



Vegetation and albedo dynamics across the desiccated Aral Sea basin: multi-scale evidence from MODIS, Landsat, and Sentinel-2

Kamal M. Muminov

Department of Space Research, Astronomical Institute, Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

ARTICLE INFO

Keywords:

Aral sea basin
Vegetation–albedo relationships
Scale dependence
Saxaul plantations
Remote sensing

ABSTRACT

The desiccated Aral Sea basin is among the world's largest human-induced dryland transformations and offers a unique setting for examining vegetation–surface interactions under rapidly evolving saline conditions. This study analysed vegetation and surface albedo dynamics from 2000 to 2025 using MODIS, Landsat, and Sentinel-2 observations across the former seabed, the Amu Darya delta, and representative saxaul plantations. Annual NDVI and surface albedo were evaluated using ordinary least-squares regression, Theil–Sen slope estimation, the Mann–Kendall trend test, detrended correlation, phase-space analysis, and local NDVI–albedo assessment. Positive NDVI trends indicated vegetation establishment across the seabed and restoration areas, while MODIS and Landsat data showed significant long-term increases in albedo over the exposed seabed. Phase-space analysis revealed a positive long-term NDVI–albedo association, contrasting with the inverse relationship typical of densely vegetated ecosystems. However, detrended analysis showed that this coupling reflected concurrent environmental transformation rather than persistent interannual vegetation–albedo interaction. Sentinel-2 observations revealed scale-dependent inverse NDVI–albedo relationships within local saxaul plantation sites, with a weaker, non-significant response in Saxaul_v1 and a stronger inverse response in Saxaul_v2. These findings demonstrate that increasing vegetation activity in saline drylands does not necessarily reduce surface albedo, highlighting the roles of substrate exposure, salinity, vegetation structure, ecological development, and spatial scale.

1. Introduction

Drylands occupy more than 40% of the Earth's land surface, support more than two billion people worldwide, and are highly sensitive to climate variability, land degradation, hydrological instability, and anthropogenic pressure. Ongoing climate change, increasing aridity, and expanding desertification are transforming dryland ecosystems globally by altering vegetation structure, surface energy balance, dust-emission regimes, and ecosystem functioning (Lioubimtseva and Henebry, 2009; Huang et al., 2016; Seddon et al., 2016; Piao et al., 2020). Satellite remote sensing has therefore become an essential tool for monitoring vegetation dynamics, ecological restoration, land degradation, and climate-related land-surface feedbacks across arid and semi-arid regions (Zhu et al., 2016; Chen et al., 2019).

Recent satellite observations have revealed widespread vegetation greening in many parts of the world, including numerous arid and semi-arid environments (Zhu et al., 2016; Chen et al., 2019; Piao et al., 2020). However, the ecological significance of greening trends remains highly context-dependent. In dryland ecosystems, increases in vegetation

indices may occur alongside ongoing land degradation, salinisation, hydrological instability, or environmental stress, thereby complicating the interpretation of remotely detected vegetation dynamics (Seddon et al., 2016; Wang et al., 2020).

Among global dryland systems, the desiccated Aral Sea basin represents one of the most dramatic examples of rapid anthropogenic environmental transformation (Micklin, 2007, 2010; Spoor, 1998; Indoitu et al., 2015). Since the second half of the twentieth century, large-scale diversion of the Amu Darya and Syr Darya rivers for irrigation has caused the severe shrinkage of the Aral Sea, exposing vast areas of former seabed characterised by saline sediments, evaporitic crusts, unstable surface conditions, and intense aeolian activity (Dukhovny, 2008; Zonn et al., 2009; Banks et al., 2022). The newly formed Aralkum Desert has become a major source of salt and dust transport in Central Asia, with important implications for regional ecosystems, agriculture, climate, and human health (Indoitu et al., 2015).

At the same time, the exposed seabed has undergone gradual but spatially heterogeneous vegetation colonisation involving halophytic pioneer species, sparse shrub communities, biological soil crusts, and

E-mail address: kamalmuminov1954@gmail.com.

<https://doi.org/10.1016/j.jaridenv.2026.105687>

Received 4 May 2026; Received in revised form 29 June 2026; Accepted 30 June 2026

Available online 2 July 2026

0140-1963/© 2026 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

large-scale anthropogenic restoration efforts, particularly saxaul (*Haloxylon* spp.) plantations (Breckle et al., 2012; Khamzina et al., 2006). Recent remote sensing studies indicate that vegetation development on the exposed seabed remains spatially fragmented and environmentally heterogeneous because of strong salinity gradients, hydrological variability, and substrate-related constraints (Shen et al., 2019; Duan et al., 2022; Conrad et al., 2020). Broader land-cover transformations across Central Asia have also been documented using long-term satellite observations, highlighting the importance of regional environmental change for understanding vegetation dynamics in arid ecosystems (Hu and Hu, 2019). The desiccated Aral Sea basin therefore provides a valuable large-scale case study for examining vegetation establishment, substrate evolution, salinisation processes, and ecological restoration along a well-defined gradient of environmental transformation.

Vegetation–albedo interactions play a central role in land-surface energy balance, ecosystem–climate feedbacks, and remote sensing interpretation (Betts, 2000; Bonan, 2008; Bright et al., 2017; Duveiller et al., 2018). In most forested and densely vegetated ecosystems, increasing vegetation cover is associated with a decline in surface albedo because vegetation absorbs a larger fraction of incoming solar radiation than bare soil (Betts, 2000; Bonan, 2008). Consequently, negative relationships between vegetation indices, such as the Normalised Difference Vegetation Index (NDVI), and surface albedo are widely reported in humid and agricultural environments (Tucker, 1979; Huete et al., 2002).

However, vegetation–albedo relationships in sparse drylands may differ substantially from those observed in densely vegetated systems. In arid environments characterised by discontinuous vegetation cover, bright saline soils, evaporitic crusts, and extensive substrate exposure, spectral responses may reflect mixed contributions from both vegetation and underlying surface materials (Okin et al., 2001; Asner, 1998). Soil salinity and evaporitic substrates can further complicate remote sensing interpretation because highly reflective surfaces may maintain elevated albedo values even during vegetation development (Metternicht and Zinck, 2003; Farifteh et al., 2008; Scudiero et al., 2015). Biological soil crusts may also contribute to surface radiative dynamics in drylands (Weber et al., 2016; Rodríguez-Caballero et al., 2018).

Despite substantial progress in remote sensing studies of the Aral Sea region, important questions remain regarding the interactions between vegetation development and surface radiative properties in newly exposed saline environments. First, most previous studies have focused on vegetation trends, land-cover change, or restoration activities without explicitly examining coupled vegetation–radiation dynamics. Second, relatively limited attention has been paid to the scale dependence of NDVI–albedo relationships across satellite sensors with contrasting spatial resolutions. Third, the physical mechanisms underlying positive, weak, or scale-dependent NDVI–albedo relationships in sparse saline drylands remain insufficiently understood. This raises a central question: under what conditions does vegetation establishment in saline drylands reduce surface albedo, and when can vegetation development coexist with persistently elevated or increasing albedo?

To address these gaps, the present study investigates long-term changes in NDVI and surface albedo in the desiccated Aral Sea basin using complementary observations from MODIS, Landsat, and Sentinel-2 acquired during 2000–2025. The combined use of these satellite datasets enables simultaneous assessment of long-term environmental trends, spatial heterogeneity, and scale-dependent vegetation–surface interactions (Claverie et al., 2018; Lausch et al., 2013). Furthermore, the multi-sensor framework provides an opportunity to evaluate how NDVI–albedo relationships vary with observation scale, an aspect that has received relatively little attention in saline dryland environments.

The objectives of this study are to: (1) quantify long-term dynamics of NDVI and surface albedo in the main landscape units of the desiccated Aral Sea basin; (2) evaluate NDVI–albedo relationships on the exposed seabed and in representative saxaul plantation sites; (3) examine how these relationships vary across spatial scales and satellite sensors; and (4) assess the role of sparse vegetation, substrate exposure, plantation

structure, and highly reflective saline surfaces in shaping observed radiative behaviour. By integrating regional and local-scale observations, this study provides new insights into scale-dependent controls on vegetation–surface interactions in saline drylands and contributes to an improved understanding of ecological transformation processes in rapidly evolving arid environments.

2. Materials and methods

2.1. Study area and regions of interest

The study focused on the desiccated Aral Sea basin in Central Asia, located between Kazakhstan and Uzbekistan (Fig. 1). Since the second half of the twentieth century, the rapid shrinkage of the Aral Sea has exposed extensive saline seabed surfaces characterised by evaporitic sediments, unstable hydrological conditions, sparse vegetation colonisation, and intense aeolian activity (Micklin, 2007, 2010; Indoitu et al., 2015). The newly formed Aralkum Desert represents one of the largest anthropogenic dryland transformations in the world and provides an important natural laboratory for investigating vegetation–surface radiative interactions under rapidly evolving saline conditions. To evaluate spatial differences in vegetation and surface radiative dynamics, three principal regions of interest (ROIs) were defined. The Seabed ROI represents newly exposed saline and evaporitic surfaces characterised by sparse and fragmented vegetation colonisation. The Delta ROI represents the Amu Darya deltaic environment, where vegetation dynamics are more strongly influenced by hydrological conditions. The Total ROI represents the broader regional-scale study area used to assess basin-wide environmental dynamics. In addition, two local Sentinel-2 study sites were selected to investigate vegetation–surface interactions at finer spatial scales. For comparability, the local Saxaul_v1 and Saxaul_v2 ROIs were standardised to approximately equal spatial extents of 3.4 km². These local sites were used to assess how plantation structure and substrate exposure influence NDVI–albedo relationships at high spatial resolution.

