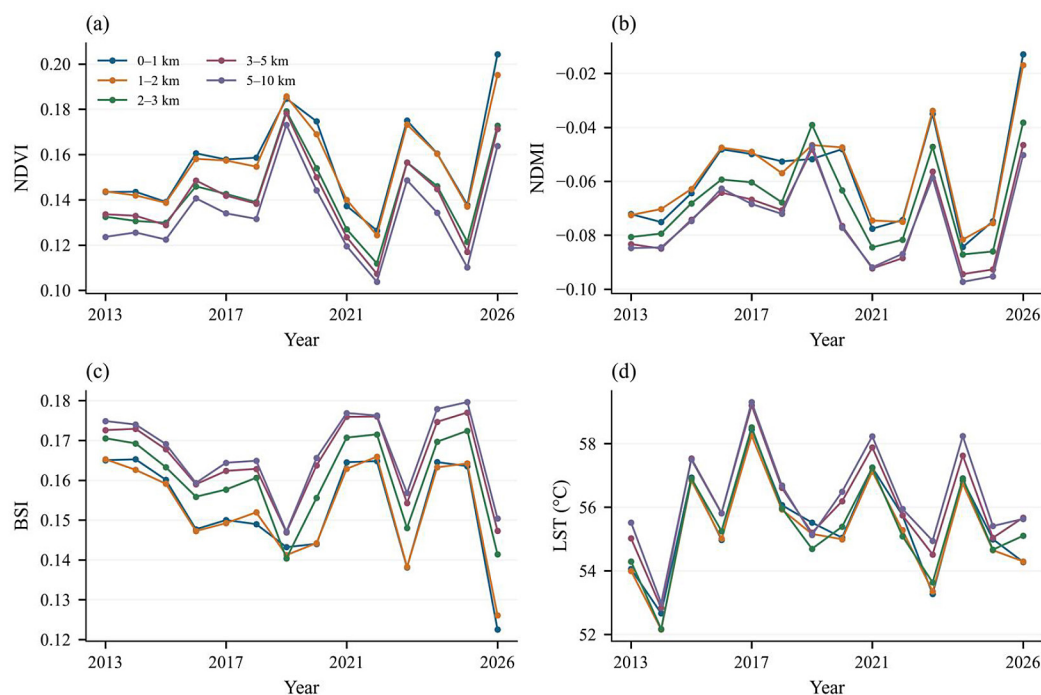


Figure 3. Annual zone means of per-cell summer median NDVI, NDMI, BSI and LST for June–August 2013–2026. Each annual cell required at least two QA-valid observations; summaries use common support across fourteen summers. Lines join annual summaries and do not establish continuous change or uncertainty intervals

Table 1. Descriptive slopes of annual zone means for 2013–2026

Distance km	Common cells	NDVI /year	NDMI /year	BSI /year	LST $^{\circ}\text{C}/\text{year}$
0–1	3491	$+0.002066$	$+0.000703$	-0.001015	-0.009243
1–2	10475	$+0.001843$	$+0.000539$	-0.001286	-0.040937
2–3	17446	$+0.001288$	$+0.000123$	-0.000347	$+0.000503$
3–5	55848	$+0.001070$	-0.000461	$+0.000176$	-0.011904
5–10	261821	$+0.001144$	-0.000498	$+0.000277$	$+0.002070$

to $+0.002829$ per year and LST from -0.106936 to $+0.060252^{\circ}\text{C}$ per year. The NDVI slope changed from positive to negative when 2026 was omitted in the 2–3, 3–5 and 5–10 km zones. NDMI and LST signs changed under omissions in every zone,

and BSI signs changed in the three outer zones. These results limit interpretations of a stable landscape-wide direction. Table 2 reports the first-zone omission results. Figure 4 shows the spatial distributions for four selected summers, and Figure 5

