Using Satellite Observations with Field Surveys to Monitor Ecosystem Restoration in AlUla, Saudi Arabia

Mateo Barco Largo[1], Meshal Alarifi[1], Sami D. Almalki[2], Shauna K. Rees[2], Benjamin P. Y.-H. Lee[2], Ahmed H. Mohamed[2,3], Abdalsamad Aldabaa[2,4], Kaoru Kakinuma[1,5,6], Yoshihide Wada[1]

[1] Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Saudi Arabia
[2] Wildlife and Natural Heritage, Royal Commission for AlUla, AlUla, Saudi Arabia
[3] Plant Ecology and Rangeland Management, Desert Research Center, Cairo, Egypt
[4] Pedology Department, Desert Research Center, Cairo, Egypt
[5] National Institute of Population and Social Security Research, Hibiya Kokusai Building 6th Floor, 2-2-3 Uchisaiwaicho, Chiyoda-ku, Tokyo 100-0011, Japan
[6] Moon Soul Graduate School of Future Strategy, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea

Keywords: NDVI, Anomaly, Landcover, Sharaan NP, Gharameel NR, Trimesters.

Abstract

AlUla, a historic town located in Northwestern Saudi Arabia, renowned for beautiful landscapes and cultural significance. With the establishment of The Royal Commission for AlUla (RCU) in 2018, remarkable efforts have been made including, establishment of national parks and nature reserves, implementation of grazing control measures, and various planting initiatives. Monitoring of these efforts has been confined to an annual scale and not on a quarterly basis, which would allow for a more detailed, short-term assessment of their impacts. This study aims to provide a quarterly assessment of NDVI-based land cover and anomaly in Sharaan NP and Gharameel NR during the year 2024. A vegetation survey was conducted in the first trimester of 2024 (Jan–Mar), where species biomass, cover, height was collected using the line-transect method. For short-term and long-term analysis images were collected from Landsat (5-9) and Sentenile-2 satellites, Landcover was derived based on NDVI from Sentinel images. While NDVI anomaly was derived from Landsat datasets. The Analysis was conducted on a trimestral basis (Q1: Jan–Mar, Q2: Apr–Jun, Q3: Jul–Sep, Q4: Oct–Dec). Mean NDVI was calculated and compared to historical averages for anomaly calculation. NDVI showed a marked increase compared to previous years (1990–2023). Vegetation cover trimestral variations were driven by seasonal changes. Sharaan NP showed the best vegetation conditions throughout the year compared to Gharameel NR which is likely due to fencing and livestock grazing exclusion. The relationship between vegetation cover and landscape variability is strongly influenced by the capacity for moisture retention in valleys, hills, and sloped terrains, underscoring the need to keep prioritizing and enhancing restoration efforts in these significant landscapes.

Introduction

Over the past seven years, AlUla has implemented various conservation measures, including establishing nature reserves, reintroducing wildlife, managing grazing, and conducting large-scale planting initiatives. However, the effectiveness of these efforts has not been assessed due to challenges in rangeland monitoring (Al-Bukhari et al., 2018). To address this, remote sensing methods have been applied, offering a cost-effective solution for monitoring rangeland degradation over large areas (Booth & Tueller, 2003; Al-Bukhari et al., 2018).

Remote sensing (RS) is a powerful tool for monitoring rangelands (Nanzad et al., 2019). It enables the comparison of healthy rangeland conditions with post-disturbance states, providing valuable insights into degradation and recovery states (Yengoh et al., 2016). In Saudi Arabia, RS has been effectively utilized for rangeland monitoring (AlGaadi et al., 2013; Mallick et al., 2021).

One of the most used remote sensing tools in the world is the Normalized Difference Vegetation Index (NDVI), it is utilized for monitoring environmental conditions such as land degradation, desertification, and drought (Hassan et al., 2018).