2.2. Satellite datasets

Multi-sensor satellite observations from MODIS, Landsat, and Sentinel-2 were used to investigate vegetation and albedo dynamics during 2000–2025 (Table 1). The combined use of these datasets enabled simultaneous analysis of long-term temporal trends, spatial heterogeneity, and scale-dependent spectral behaviour (Claverie et al., 2018; Lausch et al., 2013). Vegetation dynamics were assessed using the MODIS MOD13Q1 product, which provides 16-day NDVI composites at 250 m spatial resolution (Huete et al., 2002). Raw MODIS NDVI values were converted to physical units using the standard scale factor:

$$\text{NDVI} = \text{NDVI}_{\text{raw}} \times 0.0001$$

Surface albedo was derived from the MODIS MCD43A3 BRDF/albedo product at 500 m spatial resolution using shortwave broadband white-sky albedo (Schaaf et al., 2002; Liang, 2001; Wang et al., 2015). Albedo values were converted using the standard scale factor:

$$\text{Albedo} = \text{Albedo}_{\text{raw}} \times 0.001$$

Landsat Collection 2 Level-2 surface reflectance products from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI were used to evaluate intermediate-scale vegetation and albedo dynamics and to provide independent support for long-term patterns identified from MODIS observations. Surface reflectance values were converted using Collection 2 product-specific multiplicative scale factors and additive offsets before index calculation. NDVI was calculated as:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$$

Broadband surface albedo from Landsat imagery was calculated from

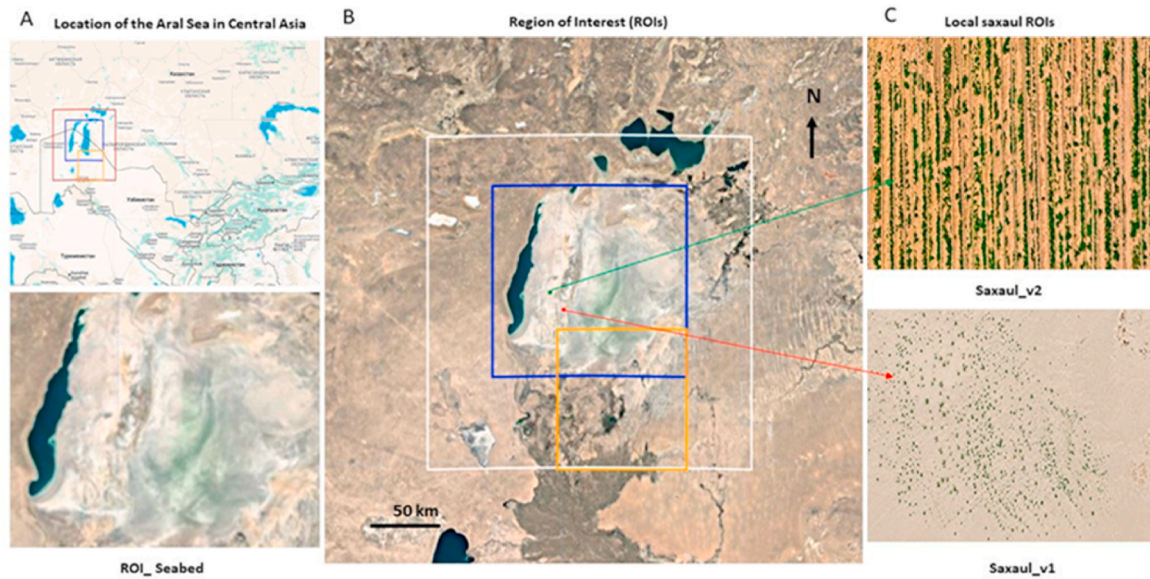


Fig. 1. Study area and selected regions of interest (ROIs) in the desiccated Aral Sea basin. (A) Geographic location of the Aral Sea in Central Asia. (B) Main ROIs used in this study, including the exposed seabed, the Amu Darya delta, and the broader regional-scale study area. (C) Examples of local saxaul ROIs with contrasting vegetation structures: Saxaul_v1, characterised by sparse and irregular vegetation distribution with substantial substrate exposure, and Saxaul_v2, characterised by a denser and more organised linear plantation pattern. High-resolution satellite image fragments are shown to illustrate differences in vegetation structure and substrate exposure; the local Sentinel-2 analytical ROIs were standardised to comparable spatial extents for quantitative analysis. The north arrow and scale bar are shown in panel B.

Table 1

Satellite datasets, spatial and temporal characteristics, and processing parameters used for the analysis of vegetation and surface albedo dynamics in the desiccated Aral Sea basin.

Dataset	Product	Spatial resolution	Temporal resolution	Study period	Variable	Scale factor	Purpose
MODIS MOD13Q1	NDVI	250 m	16 days	2000–2025	NDVI	0.0001	Long-term monitoring of vegetation dynamics
MODIS MCD43A3	White-sky shortwave albedo	500 m	Daily, aggregated annually	2000–2025	Surface albedo	0.001	Long-term assessment of land-surface reflectivity
Landsat Collection 2 Level-2	Surface reflectance	30 m	16 days	2000–2025	NDVI, albedo	Product-specific SR scaling and offset	Intermediate-scale analysis and cross-sensor comparison
Sentinel-2 Level-2A	Surface reflectance	10–20 m	5 days	2017–2025	NDVI, albedo	0.0001	High-resolution assessment of spatial heterogeneity and plantation structure

atmospherically corrected surface reflectance using established narrowband-to-broadband conversion approaches (Liang, 2001). Sentinel-2 Level-2A imagery was used to investigate fine-scale vegetation fragmentation, plantation structure, and mixed-pixel effects. The 10–20 m spatial resolution of Sentinel-2 allows sparse vegetation patches and plantation geometry to be identified more clearly than is possible with MODIS observations (Drusch et al., 2012; Claverie et al., 2018). Sentinel-2 observations were therefore used primarily for local-scale analysis of vegetation–surface interactions, plantation organisation, and substrate exposure within saxaul restoration sites.

The selected sensors provide complementary information across multiple spatial and temporal scales. MODIS products provide long-term continuous observations suitable for detecting regional vegetation and albedo trends over the period 2000–2025. Landsat data offer intermediate spatial resolution for assessing landscape-scale heterogeneity and supporting comparison with MODIS-derived patterns. Sentinel-2 imagery provides high-resolution information on vegetation structure, plantation geometry, and substrate exposure, enabling local-scale assessment of vegetation–surface interactions. For Sentinel-2, NDVI was calculated from the red and near-infrared bands, and approximate broadband surface albedo was estimated from visible, near-infrared, and shortwave-infrared reflectance bands using a narrowband-to-broadband

conversion.

$$\text{Albedo} = 0.356 \times B2 + 0.130 \times B4 + 0.373 \times B8 + 0.085 \times B11 + 0.072 \times B12 - 0.0018$$

Together, these datasets support a multi-scale analysis of vegetation and surface radiative dynamics and reduce uncertainty associated with interpretation based on a single sensor platform.

2.3. Preprocessing and quality assurance

All satellite datasets were processed using Google Earth Engine (GEE). The platform was used for data preprocessing, cloud and quality masking, annual compositing, and extraction of NDVI and albedo metrics from long-term multi-sensor observations across the selected ROIs. Preprocessing included application of product-specific quality-assurance flags, removal of low-quality observations, masking of cloud-contaminated pixels where appropriate, exclusion of invalid values, and conversion of raw digital values to physical units using dataset-specific scale factors.

Annual mean composites were generated for each year and each ROI. This temporal aggregation was used to emphasise long-term environmental dynamics and reduce sensitivity to short-term atmospheric

variability, seasonal fluctuations, and episodic environmental events. For Sentinel-2 observations, additional visual inspection was conducted to verify the consistency of local vegetation patterns, plantation geometry, and substrate exposure within the standardised Saxaul_v1 and Saxaul_v2 sites. The complete processing workflow is summarised in Supplementary Algorithm S1.

2.4. Spatial aggregation and scale analysis

Because one of the primary objectives of this study was to evaluate scale-dependent vegetation–albedo dynamics, MODIS, Landsat, and Sentinel-2 observations were analysed primarily at their native spatial resolutions rather than resampled to a common grid. Annual mean NDVI and albedo values were calculated separately for each ROI and sensor. This approach preserved sensor-specific spatial information while allowing comparison of long-term temporal behaviour across observation scales.