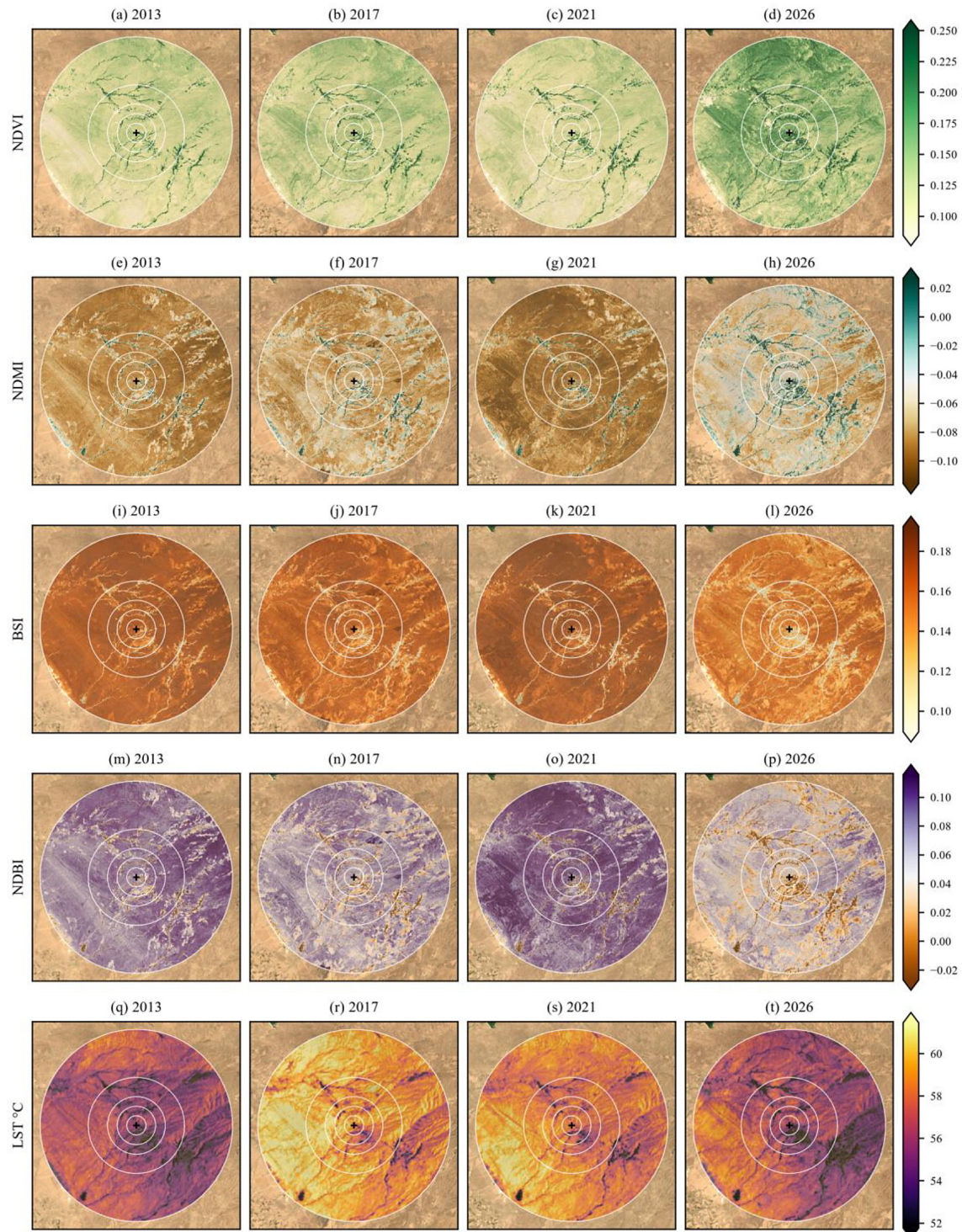


Figure 4. Original June–August summer-median index maps on common fourteen-year support, overlaid on selected Landsat natural-color scenes for 2013, 2017, 2021 and 2026. Rows show NDVI, NDMI, BSI, NDBI and LST; NDBI equals $-\text{NDMI}$. Each row uses identical pooled 2nd–98th percentile limits; extreme values are saturated for display. Circles mark 1, 2, 3, 5 and 10 km; north is upward. Supplementary Material records acquisition dates, band combinations and transparency settings. Colors do not classify degradation

Table 2. First-zone trend sensitivity to omission of individual summers

Index	Full slope /year	Minimum /year	Maximum /year	Positive / negative cases
NDVI	+0.002066	+0.000112	+0.003092	14 / 0
NDMI	+0.000703	-0.000229	+0.002829	12 / 2
BSI	-0.001015	-0.001984	-0.000126	0 / 14
LST °C	-0.009243	-0.106936	+0.060252	6 / 8