It is a powerful index that can distinguish between plants, water, and soil by using near-infrared and red-light reflectance. The values range from -1 to 1, with vegetation having higher values near 1 due to high near-infrared reflectance and low red-light reflectance. Water, which reflects more red-light than near-infrared light, has negative values around -1. Soil and bare rocks typically have values near zero, as their reflectance is similar to that of vegetation but not as pronounced (D’Allestro & Parente, 2015).

Analyzing the difference between the current NDVI value and the average NDVI value for that area over time is referred to as NDVI anomaly. Anomaly refers to finding patterns in data that deviate from the expected behavior. These deviations are often referred to as anomalies or outliers (Chandola et al., 2009). In the context of NDVI anomaly, it shows unusual changes in vegetation health. A positive anomaly means more vegetation than usual, while a negative anomaly means less vegetation or stressed plants. Spatial and temporal variations in NDVI anomalies are critical for assessing environmental changes, correlating with climatic variables such as rainfall and temperature (Nanzad al., 2019).

The objective of this study is to monitor land cover changes and NDVI anomalies in Sharaan National Park and Gharameel Nature Reserve throughout 2024 on a quarterly basis and validate the results using field survey data. Monitoring herbage changes on a quarterly basis can be beneficial for AlUla, as it provides more frequent and accurate data on vegetation dynamics. This can greatly enhance decision-making for management and restoration efforts (Yeganeh et al., 2014).

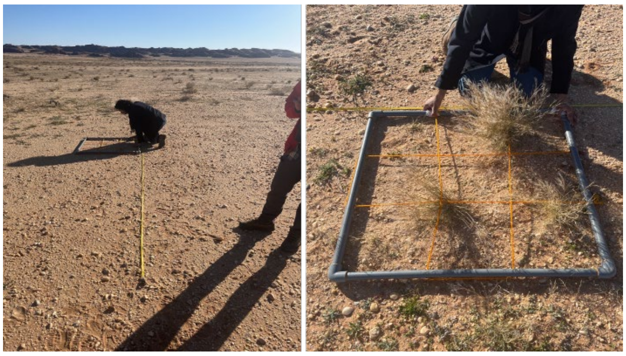

Figure 1. Vegetation survey in AlUla. left) 50-m transect line, right) 1x1m quadrat.

The main difference between Sharaan National Park and Gharameel Nature Reserve, aside from their ecological and geological characteristics, is grazing management. Sharaan National Park has excluded livestock grazing through fencing, while Gharameel NR has adopted controlled grazing, allowing local people to graze the herds in AlUla and excluding non-local herds.

2. Methods

2.1 Study Area

The research was carried out in the northwest of Saudi Arabia, in AlUla governorate in Medina Province. Two areas were surveyed, Sharaan (152,500 Ha) (Long: 38.18345702, Lat: 26.88997151), Sharaan is characterized by red sandstone buttes and sandy environments with diverse landforms, including, dunes, sandy open environments, arid thorn woodlands, rocky outcrops, ephemeral flooded depressions and abandoned agricultural lands. Vegetation in Sharaan contains 295 species from 51 families divided into 4 communities with the dominant stratum being herbaceous plants; plant community 1: Acacia gerrardii-Zizipus-Retama; plant community 2: Haloxylon salicornicum-Stipagrostis ciliata-Stipagrostis plumosa; plant community 3: Ephedra-Atermisia-Moltikiopsis; and plant community 4: Morettia-Anastatica-Heliotropium. Gharameel (211,582 Ha) (Long: 38.007967, Lat: 27.217575), is characterized by red sandstone and sandy environments and is severely degraded due to previous human activities. Landforms are mainly characterized by Sandy open environments and Rock outcrops. Vegetation in AlGharameel contains 176 species from 41 families and 5 vegetation communities. They are primarily: plant community 1: Artemisia – Ephedra – Acacia gerrardii; plant community 2: Haloxylon – Retama – Rhazia; plant community 3: Rhantherium – Kickxia – Rumex; plant community 4: Helianthemum – Gymnocarpos – Thymbra, and plant community 5: Moretta – Citrullus – Euphorbia.