The multi-sensor framework allowed mixed-pixel effects, vegetation fragmentation, spatial heterogeneity, and vegetation–substrate interactions to be assessed. Particular attention was paid to differences between regional-scale MODIS observations, intermediate-scale Landsat observations, and local-scale Sentinel-2 observations. This design made it possible to evaluate whether NDVI–albedo relationships observed at coarse spatial resolution were consistent with finer-scale vegetation and substrate patterns.

2.5. Statistical analysis

Long-term temporal trends were evaluated using both parametric and non-parametric statistical approaches. Linear regression analysis was applied to estimate trend slopes and coefficients of determination (R^2) for the NDVI and albedo time series. To improve robustness against outliers and non-normal temporal variability, Mann–Kendall trend tests and Theil–Sen slope estimators were also applied (Sen, 1968; Yue et al., 2002; Vani et al., 2023).

Relationships between NDVI and albedo were evaluated using Pearson correlation analysis and linear regression. To assess the influence of shared long-term trends, detrended anomaly correlations were additionally calculated after removing linear temporal components from each time series. This procedure allowed direct interannual NDVI–albedo coupling to be distinguished from apparent relationships driven by concurrent long-term environmental transformation.

3. Results

3.1. Long-term NDVI dynamics

Long-term vegetation dynamics differed substantially among the analysed regions of interest (Table 2; Fig. 2). The Seabed ROI exhibited a pronounced positive NDVI trend during 2000–2025, indicating progressive vegetation establishment on newly exposed surfaces of the

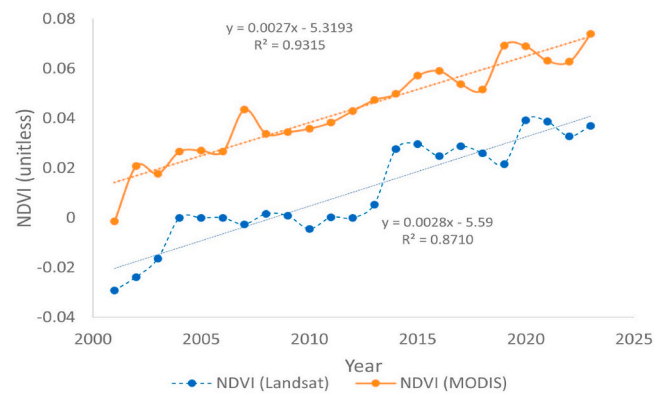


Fig. 2. Long-term NDVI dynamics in the exposed Seabed ROI derived from MODIS and Landsat observations during 2000–2025. Annual mean NDVI values are shown together with linear trend lines. Regression equations and coefficients of determination (R^2) are presented for each dataset.

former Aral Sea. In contrast, the Delta ROI maintained consistently higher NDVI values than the Seabed ROI throughout most of the study period, reflecting the continued influence of residual wetlands, riparian vegetation, and comparatively stable ecological conditions within the Amu Darya delta. The Total ROI showed intermediate characteristics because it integrates both recently exposed seabed environments and historically vegetated deltaic landscapes.

Sentinel-2 observations revealed a statistically significant negative NDVI trend within the Delta ROI during 2017–2025 (Table 2), suggesting localised reductions in vegetation greenness that may reflect short-term hydrological variability. However, long-term MODIS and Landsat observations indicated relatively stable to increasing vegetation conditions over the broader study period, highlighting the importance of observation scale and temporal coverage when interpreting vegetation dynamics.

Fig. 2 illustrates the temporal evolution of NDVI over the exposed Seabed ROI. Both MODIS and Landsat observations revealed a persistent increase in vegetation greenness throughout the study period. Linear trend analysis demonstrated a statistically significant positive trend in annual NDVI, consistent with previous observations of vegetation colonisation across the retreat zones of the Aral Sea (Shen et al., 2019; Duan et al., 2022). Similar vegetation responses have been reported in other dryland regions undergoing ecological transformation and partial revegetation (Zhu et al., 2016; Piao et al., 2020).

The observed increase in NDVI should not be interpreted as evidence of uniform ecosystem recovery. Higher-resolution Landsat and Sentinel-2 observations revealed substantial spatial heterogeneity, with vegetation development occurring in fragmented patches interspersed among saline sediments, evaporitic crusts, sandy surfaces, and partially stabilised areas. Consequently, increases in regional-scale NDVI primarily reflect aggregate vegetation establishment rather than continuous landscape-wide revegetation.

Table 2

Annual NDVI trends derived from MODIS, Landsat, and Sentinel-2 observations for the analysed regions of interest (ROIs). Trend significance was evaluated using the Mann–Kendall (MK) test.

Sensor	ROI	Period	OLS slope (yr^{-1})	R^2	MK p-value	Trend
MODIS	Seabed	2000–2025	0.002669	0.9315	3.31×10^{-10}	Significant positive
MODIS	Delta	2000–2025	0.000785	0.3088	7.17×10^{-3}	Significant positive
MODIS	Total	2000–2025	0.001023	0.4888	4.21×10^{-4}	Significant positive
Landsat	Seabed	2000–2025	0.007350	0.8644	3.02×10^{-9}	Significant positive
Landsat	Delta	2000–2025	0.003778	0.7378	6.20×10^{-6}	Significant positive
Landsat	Total	2000–2025	0.003500	0.8797	5.92×10^{-9}	Significant positive
Sentinel-2	Seabed	2017–2025	0.002913	0.8034	1.07×10^{-2}	Significant positive
Sentinel-2	Delta	2017–2025	−0.004032	0.6945	1.19×10^{-2}	Significant negative
Sentinel-2	Saxaul_v1	2017–2025	0.000242	0.2299	6.02×10^{-1}	Non-significant positive
Sentinel-2	Saxaul_v2	2017–2025	0.000980	0.2543	1.75×10^{-1}	Non-significant positive

Non-parametric statistical analyses supported the robustness of the detected trends. Mann–Kendall tests and Theil–Sen slope estimates were generally consistent with ordinary least-squares regression results, indicating that the observed increase in vegetation activity was not driven by isolated outliers or short-term anomalies but represented a persistent long-term trend. Full Theil–Sen statistics are provided in [Supplementary Table S1](#). Overall, the results indicate gradual vegetation establishment across portions of the desiccated seabed while also highlighting the strong spatial heterogeneity that characterises ecological recovery within the former Aral Sea basin.

3.2. Long-term albedo dynamics

Long-term surface albedo dynamics exhibited substantial interannual variability throughout the study period ([Fig. 3](#)). Despite pronounced year-to-year fluctuations, both MODIS and Landsat observations provided consistent evidence of increasing surface reflectivity over the exposed Seabed ROI.

Both MODIS and Landsat observations revealed a persistent increase in surface albedo over the former Aral Sea seabed during 2000–2025, despite considerable interannual variability ([Fig. 3](#)). Annual mean albedo generally increased from approximately 0.18–0.20 in the early 2000s to about 0.27–0.30 by the end of the study period. Linear regression analysis indicated positive albedo trends in both datasets. Landsat observations showed a positive trend slope of 0.0034 yr^{-1} with a high coefficient of determination ($R^2 = 0.75$), indicating a pronounced long-term increase in surface reflectivity. MODIS observations exhibited a steeper positive trend of 0.0053 yr^{-1} , but with a lower coefficient of determination ($R^2 = 0.55$), suggesting stronger interannual variability in the coarser-resolution record.

The higher variability observed in the MODIS record may reflect mixed-pixel effects, broader spatial integration of heterogeneous surface conditions, and differences in sensor characteristics and spatial resolution. The observed increase in albedo is consistent with the progressive exposure and development of highly reflective saline, sandy, and evaporitic substrates following desiccation of the Aral Sea. Although short-term fluctuations remained pronounced throughout the study period, both datasets indicate persistent surface brightening across the former seabed. Mann–Kendall tests further confirmed statistically significant positive albedo trends in both MODIS and Landsat records ([Table 3](#)), supporting the robustness of the observed long-term increase in surface reflectivity.

3.3. NDVI–albedo relationships

Relationships between NDVI and surface albedo varied substantially among the analysed regions and spatial scales ([Fig. 4](#)). Unlike the independent time-series analyses presented in [Figs. 2 and 3](#), the phase-space representation illustrates the joint evolution of vegetation activity and surface reflectivity, thereby showing whether NDVI and albedo changed coherently during environmental transformation.

The strongest positive relationship between NDVI and albedo was observed within the Seabed ROI, where annual mean NDVI and albedo increased simultaneously over time. The phase-space trajectory shows a gradual shift from low-NDVI/low-albedo conditions in the early years of the study to higher NDVI values associated with generally elevated albedo levels in later years. This pattern reflects the progressive environmental transformation of the exposed seabed following desiccation of the Aral Sea. In contrast, the Delta ROI exhibited a more scattered distribution with little directional organisation, indicating comparatively weak coupling between vegetation dynamics and surface radiative properties. The Total ROI also showed a diffuse pattern, reflecting the integration of contrasting environmental conditions and land-surface characteristics across the broader study area.