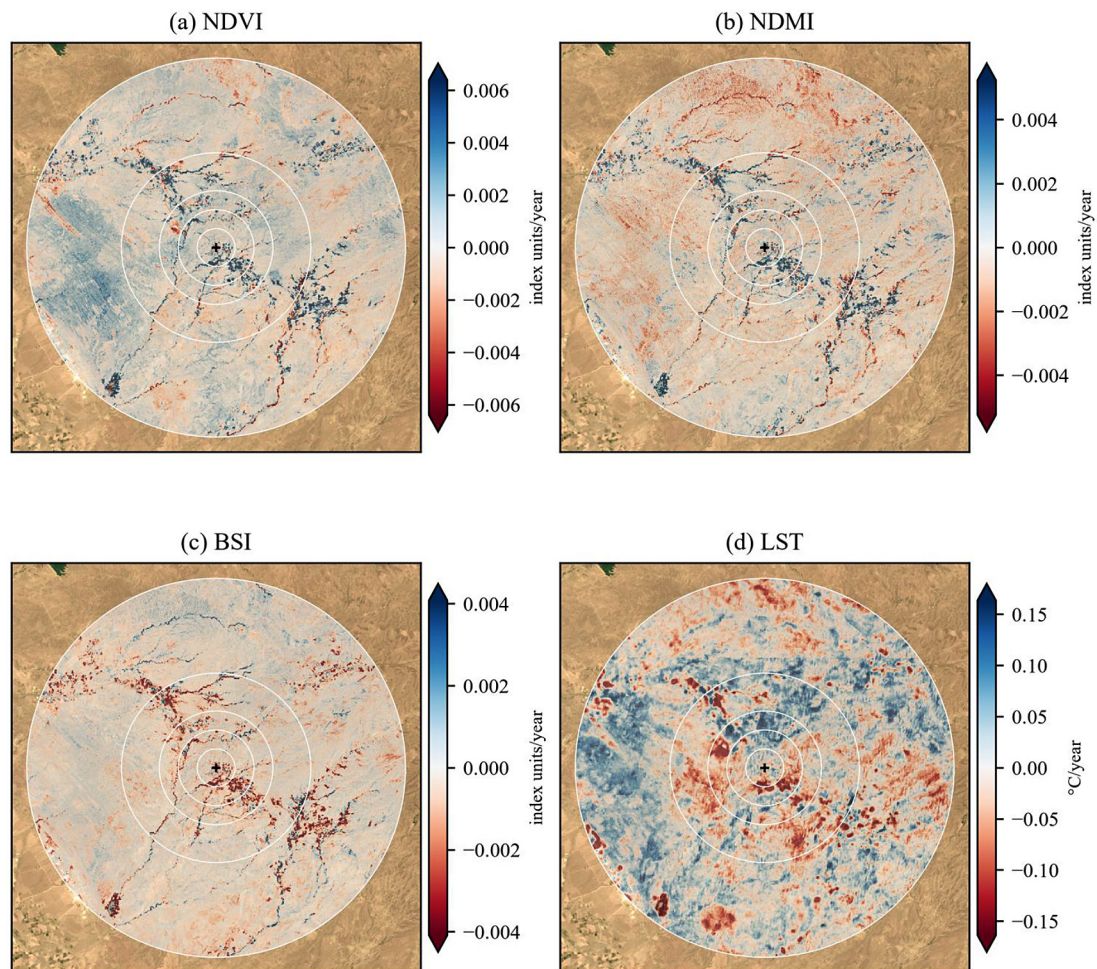


Figure 5. Original descriptive Theil–Sen pixel slopes for summers 2013–2026: (a) NDVI, (b) NDMI, (c) BSI and (d) LST, over Landsat natural-color imagery, 23 July 2021. Units are index/year or °C/year. Symmetric limits use each panel’s 98th percentile of absolute slope; extremes are saturated for display. Circles mark 1, 2, 3, 5 and 10 km. No pixel-level significance, minimum-effect threshold or causal attribution is assigned. NDMI would invert the NDMI map; display details are retained in Supplementary Material

maps the descriptive pixel-level slopes for the full fourteen-summer series.

Fourteen omission scenarios per index. The original common pixel support is fixed. Ranges are sensitivity summaries, not confidence intervals. Figure 6 displays the year-omission ranges for all five distance zones.

The four-sign screening condition occurred in 219 of 3,491 common first-zone cells (6.27%).

The corresponding proportions were 5.81%, 6.06%, 8.45%, and 9.48% in the successive outer zones. This screening condition identifies locations for investigation of possible degradation, but does not estimate validated degraded area. The absence of a simple outward decline in sign agreement does not establish an industrial exposure gradient or exclude refinery effects. Table 3 gives the zone-specific counts and percentages.

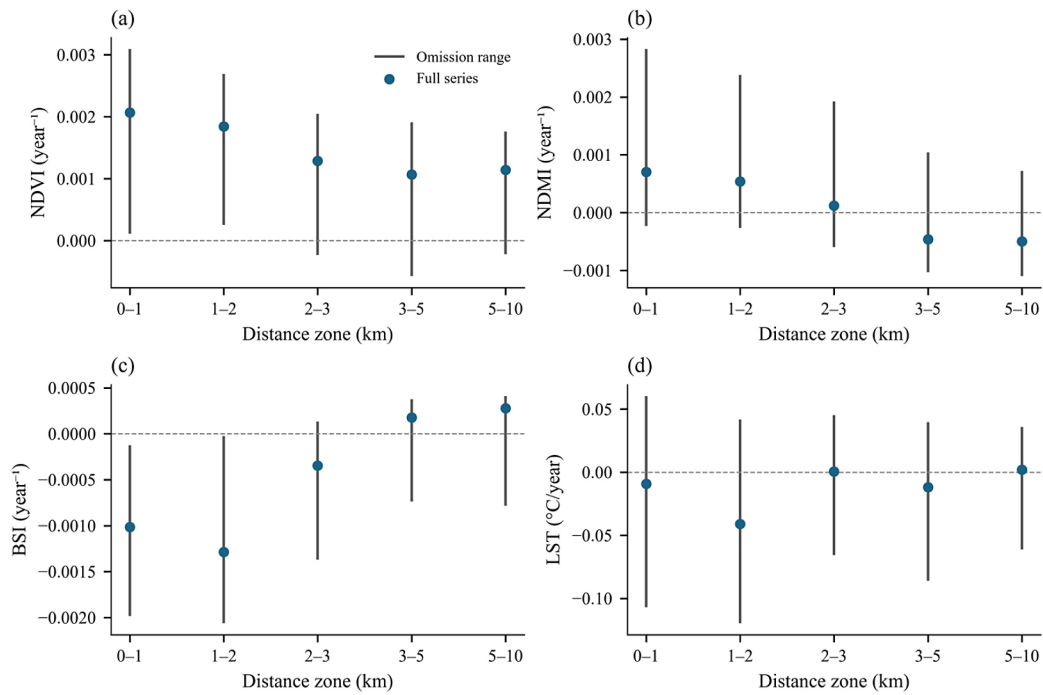


Figure 6. Sensitivity of annual zone-mean slopes to omission of individual summers: (a) NDVI, (b) NDMI, (c) BSI and (d) LST. Blue points are full-series slopes and vertical lines span the fourteen omission scenarios. Ranges are not confidence intervals. The fourteen-year common cell support remains fixed when an annual summary is omitted. Analytical output generated in this study from the processed Landsat observations.