2.2 Vegetation Survey

From January 28 to March 6, 2024, a vegetation survey was carried out using a line transect sampling method (Canfield, 1941) (Figure 1). At each site, a 50-meter transect line was laid out and vegetation analyses at 5-meter intervals using a 1-square meter quadrat was conducted. 10 quadrants per site were thus examined. For data collection, vegetation cover, height, and biomass of each plant species were collected. 12 Sites were taken in Sharaan NP and 12 sites in Gharameel NR.

2.3 Satellite Image Processing

We used the Google Earth Engine (GEE) platform to access Landsat and Sentinel-2 image collections, leveraging the strengths of both missions to perform long-term and short-term NDVI analysis. Specifically, we used Landsat 5 to 9 Surface Reflectance Collection (Collection 2 - Level 2 - Tier 1) and Sentinel-2 Multispectral Instrument (MSI) data. The cross-calibrated sensors of the Landsat and Sentinel missions enhance the reliability of cross-satellite comparisons (USGS, 2019). Processed images were imported into ArcGIS Pro, where they were resampled and masked to the study region.

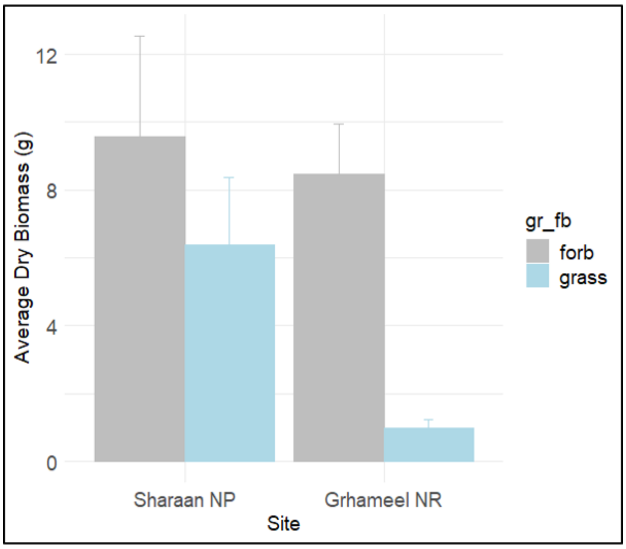

Figure 2. Bar Graph Showing the average grasses and forbs dry biomass across the study sites. (Sharaan: Fenced, Gharameel: Controlled grazing,). Error bars indicate the standard error of the mean. Grasses are shown in the blue bars, and forbs are shown in the gray

2.4 Copernicus/Sentinel-2 Image Processing

As part of the European Union's Copernicus Earth Observation program, the European Space Agency (ESA) launched the Sentinel-2 constellation in 2014 and 2017. The Sentinel-2 mission provides multispectral imagery with spatial resolutions of 10 m (visible and near-infrared bands), 20 m (red-edge and shortwave infrared bands), and 60 m (atmospheric correction bands), with a five-day revisit time using a two-satellite constellation. Compared to Landsat, Sentinel-2 offers higher spatial resolution in the visible and shortwave infrared bands and an improved revisit time of approximately 2.5 days (Li & Roy, 2017). To analyze vegetation changes over time, Sentinel-2 imagery was used to calculate NDVI at a trimester scale throughout 2024. NDVI was computed for four time periods: January – March, April – June, July – September, and October – December 2024. In addition, true-color and false-color infrared maps were generated for each trimester to enhance the visualization of land cover changes across the study area. To ensure cloud-free analysis, the Scene Classification (SCL) band was used to detect and mask clouds and cloud shadows, following the SCL band algorithm (ESA, 2023).

2.5. Landsat Image Processing

Multiple satellites in the Landsat series have been launched since the first mission in 1972. In this study, the Landsat 5 to 9 Surface Reflectance Collection was used, providing imagery at approximately 16-day intervals. This collection ensures geolocation accuracy, temporal consistency, and interoperability across time, and meets the required geometric and radiometric quality standards.