Importantly, the positive relationship observed for the Seabed ROI should not be interpreted as evidence of a simple direct causal link between vegetation development and increasing albedo. Detrended anomaly analysis demonstrated that the original positive NDVI–albedo coupling weakened substantially after removal of long-term linear trends. This result suggests that a substantial component of the observed relationship reflected concurrent long-term environmental changes during progressive desiccation and landscape transformation. The phase-space trajectory therefore indicates environmental co-evolution rather than persistent direct vegetation–radiation coupling alone.

This co-evolution likely reflects two simultaneous processes. First, gradual vegetation colonisation occurred through natural establishment of halophytic species and anthropogenic afforestation efforts, including large-scale saxaul plantations ([Breckle et al., 2012](#); [Khamzina et al., 2006](#)). Second, continued exposure of saline sediments and evaporitic crusts increased the abundance of highly reflective surfaces across the former seabed ([Metternicht and Zinck, 2003](#); [Farifteh et al., 2008](#); [Scudiero et al., 2015](#)). Consequently, vegetation development and increasing surface reflectivity proceeded simultaneously as components of broader post-desiccation landscape evolution. Similar complexities have been reported in dryland ecosystems where sparse vegetation, soil brightness, substrate exposure, vegetation geometry, and mixed spectral signals strongly influence remotely sensed reflectance characteristics ([Okin et al., 2001](#); [Asner, 1998](#); [Rodríguez-Caballero et al., 2018](#)).

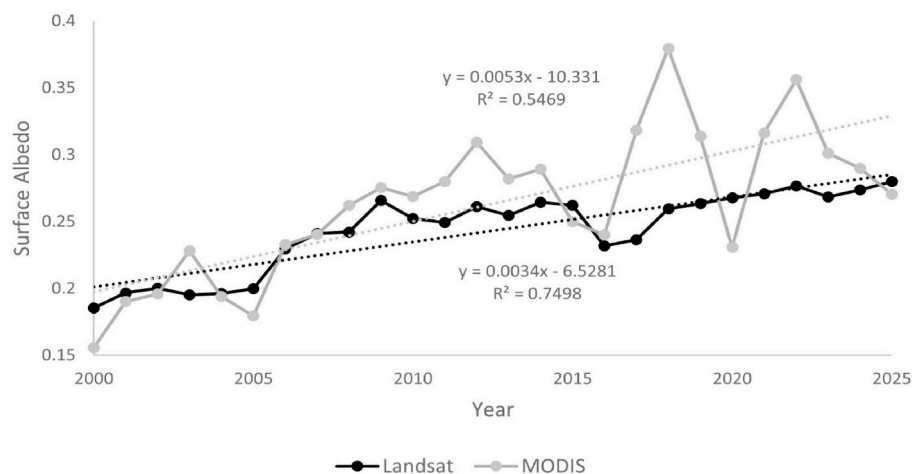


Fig. 3. Long-term surface albedo dynamics over the exposed Seabed ROI derived from MODIS and Landsat observations during 2000–2025. Annual mean albedo values are shown together with linear trend lines. Regression equations and coefficients of determination (R^2) are shown for each dataset.

Table 3

Annual surface albedo trends derived from MODIS, Landsat, and Sentinel-2 observations for the analysed regions of interest (ROIs). Trend significance was evaluated using the Mann–Kendall (MK) test.

Sensor	ROI	Period	OLS slope (yr ⁻¹)	R ²	MK p-value	Trend
MODIS	Seabed	2000–2025	0.005300	0.5469	1.25×10^{-4}	Significant positive
MODIS	Delta	2000–2025	0.001547	0.0804	1.72×10^{-1}	Non-significant positive
MODIS	Total	2000–2025	0.002358	0.3505	5.11×10^{-3}	Significant positive
Landsat	Seabed	2000–2025	0.003365	0.7498	1.24×10^{-6}	Significant positive
Landsat	Delta	2000–2025	0.000957	0.2851	2.60×10^{-2}	Significant positive
Landsat	Total	2000–2025	0.001216	0.3916	1.02×10^{-3}	Significant positive
Sentinel-2	Seabed	2017–2025	0.006542	0.7161	9.15×10^{-3}	Significant positive
Sentinel-2	Delta	2017–2025	0.004530	0.7485	4.88×10^{-3}	Significant positive
Sentinel-2	Saxaul_v1	2017–2025	0.003739	0.2059	2.51×10^{-1}	Non-significant positive
Sentinel-2	Saxaul_v2	2017–2025	-0.005490	0.1432	2.51×10^{-1}	Non-significant negative

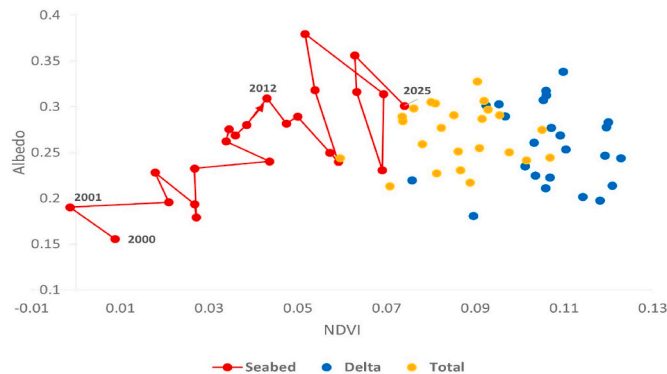


Fig. 4. Phase-space representation of annual NDVI and surface albedo dynamics derived from MODIS observations for the Seabed, Delta, and Total regions of the Aral Sea basin during 2000–2025. The red trajectory illustrates the temporal evolution of the Seabed ROI. Selected years are labelled to highlight changes in coupled NDVI–albedo dynamics over time.

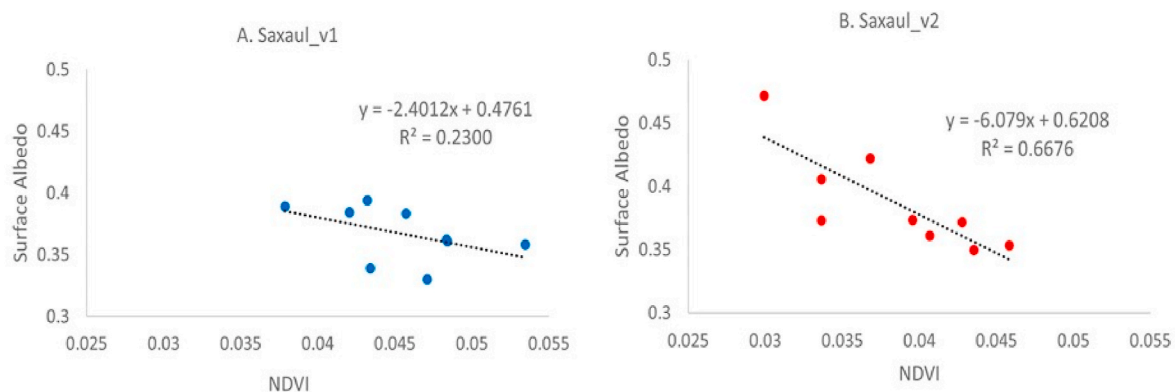
Comparison among satellite sensors further highlighted pronounced scale dependence. Coarse-resolution MODIS observations produced

smoother temporal trajectories and stronger integrated regional relationships, whereas higher-resolution Landsat and Sentinel-2 imagery revealed substantially greater spatial heterogeneity and more fragmented vegetation structure. These differences emphasise the importance of spatial scale when interpreting vegetation–albedo relationships in environmentally heterogeneous dryland systems.

Overall, the phase-space analysis indicates that vegetation development on the exposed seabed of the Aral Sea occurred concurrently with long-term changes in surface albedo. However, the observed relationship cannot be reduced to a simple one-to-one coupling between NDVI and albedo. Instead, both variables appear to have co-evolved under the combined influence of vegetation colonisation, substrate exposure, salinity dynamics, and large-scale environmental transformation.

3.4. Local-scale Sentinel-2 analysis of saxaul plantations

To further investigate vegetation–surface interactions at finer spatial scales, Sentinel-2 observations were analysed for two representative saxaul plantation areas located on the exposed seabed of the former Aral Sea (Fig. 5). Unlike regional-scale MODIS analysis, which integrates heterogeneous surface conditions over large areas, Sentinel-2 data provide finer spatial detail on local vegetation structure, plantation density,



C. Local Sentinel-2 NDVI–albedo regression statistics, 2017–2025

ROI	Slope	Incept	R ²	r	p-value	Interpretation
Saxaul_v1	-2.2012	0.4761	0.2300	-0.4796	0.1914	Weak-to-moderate inverse non-significant
Saxaul_v2	-6.0790	0.6208	0.6676	-0.8171	0.0072	Strong inverse, statistically significant

Fig. 5. Relationships between annual mean NDVI and surface albedo derived from Sentinel-2 observations during 2017–2025 for two representative saxaul plantation sites located on the exposed seabed of the former Aral Sea: (A) Saxaul_v1 and (B) Saxaul_v2. The ROIs were standardised to comparable spatial extents of approximately 3.4 km² for local-scale analysis. Dotted lines indicate linear regression fits, and coefficients of determination (R²) are shown.

and substrate exposure. For comparability, the two local ROIs were standardised to approximately equal spatial extents of 3.4 km².