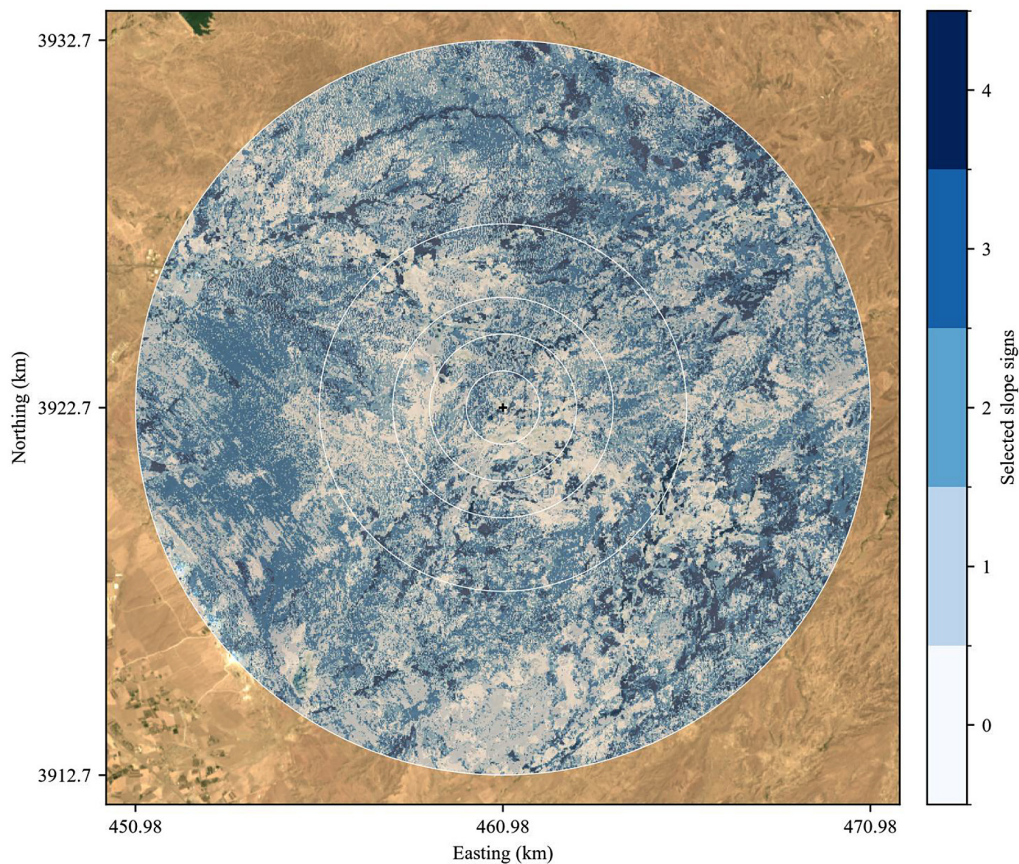


Figure 7. Original spatial agreement of selected slope signs for 2013–2026 over Landsat natural-color imagery, 23 July 2021, UTM 38N. The count is an exploratory screen, not a degradation score. Four-sign cells require further examination; size and proximity do not establish an industrial cause. Circles mark 1, 2, 3, 5 and 10 km; transparency details are retained in Supplementary Material.

Table 3. Cells meeting the four-sign screening condition

Distance km	Common cells	Four-sign cells	Percentage %
0–1	3491	219	6.27
1–2	10475	609	5.81
2–3	17446	1057	6.06
3–5	55848	4719	8.45
5–10	261821	24809	9.48

Selected signs: negative NDVI and NDMI with positive BSI and LST. Zero identifies sign only. These percentages are not validated degraded area or severity, and the indices are not independent confirmations.

Supplementary scene checks, spatial context and soil associations

Supplementary Material reports the selected-scene quality checks, directional contrasts, land-cover standardization and seasonal robustness. The new comparison of 1 and 17 July 2007, Level-1 checks and independent station-weather evidence are reported in Tables S7 and S8. They establish different acquisition conditions but do not uniquely quantify the causes of the discrepancy. Both 2007 acquisitions remain outside the primary 2013–2026 annual trends and endpoint comparisons.

All 20 soil locations fell within 1 km of the reference point. The field dataset consequently provides no metal measurements for the outer zones. Some published overall means also differed from those recalculated from the individual table entries. For Ni, the published value was 149.33 ppm and the row-based mean was 150.045 ppm. Individual sample values were retained unchanged, and the discrepancy was documented separately.

The 20 locations occupied distinct containing cells on the 30 m grid. Nevertheless, four sample pairs had overlapping 3×3 extraction windows: S2–S3 shared one cell, S9–S10 and S13–S14 shared three cells each, and S15–S16 shared two cells. Neighborhood means therefore partly shared spatial support for these pairs. Distinct containing cells do not establish independence of either the landscape observations or their underlying thermal information.

Using neighborhood means, illustrative exploratory coefficients included Hg–NDMI at -0.630 , Hg–BSI at $+0.583$, and Ni–NDVI

at -0.496 . These examples are drawn from the full set of relationships and are not independently confirmed hypotheses. Under the location-shift scenarios, the coefficients ranged from -0.630 to -0.414 , $+0.402$ to $+0.720$, and -0.556 to -0.412 , respectively. Their signs persisted in those scenarios, but their magnitudes varied. These findings do not demonstrate that a Landsat index directly measures metal concentration.