The two selected sites differed in plantation structure and substrate exposure. Saxaul_v1 was characterised by sparse and irregular vegetation distribution with substantial exposure of bright saline and sandy substrates, whereas Saxaul_v2 represented a denser and more organised linear plantation structure with reduced substrate exposure (Fig. 1). Both sites exhibited inverse NDVI–albedo relationships, although the strength of the relationship differed substantially between ROIs.

For Saxaul_v1, the relationship was weak to moderate and negative (slope = -2.4012 , intercept = 0.4761 , $R^2 = 0.2300$, $r = -0.4796$, $p = 0.1914$). This indicates that higher NDVI was generally associated with lower surface albedo, but the relationship was not statistically significant and showed considerable interannual scatter. The relatively low explanatory power suggests that surface reflectivity in this ROI remained strongly influenced by heterogeneous substrate conditions, including exposed saline sediments, sandy surfaces, and mixed land-cover components.

For Saxaul_v2, the inverse relationship was substantially stronger and statistically significant (slope = -6.0790 , intercept = 0.6208 , $R^2 = 0.6676$, $r = -0.8171$, $p = 0.0072$). This indicates that increasing vegetation activity was more clearly associated with decreasing surface reflectivity. The stronger relationship is consistent with the interpretation that denser and more spatially coherent vegetation can partially mask highly reflective background surfaces and reduce surface albedo by increasing absorption of incoming solar radiation (Betts, 2000; Bonan, 2008).

These results indicate that local vegetation structure strongly modulates the NDVI–albedo relationship. In more heterogeneous plantation areas such as Saxaul_v1, exposed saline substrates and mixed surface conditions weaken the vegetation signal. In denser plantation systems such as Saxaul_v2, vegetation cover becomes sufficiently coherent to reduce the influence of the underlying bright substrate, producing a stronger inverse NDVI–albedo response.

These findings are consistent with previous studies showing that sparse vegetation geometry, mixed spectral signals, and incomplete canopy closure strongly influence reflectance dynamics in arid environments (Asner, 1998; Okin et al., 2001). They also support the interpretation that vegetation–albedo relationships are strongly scale-dependent. Although regional-scale MODIS and Landsat analyses indicated a long-term positive association between NDVI and albedo during broader environmental transformation, local-scale Sentinel-2 observations showed that vegetation can suppress albedo where plant cover is sufficiently coherent.

Because the Sentinel-2 record covers a relatively short period (2017–2025; $n = 9$ annual observations), these regression results should be interpreted as local-scale tendencies rather than definitive long-term trends. Nevertheless, the difference between Saxaul_v1 and Saxaul_v2 indicates that vegetation density, plantation structure, and substrate exposure jointly regulate surface radiative properties within the desiccated Aral Sea environment. These observations reinforce the importance of vegetation structure and spatial scale when interpreting remote sensing indicators of vegetation development and ecological restoration in saline dryland landscapes.

3.5. Statistical summary

The principal trend statistics derived from MODIS, Landsat, and Sentinel-2 observations are summarised in Tables 2 and 3. In these analyses, MODIS and Landsat were used primarily to characterise long-term regional-scale vegetation and albedo dynamics, whereas Sentinel-2 was used to evaluate local-scale responses within representative saxaul plantation sites.

Overall, the statistical analyses indicate predominantly positive NDVI trends across the exposed seabed and other analysed ROIs, accompanied by generally increasing or stable albedo conditions

depending on sensor, region, and spatial scale. The Seabed ROI exhibited the most pronounced and consistent positive NDVI trends among the analysed regions, supporting the interpretation of progressive vegetation establishment on the desiccated Aral Sea floor. These findings are consistent with previous studies reporting vegetation colonisation and heterogeneous vegetation development on newly exposed surfaces (Shen et al., 2019; Duan et al., 2022; Conrad et al., 2020).

Linear regression analysis revealed positive NDVI slopes for the Seabed ROI across multiple datasets, whereas albedo trends were generally weaker and more variable among sensors and regions. This contrast highlights the influence of spatial resolution, surface heterogeneity, and exposed saline substrates on the interpretation of dryland radiative dynamics. Analyses of NDVI–albedo relationships demonstrated substantial variation among regions and spatial scales. The strongest positive relationships were observed on the exposed seabed, whereas the Delta ROI exhibited weak or near-neutral associations.

Detrended analyses showed that the positive NDVI–albedo coupling weakened substantially after removal of long-term temporal trends. For the MODIS Seabed time series, the original positive NDVI–albedo correlation ($r = 0.61$, $p = 0.001$) disappeared after detrending ($r = -0.003$, $p = 0.987$). This indicates that the observed positive NDVI–albedo association primarily reflects concurrent vegetation development and surface transformation on the exposed seabed, rather than persistent direct coupling between the two variables at interannual timescales.

Non-parametric statistical approaches further supported the robustness of the detected trends. Mann–Kendall tests and Theil–Sen slope estimators were generally consistent with ordinary least-squares regression results, indicating that the observed vegetation and albedo dynamics were not driven by isolated outliers or short-term anomalies (Sen, 1968; Yue et al., 2002; Vani et al., 2023). Full robust trend statistics, including Theil–Sen slope estimates and Mann–Kendall test results, are provided in Supplementary Tables S1 and S2.

The local Sentinel-2 analysis revealed scale-dependent vegetation–albedo responses between the two saxaul plantation sites. The standardised Saxaul_v1 site exhibited a weak-to-moderate inverse but statistically non-significant NDVI–albedo relationship, indicating that vegetation effects were partly obscured by heterogeneous substrate conditions and interannual variability. In contrast, Saxaul_v2 demonstrated a stronger inverse NDVI–albedo relationship, suggesting that more coherent vegetation cover can locally suppress background reflectance. These findings indicate that vegetation density, canopy continuity, and substrate exposure jointly regulate local-scale radiative behaviour in the desiccated Aral Sea environment and are consistent with previous observations of sparse dryland ecosystems characterised by strong substrate influence (Okin et al., 2001; Asner, 1998; Rodríguez-Caballero et al., 2018).

Taken together, the results suggest that NDVI–albedo relationships in the desiccated Aral Sea basin reflect the combined influence of long-term environmental transformation, substrate exposure, vegetation establishment, local vegetation structure, and scale-dependent observation effects. The broad consistency of the observed patterns across multiple sensors and analytical approaches supports the interpretation of the reported vegetation–surface interactions.

4. Discussion

The results of this study indicate that vegetation–albedo relationships in the desiccated Aral Sea basin reflect the combined influence of progressive desiccation, exposure of saline substrates, vegetation establishment, and spatial heterogeneity. The integration of MODIS, Landsat, and Sentinel-2 observations enabled vegetation–surface interactions to be analysed across multiple spatial scales and revealed substantial differences among landscape units, environmental conditions, and sensor resolutions.

The exposed seabed exhibited increasing NDVI together with increasing or persistently elevated surface albedo during 2000–2025,

whereas the Amu Darya delta showed comparatively weak or near-neutral vegetation–albedo relationships. At first glance, these findings may appear inconsistent with the classical inverse NDVI–albedo relationships commonly reported for densely vegetated ecosystems, where increasing vegetation cover typically reduces surface reflectance (Betts, 2000; Bonan, 2008; Bright et al., 2017; Duveiller et al., 2018). However, the desiccated Aral Sea basin represents a fundamentally different environmental setting, characterised by highly reflective saline substrates, evaporitic crusts, sparse vegetation cover, and extensive exposure of the underlying surface.

An exception to the generally positive vegetation trends was observed for the Delta ROI in the Sentinel-2 record, where a significant negative NDVI trend was detected during 2017–2025. This result should be interpreted in the context of the relatively short Sentinel-2 observation period compared with the longer MODIS and Landsat records (Claverie et al., 2018; Drusch et al., 2012). Delta ecosystems are strongly influenced by fluctuations in hydrological conditions, soil moisture availability, and wetland dynamics (Duan et al., 2022). Consequently, the negative Sentinel-2 trend is more likely to reflect recent local-scale environmental variability than a persistent long-term decline in vegetation conditions. This interpretation is supported by the positive NDVI trends observed for the Delta ROI in the longer MODIS and Landsat time series. These findings should also be considered within the broader context of long-term hydrological transformation in the Aral Sea basin, where irrigation-driven river regulation and declining inflow fundamentally altered surface conditions, salinity patterns, and ecological trajectories (Dukhovny, 2008; Micklin, 2010; Zonn et al., 2009).

A key finding of this study is that the positive NDVI–albedo relationship observed in the non-detrended MODIS time series for the Seabed ROI weakened substantially after detrending. Although the original relationship was statistically significant, the correlation disappeared after removal of long-term temporal trends. This result indicates that the observed association primarily reflected concurrent long-term environmental transformation rather than persistent inter-annual coupling between vegetation activity and surface albedo. Vegetation establishment and increasing surface reflectivity therefore appear to have progressed simultaneously during transformation of the former lakebed, although their interannual variability remained largely independent.

This interpretation is consistent with the environmental history of the Aral Sea basin. Following large-scale desiccation of the Aral Sea, extensive areas of the former seabed were exposed, resulting in newly formed saline environments characterised by evaporitic sediments, intense aeolian activity, increased dust emissions, and challenging conditions for vegetation establishment (Micklin, 2007, 2010; Indoitu et al., 2015; Banks et al., 2022). At the same time, these newly exposed surfaces underwent gradual colonisation through establishment of halophytic vegetation, development of biological soil crusts, and anthropogenic restoration efforts, including large-scale saxaul plantation programmes (Breckle et al., 2012; Khamzina et al., 2006; Salmukhanbetova et al., 2021). Biological soil crusts can contribute substantially to surface reflectance and ecosystem functioning in drylands, further complicating the interpretation of vegetation-based remote sensing indicators (Weber et al., 2016).

The combined MODIS, Landsat, and Sentinel-2 observations suggest that vegetation establishment occurred concurrently with the continued dominance of bright saline and evaporitic surfaces across large portions of the landscape. Under such conditions, increases in NDVI are not necessarily accompanied by decreases in surface albedo. This pattern contrasts with many global analyses in which vegetation cover change is associated with systematic modifications of land-surface albedo and climate feedbacks (Duveiller et al., 2018). Instead, both variables may respond simultaneously to broader environmental transformation processes. Similar complexities have been reported in other dryland systems where soil brightness, substrate exposure, and sparse vegetation geometry strongly influence remotely sensed reflectance characteristics (Okin

et al., 2001; Asner, 1998; Smith et al., 2019).

The importance of substrate effects is further supported by studies of saline soils and evaporitic environments. Highly reflective salt-affected surfaces can maintain elevated albedo values even where vegetation cover increases (Metternicht and Zinck, 2003; Farifteh et al., 2008; Scudiero et al., 2015; Allbed and Kumar, 2013). Consequently, NDVI and albedo in saline drylands can reflect combined contributions from vegetation and substrate properties rather than vegetation structure alone.

The local Sentinel-2 analysis provides additional insight into the mechanisms controlling vegetation–albedo relationships. In the standardised Saxaul_v1 site, the NDVI–albedo relationship was weak to moderate, inverse, and statistically non-significant, indicating that vegetation effects were partly obscured by heterogeneous substrate conditions and interannual variability. In contrast, Saxaul_v2 exhibited a substantially stronger inverse NDVI–albedo relationship, suggesting that where vegetation cover becomes more coherent, it can partially mask highly reflective substrates and produce a more classical radiative response. The contrast between the two sites highlights the role of vegetation density, canopy continuity, spatial organisation, and substrate exposure in shaping local-scale surface reflectivity. Because the local Sentinel-2 ROIs were standardised to comparable areas, the contrast between Saxaul_v1 and Saxaul_v2 more directly reflects differences in vegetation structure and substrate exposure rather than differences in ROI size.

These local-scale inverse relationships, particularly the stronger response observed for Saxaul_v2, further highlight the importance of spatial scale in remote sensing analyses. Coarse-resolution MODIS observations integrate heterogeneous combinations of vegetation patches, saline sediments, residual moisture zones, and restoration areas within individual pixels. Such mixed-pixel effects can produce integrated regional responses that differ substantially from local-scale processes observed by higher-resolution sensors. The stronger increase in albedo detected by MODIS relative to Landsat further illustrates the influence of spatial scale and aggregation effects on the interpretation of dryland surface dynamics (Claverie et al., 2018). The more pronounced positive coupling observed at the MODIS scale likely reflects landscape-level environmental transformation rather than uniform ecological processes occurring throughout the study area. This scale dependence is consistent with previous studies emphasising the importance of multi-scale approaches for interpreting vegetation indicators across heterogeneous landscapes (Lausch et al., 2013).

The observed increase in vegetation should not be interpreted as evidence of complete ecosystem recovery. Instead, the results indicate fragmented and spatially heterogeneous vegetation establishment and partial ecological recovery under persistent salinity, hydrological instability, and climatic stress. Recent studies have reached similar conclusions, documenting uneven vegetation development and strong environmental constraints within the Aral Sea region (Shen et al., 2019; Duan et al., 2022; Conrad et al., 2020). Positive NDVI trends therefore likely represent partial stabilisation and localised vegetation establishment rather than restoration of pre-desiccation ecosystem conditions. Such patterns illustrate the importance of combining vegetation indicators with complementary environmental information when assessing land degradation and ecological recovery in drylands (Wang et al., 2020).

More broadly, the desiccated Aral Sea basin provides an important case study for investigating vegetation–radiation interactions in rapidly transforming dryland environments. Although global greening studies often emphasise vegetation expansion as a driver of decreasing surface albedo and altered climate feedbacks (Zhu et al., 2016; Seddon et al., 2016; Chen et al., 2019; Piao et al., 2020), the present study shows that vegetation development in saline drylands can occur simultaneously with persistently elevated surface reflectance. Such environments require careful interpretation of remote sensing indicators because vegetation trends alone may not fully capture the complexity of

the underlying environmental change.

Overall, the results indicate that vegetation–albedo relationships in saline drylands cannot be interpreted solely through the classical paradigm of increasing vegetation leading to decreasing surface albedo. In the desiccated Aral Sea basin, vegetation establishment occurred within a landscape undergoing simultaneous desiccation, salinisation, substrate exposure, and ecological restoration. Consequently, observed vegetation–surface interactions emerged from the combined effects of vegetation dynamics, substrate properties, and landscape-scale environmental transformation. These findings highlight the importance of multi-scale and multi-sensor approaches for interpreting vegetation–surface interactions and evaluating ecological restoration in dryland ecosystems.

5. Limitations and uncertainties

Several limitations should be considered when interpreting the results of this study.

First, the analysis relies primarily on satellite-derived observations and therefore is subject to uncertainties associated with sensor characteristics, atmospheric correction procedures, surface reflectance retrieval, and broadband albedo estimation. Although MODIS, Landsat, and Sentinel-2 products have been extensively validated and are widely used in environmental monitoring applications (Huete et al., 2002; Schaaf et al., 2002; Drusch et al., 2012; Claverie et al., 2018), residual uncertainties inevitably remain in the estimation of NDVI and surface albedo.

Second, differences in spatial resolution among satellite datasets can influence the interpretation of vegetation–albedo relationships. MODIS observations integrate heterogeneous surface components within individual pixels, including sparse vegetation, saline sediments, evaporitic crusts, residual moisture zones, and restoration areas. Consequently, coarse-resolution observations may emphasise landscape-scale environmental responses, whereas Landsat and Sentinel-2 observations capture finer-scale spatial variability and vegetation structure. Although this scale dependence represents an important result of the present study, it also constitutes a source of uncertainty when relationships derived from different sensors are compared.

Third, NDVI is sensitive not only to vegetation abundance but also to soil background effects, particularly in sparsely vegetated drylands. The relationship between vegetation indices and actual vegetation cover may become especially uncertain where subpixel vegetation fractions remain low (Purevdorj et al., 1998). Bright saline soils, evaporitic surfaces, and exposed sediments can influence spectral responses and affect the interpretation of vegetation dynamics (Huete and Jackson, 1987; Huete, 1988; Gilabert et al., 2002). Positive NDVI trends should therefore be interpreted as indicators of increasing vegetation activity rather than direct measures of vegetation biomass or ecosystem recovery.

Fourth, surface albedo is controlled by multiple environmental factors, including soil moisture, salinity, sediment composition, vegetation structure, biological soil crusts, and seasonal surface conditions (Liang, 2001; Weber et al., 2016; Rodríguez-Caballero et al., 2018). Consequently, changes in albedo cannot be attributed exclusively to vegetation dynamics. The observed NDVI–albedo relationships likely reflect the combined influence of several interacting environmental processes operating simultaneously within the desiccated Aral Sea landscape. In addition, potential lagged responses of vegetation development and surface albedo to changes in groundwater conditions and hydrological processes were not explicitly investigated. Precipitation and soil-moisture variability were also not explicitly incorporated into the present analysis and may contribute to interannual vegetation fluctuations within the study area. Future studies integrating remote sensing observations with hydrological and soil measurements could help quantify these delayed ecosystem responses more effectively.

Fifth, statistical analyses were based primarily on annual mean values. Annual aggregation reduces short-term variability and facilitates

detection of long-term trends; however, it can also obscure seasonal behaviour, episodic climatic events, and short-term vegetation responses. Consequently, seasonal differences in vegetation phenology and short-lived responses to favourable climatic conditions may not be fully represented in the annual time series. Future studies incorporating seasonal and intra-annual analyses could provide additional information on vegetation–surface interactions and environmental dynamics across the former Aral Sea basin.