Landscape standardization retained the positive first-minus-outer NDVI contrast and negative LST contrast across all examined schemes. Seasonal and equal-month summaries preserved the first-zone greenness difference between selected summers without consistent cooling. Numerical contrasts and common-support counts are provided in Supplementary Material.

At the soil locations, 2026-minus-2021 differences in 3×3 summer-index means averaged $+0.07937$ for NDVI, $+0.07176$ for NDMI, -0.05012 for BSI and -3.02472°C for LST. NDVI increased at nineteen locations and decreased at Sh1; NDMI increased and BSI and LST decreased at all twenty locations. These endpoint differences do not establish continuous recovery or a change in metal concentration. No containing cell at the twenty locations met all four annual slope-sign conditions, although some neighboring cells did. In the temporal hindcasts, trend extrapolation did not outperform the historical-mean baseline for any of the four nonredundant indices at the examined horizons. Consequently, no future degradation projections were released. Varying valid neighborhood support, clustered sites, unmodelled climate and land-use influences, and the absence of calibrated prediction intervals limit this forecasting experiment.

The soil-location follow-up was also checked under eight shared location shifts and the original positions. Zero-shift outputs reproduced the saved results, while 29 of 44

all-sample metal–change associations retained their signs across all nine scenarios. Supplementary Material records the offsets and interpretive limits; sign persistence is not significance or predictive validation.

Supporting results for soil locations and temporal prediction

Tables 4 and 5 and Figure 8 provide the numerical support for the soil-location follow-up and hindcast results described in the main text. Differences are 2026 minus 2021 using paired-valid 3×3 neighborhood means. Index differences are dimensionless except LST in °C. No 2026 soil-metal measurements are available; these values do not measure metal change.

Training used at least eight summers. Cases are not independent. MAE is in index units or °C for LST. The historical mean outperformed Theil–Sen at every tested index and horizon; forecasts for 2028 and 2030 were not adopted.

Conditional trend uncertainty and original spatial stability maps

None of the 20 index–zone trends met a Holm-adjusted 0.05 criterion for block lengths two, three or four years. For the first zone, all four primary 95% percentile intervals included zero (Table 6). These unadjusted intervals describe conditional uncertainty for individual series, whereas the adjusted probabilities address the 20-test family. Lack of rejection does not establish that the underlying trends are zero. Complete results for all zones and block settings are provided in the accompanying analysis files.

Fourteen annual means; 19,999 replicates; primary block length three years. Intervals are individual, unadjusted percentile intervals. Holm probabilities account for 20 index–zone tests. Index slopes are dimensionless per year except LST in °C per year.

Figure 9 adds an original spatial analysis of the annual composites. Among the 3,491

Table 4. Summer-composite differences at twenty soil locations between 2021 and 2026

Index	Mean difference	Median difference	Positive sites	Negative sites
NDVI	+0.07937	+0.06780	19	1
NDMI	+0.07176	+0.05995	20	0
BSI	-0.05012	-0.03817	0	20
NDBI	-0.07176	-0.05995	0	20
LST °C	-3.02472	-2.96950	0	20

Table 5. Mean absolute errors in expanding-origin hindcasts

Index	Horizon years	Site-year cases	Last value	Historical mean	Theil–Sen
NDVI	1	120	0.03885	0.02953	0.03783
NDVI	2	100	0.04637	0.02967	0.03586
NDVI	4	60	0.04127	0.03123	0.05017
NDMI	1	120	0.03718	0.02921	0.03924
NDMI	2	100	0.04377	0.02941	0.03743
NDMI	4	60	0.04199	0.03488	0.05331
BSI	1	120	0.02520	0.01934	0.02682
BSI	2	100	0.02970	0.01969	0.02576
BSI	4	60	0.02893	0.02305	0.03678
LST °C	1	120	2.06393	1.37677	1.70571
LST °C	2	100	2.07309	1.27552	1.68125
LST °C	4	60	1.87360	1.23567	2.13482

Table 6. Conditional residual block-bootstrap uncertainty for first-zone annual trends

Index	Slope per year	95% interval	Unadjusted p	Holm p
NDVI	+0.002066	[-0.000606, +0.004163]	0.08920	1.00000
NDMI	+0.000703	[-0.001416, +0.002826]	0.37695	1.00000
BSI	-0.001015	[-0.002388, +0.000335]	0.13270	1.00000
LST (°C)	-0.009243	[-0.239906, +0.170775]	0.67575	1.00000