Sixth, direct field measurements of vegetation cover, soil salinity, surface reflectance, albedo, and plantation structure were not available for validation of the satellite-derived observations. Although the detected patterns are consistent with published studies and known environmental conditions in the region (Breckle et al., 2012; Khamzina et al., 2006; Duan et al., 2022), future integration of field surveys and ground-based measurements would strengthen the interpretation of remotely detected indicators.

Finally, the local Sentinel-2 analysis was restricted to two representative saxaul plantation sites and a relatively short observation period (2017–2025; $n = 9$ annual observations). Although the two local ROIs were standardised to comparable spatial extents for the NDVI–albedo analysis, they cannot fully represent the diversity of ecological conditions, restoration histories, plantation ages, and substrate environments present throughout the Aral Sea basin.

In addition, the present study focused on NDVI as a widely used indicator of vegetation activity. Alternative vegetation metrics specifically designed for sparsely vegetated environments, such as SAVI, MSAVI, and fractional vegetation cover, were not evaluated and may provide additional information on vegetation–surface interactions in saline drylands. Their integration represents a promising direction for future research.

Despite these limitations, the combined use of MODIS, Landsat, and Sentinel-2 observations provides a robust multi-scale framework for investigating vegetation and surface radiative dynamics in one of the world's largest anthropogenic dryland environments. The consistency of the principal patterns across independent satellite datasets, together with the complementary information provided by different spatial resolutions, supports the main conclusions. At the same time, differences among sensors provide important information on the roles of spatial heterogeneity, vegetation structure, substrate exposure, and mixed-pixel effects in shaping vegetation–albedo relationships within the desiccated Aral Sea basin.

6. Conclusions

This study investigated long-term vegetation and surface albedo dynamics in the desiccated Aral Sea basin using a multi-sensor remote sensing framework based on MODIS, Landsat, and Sentinel-2 observations. The results revealed substantial spatial variability in vegetation development and surface radiative behaviour among the main landscape units of the former Aral Sea environment. Positive NDVI trends were observed in most regions, indicating ongoing vegetation establishment and partial ecological stabilisation of newly exposed surfaces.

A major finding of the study is that vegetation development on the exposed seabed occurred concurrently with increasing or persistently elevated surface albedo. This pattern contrasts with the classical inverse vegetation–albedo relationships commonly reported for densely vegetated ecosystems and highlights the importance of saline substrates, evaporitic crusts, and fragmented vegetation structure in shaping surface reflectance in dryland environments.

The analysis further demonstrated that NDVI–albedo relationships are strongly scale-dependent. At the regional scale, MODIS observations indicated a long-term positive association between vegetation activity and surface reflectivity during ongoing environmental transformation. In contrast, local-scale Sentinel-2 observations revealed inverse NDVI–albedo relationships within the standardised saxaul plantation sites, although the strength of the relationship differed between ROIs. Saxaul_v1 exhibited a weak-to-moderate inverse but statistically non-

significant relationship, whereas Saxaul_v2 showed a substantially stronger inverse response. These findings suggest that vegetation density, canopy continuity, spatial organisation, and substrate exposure jointly influence local-scale radiative dynamics.

This study provides new insights into the interpretation of remotely sensed vegetation and albedo indicators in saline drylands. Positive NDVI trends in the desiccated Aral Sea basin should not automatically be interpreted as evidence of uniform ecosystem recovery. Instead, vegetation development occurs within a complex environmental context characterised by salinity, substrate heterogeneity, hydrological instability, and ongoing landscape transformation.

From a practical perspective, the findings contribute to the evaluation of ecological restoration and afforestation programmes implemented across the former seabed of the Aral Sea. Understanding how vegetation structure influences surface radiative properties can improve monitoring of saxaul plantation development, land stabilisation processes, and dust mitigation efforts in the Aralkum Desert and adjacent regions.

More broadly, the multi-scale remote sensing framework applied in this study may be relevant to other dryland environments where vegetation dynamics interact with highly reflective substrates. Future studies integrating field observations, seasonal analyses, soil salinity measurements, hydrological data, and additional spectral indicators could further improve understanding of vegetation-surface interactions and environmental change in saline and arid ecosystems.

Funding

This research received no external funding.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author gratefully acknowledges colleagues from the Department of Space Research, Astronomical Institute, Academy of Sciences of the Republic of Uzbekistan, for their helpful comments, discussions, and support during the preparation of this manuscript. The author also acknowledges the providers of the MODIS, Landsat, and Sentinel-2 satellite datasets used in this study, as well as the Google Earth Engine platform for providing access to satellite archives and cloud-based computational resources.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jaridenv.2026.105687>.

Data availability

The satellite datasets used in this study are publicly available from the MODIS, Landsat, and Sentinel-2 archives through Google Earth Engine. The processed data and scripts used in the analyses are available from the author upon reasonable request.

References

- Allbed, A., Kumar, L., 2013. Soil salinity mapping and monitoring in arid and semi-arid regions using remote sensing technology: a review. *Adv. Rem. Sens.* 2, 373–385. <https://doi.org/10.4236/ars.2013.24040>.
- Asner, G.P., 1998. Biophysical and biochemical sources of variability in canopy reflectance. *Rem. Sens. Environ.* 64, 234–253. [https://doi.org/10.1016/S0034-4257\(98\)00014-5](https://doi.org/10.1016/S0034-4257(98)00014-5).

- Banks, J.R., Heinold, B., Schepanski, K., 2022. Impacts of the desiccation of the Aral Sea on the Central Asian dust life-cycle. *J. Geophys. Res. Atmos.* 127. <https://doi.org/10.1029/2022JD036618> e2022JD036618.
- Betts, R.A., 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408, 187–190. <https://doi.org/10.1038/35041545>.
- Bonan, G.B., 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320, 1444–1449. <https://doi.org/10.1126/science.1155121>.
- Aralkum—A man-made desert: the desiccated floor of the Aral Sea (Central Asia). In: Breckle, S.-W., Wucherer, W., Dimeyeva, L.A., Ogar, N.P. (Eds.), 2012. *Ecological Studies*, 218. Springer, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-642-21117-1>.
- Bright, R.M., Davin, E., O'Halloran, T., Pongratz, J., Zhao, K., Cescatti, A., 2017. Local temperature response to land cover and management change driven by non-radiative processes. *Nat. Clim. Change* 7, 296–302. <https://doi.org/10.1038/nclimate3250>.
- Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R.K., Fuchs, R., Brovkin, V., Ciais, P., Fensholt, R., Tømmervik, H., Bala, G., Zhu, Z., Nemani, R.R., Myneni, R.B., 2019. China and India lead in greening of the world through land-use management. *Nat. Sustain.* 2, 122–129. <https://doi.org/10.1038/s41893-019-0220-7>.
- Claverie, M., Ju, J., Masek, J.G., Dungan, J.L., Vermote, E.F., Roger, J.-C., Skakun, S., Justice, C., 2018. The harmonized landsat and Sentinel-2 surface reflectance data set. *Rem. Sens. Environ.* 219, 145–161. <https://doi.org/10.1016/j.rse.2018.09.002>.
- Conrad, C., Usman, M., Morper-Busch, L., Schönbrodt-Stitt, S., 2020. Remote sensing-based assessments of land use, soil and vegetation status, crop production and water use in irrigation systems of the Aral Sea basin: a review. *Water Secur.* 11, 100078. <https://doi.org/10.1016/j.wasec.2020.100078>.
- Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., Bargellini, P., 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Rem. Sens. Environ.* 120, 25–36. <https://doi.org/10.1016/j.rse.2011.11.026>.
- Duan, Z., Wang, X., Shakhimardan, S., Sun, L., Liu, W., Luo, Y., 2022. Impacts of lake water change on vegetation development in the retreat area of the Aral Sea. *J. Hydrol.* 613, 128416. <https://doi.org/10.1016/j.jhydrol.2022.128416>.
- Dukhovny, V.A. (Ed.), 2008. *Comprehensive Remote Sensing and Ground-based Studies of the Dried Aral Sea Bed. Scientific Information Center of the Interstate Commission for Water Coordination of Central Asia*, Tashkent, p. 172.
- Duveiller, G., Hooker, J., Cescatti, A., 2018. The mark of vegetation change on Earth's surface energy balance. *Nat. Commun.* 9, 679. <https://doi.org/10.1038/s41467-017-02810-8>.
- Farifteh, J., van der Meer, F., van der Meijde, M., Atzberger, C., 2008. Spectral characteristics of salt-affected soils: a laboratory experiment. *Geoderma* 145, 196–206. <https://doi.org/10.1016/j.geoderma.2008.03.011>.
- Gilbert, M.A., González-Piqueras, J., García-Haro, F.J., Meliá, J., 2002. A generalized soil-adjusted vegetation index. *Rem. Sens. Environ.* 82, 303–310. [https://doi.org/10.1016/S0034-4257\(02\)00048-2](https://doi.org/10.1016/S0034-4257(02)00048-2).
- Hu, Y., Hu, Y., 2019. Land cover changes and their driving mechanisms in central Asia from 2001 to 2017 supported by google Earth engine. *Remote Sens.* 11, 554. <https://doi.org/10.3390/rs11050554>.
- Huang, J., Yu, H., Guan, X., Wang, G., Guo, R., 2016. Accelerated dryland expansion under climate change. *Nat. Clim. Change* 6, 166–171. <https://doi.org/10.1038/nclimate2837>.
- Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). *Rem. Sens. Environ.* 25, 295–309. [https://doi.org/10.1016/0034-4257\(88\)90106-X](https://doi.org/10.1016/0034-4257(88)90106-X).
- Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Rem. Sens. Environ.* 83, 195–213. [https://doi.org/10.1016/S0034-4257\(02\)00096-2](https://doi.org/10.1016/S0034-4257(02)00096-2).
- Huete, A.R., Jackson, R.D., 1987. Suitability of spectral indices for evaluating vegetation characteristics on arid rangelands. *Rem. Sens. Environ.* 23, 213–232. [https://doi.org/10.1016/0034-4257\(87\)90038-1](https://doi.org/10.1016/0034-4257(87)90038-1).
- Indoit, R., Kozhoridze, G., Batyrbaeva, M., Vitkovskaya, I., Orlovsky, N., Blumberg, D., Orlovsky, L., 2015. Dust emission and environmental changes in the dried bottom of the Aral Sea. *Aeolian Res.* 17, 101–115. <https://doi.org/10.1016/j.aeolia.2015.02.004>.
- Khamzina, A., Lamers, J.P.A., Worbes, M., Botman, E., Vlek, P.L.G., 2006. Assessing the potential of trees for afforestation of degraded landscapes in the Aral Sea Basin of Uzbekistan. *Agrofor. Syst.* 66, 129–141. <https://doi.org/10.1007/s10457-005-4677-1>.
- Lausch, A., Pause, M., Merbach, I., Zacharias, S., Doktor, D., Volk, M., Seppelt, R., 2013. A new multiscale approach for monitoring vegetation using remote sensing-based indicators in laboratory, field, and landscape. *Environ. Monit. Assess.* 185, 1215–1235. <https://doi.org/10.1007/s10661-012-2627-8>.
- Liang, S., 2001. Narrowband to broadband conversions of land surface albedo: I. Algorithms. *Rem. Sens. Environ.* 76, 213–238. [https://doi.org/10.1016/S0034-4257\(00\)00205-4](https://doi.org/10.1016/S0034-4257(00)00205-4).
- Lioubimtseva, E., Henebry, G.M., 2009. Climate and environmental change in arid central Asia: impacts, vulnerability, and adaptations. *J. Arid Environ.* 73, 963–977. <https://doi.org/10.1016/j.jaridenv.2009.04.022>.
- Metternicht, G.I., Zinck, J.A., 2003. Remote sensing of soil salinity: potentials and constraints. *Rem. Sens. Environ.* 85, 1–20. [https://doi.org/10.1016/S0034-4257\(02\)00188-8](https://doi.org/10.1016/S0034-4257(02)00188-8).
- Micklin, P., 2007. The Aral Sea disaster. *Annu. Rev. Earth Planet Sci.* 35, 47–72. <https://doi.org/10.1146/annurev.earth.35.031306.140120>.
- Micklin, P., 2010. The past, present, and future Aral Sea. *Lakes Reservoirs Res. Manage.* 15, 193–213. <https://doi.org/10.1111/j.1440-1770.2010.00437.x>.