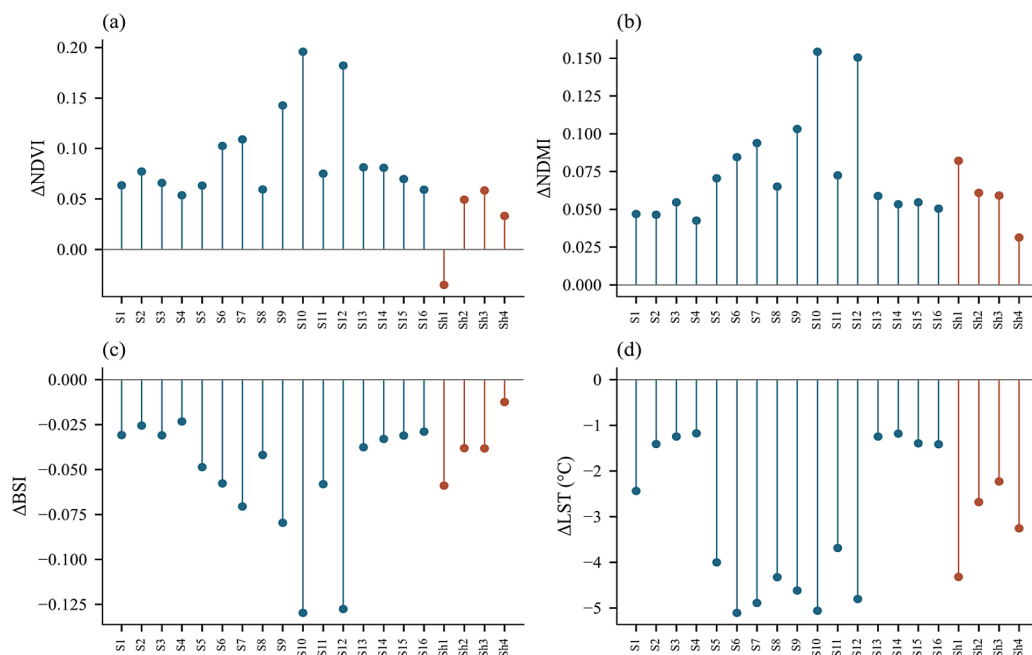


Figure 8. Differences between 2026 and 2021 summer composites at the twenty soil locations. Blue indicates S1–S16 and orange Sh1–Sh4. Stems connect each difference to zero and are not uncertainty intervals. NDBI is omitted because it equals –NDMI; it is retained in Table 4. Endpoint differences do not establish continuous recovery or pollution reduction.

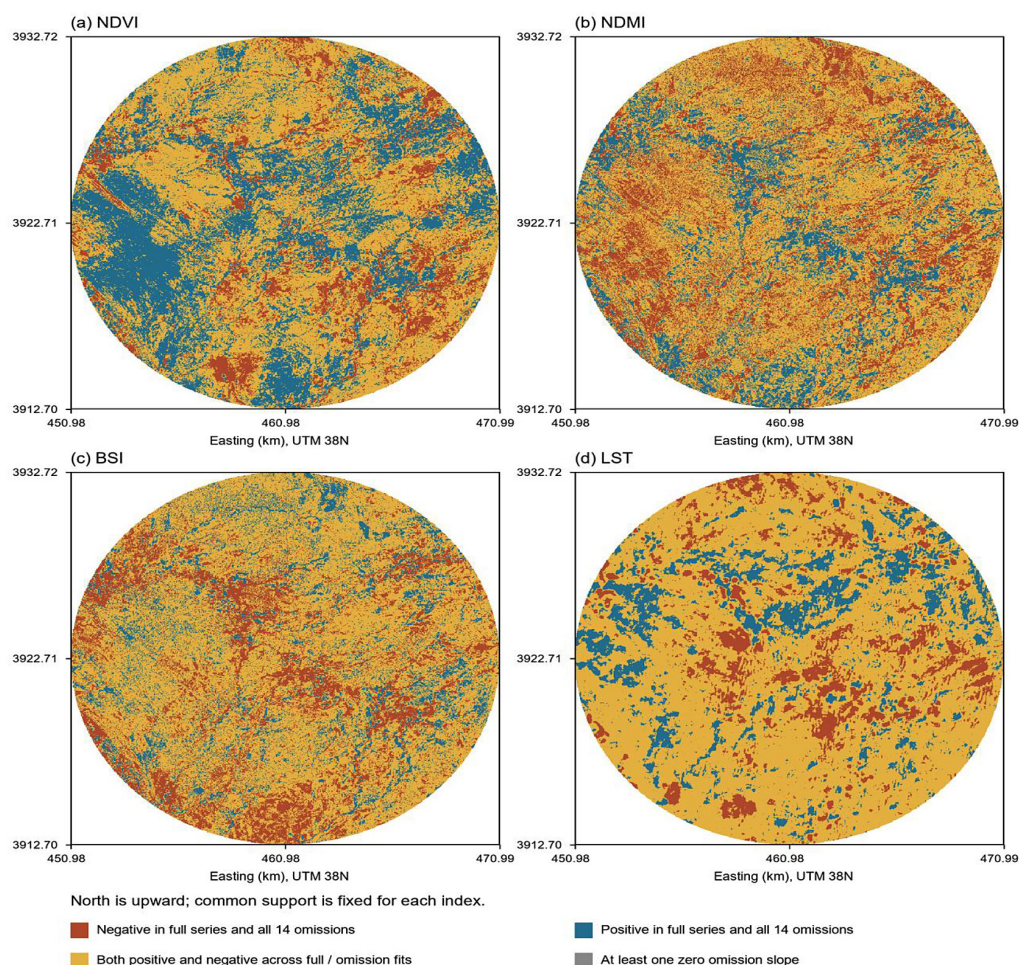


Figure 9. Original pixel-level direction stability for 2013–2026: (a) NDVI, (b) NDMI, (c) BSI and (d) LST. Negative and positive categories retain their sign in the full series and all fourteen single-year omissions. Mixed cells exhibit both signs; gray cells have a zero omission slope. Full-series common valid support is fixed for each index. Axes are WGS84 / UTM 38N in kilometres; white denotes outside-support cells. Categories describe temporal sensitivity, not significance, degradation thresholds or validated degradation.

first-zone NDVI cells, 1,203 (34.46%) remained positive in the full record and every omission, 291 (8.34%) remained negative, and 1,997 (57.20%) exhibited both signs across these fits. Thus, persistence of the zone-mean NDVI sign does not imply persistence at each cell. The map evaluates sign stability without changing the original four-sign screening percentages.