- Okin, G.S., Murray, B., Schlesinger, W.H., 2001. Degradation of sandy arid shrubland environments: observations, process modelling, and management implications. *J. Arid Environ.* 47, 123–144. <https://doi.org/10.1006/jare.2000.0711>.
- Piao, S., Wang, X., Park, T., Chen, C., Lian, X., He, Y., Bjerke, J.W., Chen, A., Ciais, P., Tømmervik, H., Nemani, R.R., Myneni, R.B., 2020. Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.* 1, 14–27. <https://doi.org/10.1038/s43017-019-0001-x>.
- Purevdorj, T., Tateishi, R., Ishiyama, T., Honda, Y., 1998. Relationships between percent vegetation cover and vegetation indices. *Int. J. Rem. Sens.* 19, 3519–3535. <https://doi.org/10.1080/014311698213795>.
- Rodríguez-Caballero, E., Castro, A.J., Chamizo, S., Quintas-Soriano, C., García-Llorente, M., Cantón, Y., Weber, B., 2018. Ecosystem services provided by biocrusts: from ecosystem functions to social values. *J. Arid Environ.* 159, 45–53. <https://doi.org/10.1016/j.jaridenv.2017.09.005>.
- Salmukhanbetova, ZhK., Imanalynova, A.A., Dimeyeva, L.A., Zverev, N.E., 2021. State of saxaul plantations in Kazakhstan's part of the Aral Sea region. *Central Asian J. Water Res.* 7 (1), 128–157. <https://doi.org/10.29258/CAJWR/2020-R1.v7-1/128-157.eng>.
- Schaaf, C.B., Gao, F., Strahler, A.H., Lucht, W., Li, X., Tsang, T., Strugnell, N.C., Zhang, X., Jin, Y., Muller, J.-P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d'Entremont, R.P., Hu, B., Liang, S., Privette, J. L., Roy, D., 2002. First operational BRDF, albedo nadir reflectance products from MODIS. *Rem. Sens. Environ.* 83, 135–148. [https://doi.org/10.1016/S0034-4257\(02\)00091-3](https://doi.org/10.1016/S0034-4257(02)00091-3).
- Scudiero, E., Skaggs, T.H., Corwin, D.L., 2015. Regional-scale soil salinity assessment using Landsat ETM+ canopy reflectance. *Rem. Sens. Environ.* 169, 335–343. <https://doi.org/10.1016/j.rse.2015.08.026>.
- Seddon, A.W.R., Macias-Fauria, M., Long, P.R., Benz, D., Willis, K.J., 2016. Sensitivity of global terrestrial ecosystems to climate variability. *Nature* 531, 229–232. <https://doi.org/10.1038/nature16986>.
- Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* 63, 1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>.
- Shen, H., Abuduwalli, J., Ma, L., Samat, A., 2019. Remote sensing-based land surface change identification and prediction in the Aral Sea bed, central Asia. *Int. J. Environ. Sci. Technol.* 16, 2031–2046. <https://doi.org/10.1007/s13762-018-1801-0>.
- Smith, W.K., Dannenberg, M.P., Yan, D., Herrmann, S., Barnes, M.L., Barron-Gafford, G. A., Biederman, J.A., Ferrenberg, S., Fox, A.M., Hudson, A.R., Knowles, J.F., MacBean, N., Moore, D.J.P., Nagler, P.L., Reed, S.C., Rutherford, W.A., Scott, R.L., Wang, X., Yang, J., 2019. Remote sensing of dryland ecosystem structure and function: progress, challenges, and opportunities. *Rem. Sens. Environ.* 233, 111401. <https://doi.org/10.1016/j.rse.2019.111401>.
- Spoor, M., 1998. The Aral Sea Basin crisis: transition and environment in former Soviet Central Asia. *Dev. Change* 29, 409–435. <https://doi.org/10.1111/1467-7660.00084>.
- Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Rem. Sens. Environ.* 8, 127–150. [https://doi.org/10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0).
- Vani, P.C., Sahoo, B.C., Paul, J.C., Sahu, A.P., Mohapatra, A.K.B., 2023. Trend analysis in gridded rainfall data using Mann–Kendall and Spearman's rho tests in Kesinga Catchment of Mahanadi River Basin, India. *Pure Appl. Geophys.* 180, 4339–4353. <https://doi.org/10.1007/s00024-023-03379-8>.
- Wang, D., Liang, S., He, T., Yu, Y., Schaaf, C., Wang, Z., 2015. Estimating daily mean land surface albedo from MODIS data. *J. Geophys. Res. Atmos.* 120, 4825–4841. <https://doi.org/10.1002/2015JD023178>.
- Wang, X., Chen, Y., Li, Z., Fang, G., Wang, F., Liu, H., 2020. The impact of climate change and human activities on the Aral Sea Basin over the past 50 years. *Atmos. Res.* 245, 105125. <https://doi.org/10.1016/j.atmosres.2020.105125>.
- Weber, B., Büdel, B., Belnap, J. (Eds.), 2016. *Biological Soil Crusts: an Organizing Principle in Drylands*. Ecological Studies, 226. Springer, Cham. <https://doi.org/10.1007/978-3-319-30214-0>.
- Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.* 259, 254–271. [https://doi.org/10.1016/S0022-1694\(01\)00594-7](https://doi.org/10.1016/S0022-1694(01)00594-7).
- Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. *Nat. Clim. Change* 6, 791–795. <https://doi.org/10.1038/nclimate3004>.
- Zonn, I.S., Glantz, M.H., Kostianoy, A.G., Kosarev, A.N., 2009. *The Aral Sea Encyclopedia*. Encyclopedia of Seas. Springer, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-540-85088-5>.