DISCUSSION

Spatial contrasts and the meaning of the screening condition

The indicator mismatch opposes a uniform degradation interpretation. First-zone positive mean NDVI and NDMI trends coincide with declining BSI, whereas outer-zone greening accompanies declining NDMI and increasing BSI. The larger outermost-zone screening proportion does not support a simple distance-based exposure pattern, although it cannot exclude an uneven industrial contribution. Shared spectral inputs also prevent treating sign agreement as confirmation by independent measurements. The four-sign condition identifies directions requiring investigation without establishing a calibrated effect threshold or loss of land function (D'Acunto et al., 2024).

Opposing within-class thermal contrasts show why circular averages require landscape context: first-zone grassland was cooler, but built-up cells were warmer, than their outer-zone counterparts. Land-cover and terrain standardization retained the NDVI and LST contrasts across the examined schemes, without controlling irrigation, soil properties or within-class surface differences. Sector variation reinforces this need for comparable landscape settings; circular distance zones are not measured exposure levels.

Daytime cooling of developed surfaces relative to exposed dry land is physically plausible (Lazzarini et al., 2013), consistent with the Iranian basin comparison (Dehghan Rahimabadi et al., 2024). Reference selection and summary statistics likewise affect thermal interpretation in industrial settings (Hamdi et al., 2025). These studies do not establish a refinery benefit at Shwan. Because the outer zone is not a verified unaffected control, its temperature cannot define a causal refinery heat-island effect.

Temporal sensitivity and climate covariation

Selected July endpoints indicate first-zone greening and cooling, but summer composites preserve the greenness difference without consistent cooling. First-zone NDVI and BSI mean slopes retain their signs under every omission; NDMI and LST do not. Removing 2026 substantially reduces NDVI magnitude and reverses its sign in the three outer zones. The direction evidence is therefore more persistent locally than across the landscape, while neither sign persistence nor an endpoint contrast establishes significance or continuous recovery.

NDVI covariation with antecedent rainfall offers a competing explanation for greening. Its positive association persists under year omissions, consistent with moisture influencing vegetation expression. The analysis does not separate rainfall from management, shared temporal variation or industrial influences. Final-summer sensitivity should consequently be assessed alongside climate context. The residual block bootstrap quantifies conditional trend uncertainty without fitting a climate-adjusted causal model.

The 2007 discrepancy was investigated using a second Landsat 5 scene from 1 July, with identical path/row, Level-2 scaling, QA rules and aligned common support. Across 349,034 paired cells, mean NDVI was 0.10224 on 1 July and 0.06188 on 17 July; mean Level-2 LST was 54.57521°C and 36.94082°C, respectively. Level-1 processing also retained substantial spectral and thermal contrasts, so a Level-2 scaling error in the local analysis does not explain them. Kirkuk AB station reports near the overpasses recorded air temperatures of 41°C versus 34°C, dew points of −3°C versus 10°C, and visibility of 9.0 versus 3.2 km, with dust/haze on 1 July and blowing dust on 17 July (NOAA NCEI, n.d.; Supplementary Material, Tables S7–S8). These regional observations support unequal meteorological and atmospheric conditions. The station is approximately 20 km away, air temperature is not LST, and the reports are not exactly simultaneous; they cannot attribute the entire 17.63°C LST difference to weather or demonstrate a sensor defect. Neither date is a dust-free control. The original 17 July scene is preserved, and no primary trend estimate depends on either 2007 acquisition.

The conditional bootstrap and omission map address different questions: uncertainty in annual

aggregate slopes and local dependence of slope direction on individual summers. No series survives Holm adjustment at any examined block length. This limits evidence for systematic trends without proving stability or absence of industrial effects. The short record, stationarity assumptions and climate covariation remain material. The mixed first-zone pixel signs also preclude extending a persistent zone-average direction to every location.

Scope of the soil evidence and predictive limits

The twenty first-zone soil samples cannot validate regional screening or a refinery-to-background metal gradient. Their January collection, July image linkage and 0–20 cm depth differ from satellite timing and physical support. Local associations cannot identify an emission source. The published Shwan investigation provides sampling context (Al-Teay and Al-Jumaily, 2023), while broader evidence of multiple natural and anthropogenic influences cautions against single-source attribution (Al-Gburi et al., 2023).

Analytical provenance further constrains the secondary soil evidence. The thesis documents reference-material analysis and one laboratory repeat, but these records do not establish campaign-wide precision or independently certified accuracy. Calculated recoveries were 139.17% for Mo and 80% for Cd; no documented acceptance criterion was verified. The printed Hg unit in the reference-material table and original S5 entries for Co and Cd that differ between source tables remain unresolved. Mn and Fe values are numerically consistent with oxide-to-element conversion within reported rounding, but the repeat-table labels do not establish oxide reporting (Supplementary Material, Tables S2–S5). This possible explanation is not used to replace primary concentrations. A blank in the organic-matter procedure does not establish a metal-analysis blank. Laboratory repeat analysis is not a second field-sampling campaign. Several reference-table comparison pairs also occur in an earlier XRF study of another setting (Meriç et al., 2009; Supplementary Material S1, Table S6). Without original batch records, the thesis comparison table is not treated as independently verified campaign-specific ICP-MS quality control. According to the authors, the original soil samples are no longer retained; repeat laboratory measurement of those specimens is therefore unavailable. This does not

prevent computational reanalysis of the recorded concentrations.

Reflectance–metal associations need not involve direct absorption by the metals (Rathod et al., 2016). Reviews emphasize mediation through soil constituents, vegetation and environmental properties, together with site-specific calibration requirements (Wang et al., 2024; Lovynska et al., 2024). Soil composition, moisture and land use could influence both concentrations and image values at Shwan. The observed coefficients are exploratory associations rather than concentration-retrieval functions.

Shared neighborhood cells, clustered locations and coarser native thermal information constrain independence. Persistent coefficient signs under hypothetical shared shifts demonstrate robustness only to those shifts; they do not verify datum, positioning accuracy or sample independence. Changing magnitudes, multiple exploratory associations and absent independent validation limit evidential weight. Follow-up should test prespecified relationships in additional samples and comparable background settings, without increasing apparent sample size through extra pixels or redundant indices.

Selected-year Shwan–Altun Kopri work provides regional context (Ibrahim and Azeez, 2024), and the KAT framework supplies a related monitoring comparison (Abdulqader and Jasim, 2026). Here, annual observations reveal reversals obscured by selected dates. Figures 4–7 and 9 are original study-derived analytical products, supporting spatial monitoring without establishing direct metal detection or a causal refinery effect.

The soil-location endpoint differences do not demonstrate reduced metal concentrations. Theil–Sen extrapolation also failed to outperform the historical mean in the examined hindcasts, providing no demonstrated forecasting advantage. Other predictive studies incorporated ground hyperspectral data and external verification (Liu et al., 2025), or calibrated multispectral models (Sourghali et al., 2026). Their results cannot validate the uncalibrated Shwan associations or justify mechanical extrapolation.

Uncertainty and monitoring implications

Visual examination of fifteen representative point contexts identified agricultural parcels, tracks, exposed surfaces, vegetation and incised terrain as competing landscape influences.

Twenty-two dated screenshots were retained; differing seasons and unassessed registration prevent change validation. Supplementary Material S1 details site selection, imagery dates, land-cover proportions, antecedent rainfall and regional winds. These contextual observations do not identify contamination, quantify erosion or establish exposure to refinery emissions.

Measurement uncertainty includes the historical scene anomaly, provisional datum, timing mismatch, unequal support and residual retrieval error. Temporal uncertainty includes year sensitivity and climate covariation; attribution uncertainty includes exposure and management differences and missing background metal samples. Sensitivity analyses address selected measurement and temporal questions, not causal attribution. Descriptive omission ranges and spatial screening remain separate from conditional zone-level inference. An unestablished refinery effect does not imply environmental safety.

Without repeat metal measurements, higher NDVI and lower BSI at sampling locations concern surface condition rather than chemical recovery. The field data cannot calibrate degradation thresholds, validate the four-sign condition or support health-risk assessment. These chemical and functional outcomes require independent measurements.

The maps can guide comparisons of screened and unscreened locations with matched cover and terrain, repeat sampling at documented sites and suitable background sites. Chemistry and functional indicators would test contamination and land-function loss; management and source information would strengthen attribution. Iraqi petroleum-waste evidence supports monitoring priority (Sharif, 2026), while soil-specific Pb research supports direct chemical assessment (Al-Robai et al., 2021). Neither establishes the cause at Shwan.

CONCLUSIONS

The fourteen-summer Landsat record reveals heterogeneous land-condition change around Shwan Refinery. First-zone positive NDVI and negative BSI slopes of annual means retained their signs under all year omissions, but their magnitudes were sensitive to 2026; NDMI and LST directions were less persistent. No index–zone trend met the Holm-adjusted significance criterion in the conditional block-bootstrap assessment.

Pixel-level omission maps showed local sign reversals despite a persistent zone-mean NDVI direction. Greenness alone therefore did not characterize the combined spectral and thermal change, and NDBI supplied no independent evidence because it equals $-NDMI$.

The four-sign screening condition occurred in 31,413 common-support cells, including 6.27% of first-zone cells and 9.48% of outermost-zone cells. It identifies a specific combination of observed directions rather than a validated degraded area. The spatial pattern does not establish a simple refinery-exposure gradient or generalized persistent degradation caused by refinery operations. The available observational design does not establish a causal relationship between refinery operations and the observed changes in remote-sensing indices.

At the twenty soil locations, 2026-minus-2021 summer-composite comparisons showed higher NDVI at nineteen sites, higher NDMI and lower BSI at all twenty, and an average LST difference of -3.02°C . These are surface-condition contrasts, not measured chemical recovery. Theil–Sen extrapolation did not outperform the historical mean in any examined hindcast setting, so the annual slopes did not provide a demonstrated forecasting advantage. The combined observational evidence neither excludes an industrial contribution nor establishes environmental safety.

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