Landsat 5 is equipped with the Thematic Mapper (TM) sensor, featuring 7 spectral bands, 8-bit quantization, and a spatial resolution of 30 m. Landsat 7 carries the Enhanced Thematic Mapper Plus (ETM+), an improved version of the TM sensor, also with 7 bands, 8-bit quantization, and a spatial resolution of 30 m. Additionally, Landsat 7 offers a 15 m panchromatic band and a 60 m thermal infrared band. Landsat 8 and 9 maintain a 30 m spatial resolution across all bands, ensuring data consistency with previous missions. These satellites feature the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), with improvements in quantization to 12-bit and additional bands, including coastal aerosol and cirrus bands (Hemati et al., 2021).

In this context, the Landsat 5, 7, 8, and 9 missions provide a continuous historical record, making them ideal for long-term vegetation analysis. These satellites offer imagery with a spatial resolution of 30 m for the bands used in NDVI calculation, with a revisit cycle of 16 days. The Landsat 5 to 9 collection was processed to calculate NDVI anomalies and NDVI time series for the 1990–2024 period.

Surface Reflectance Near Infrared and Red bands (SR_B) were used for NDVI calculation. For Landsat missions 5 to 7, the Near Infrared and Red bands correspond to SR_B4 and SR_B3, respectively, while for Landsat missions 8 and 9, these bands correspond to SR_B5 (Near Infrared) and SR_B4 (Red), respectively.

To improve the accuracy of the data, scaling and offset factors were applied to the optical bands used in NDVI calculation. The scaling factor was 2.75e-05, and the offset factor was -0.2, as shown in the formula (Equation 1):

$$\boldsymbol{OB = SR_B \times (2.75e-05) + (-0.2)} \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{1})$$

Where OB is the scaled Optical Bands, and SRB is the Near Infrared and Red bands. Finally, Pixel Quality Assessment (QA_Pixel) bands were used to perform cloud masking on all the images for the study area.

2.6 Landcover Calculation

2.6.1 NDVI Calculation

NDVI is a key indicator of net primary productivity and vegetation health, enabling differentiation between vegetation and other types of land cover. It also helps in assessing the overall condition of vegetation, defining and visualizing vegetated areas, and detecting abnormal changes in vegetation growth. Additionally, NDVI anomalies have been used to capture the current state of vegetation relative to its average conditions over a specific period (Li et al. 2014).

For processing the image collection, the time period was defined on a trimestral basis: January-March (Q1), April-June (Q2), July-September (Q3), and October-December (Q4). For all datasets from Landsat and Sentinel, NDVI was calculated using the following formula (Equation (2)):

$$\boldsymbol{NDVI = \frac{NIR - Red}{NIR + Red}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{2})$$

Where NIR is the near-infrared band, and Red is the red band of the satellite imagery, which for Sentinel corresponds to bands 8 (NIR) and 4 (Red), respectively, while for Landsat 5 and 7, they correspond to bands 4 (NIR) and 3 (Red). For Landsat missions 8 and 9, bands 5 (NIR) and 4 (Red) were used. Based on the NDVI results, land cover classifications were then assigned.

2.7 Anomaly Calculation

NDVI anomaly captures changes in vegetation relative to average conditions for a given period. The data used to calculate the anomaly spans from January 1990 to the present. The mean NDVI value was calculated for each trimester (January to March, April to June, July to September, and October to December) from 1990 to 2023. These yearly means were then compared to the corresponding trimester means for 2024 using Landsat images.

To calculate the NDVI anomaly, the mean NDVI for each trimester (January to March, April to June, July to September, October to December) for each year from 1990 to 2024 was computed using the following formula (Equation (3)):

$$\boldsymbol{NDVImean_i = \frac{(NDVI_1 + NDVI_2 + \cdots NDVI_n)}{n}} \ldots\ldots (\mathbf{3})$$

Where NDVImean_i is the mean NDVI value of each trimester (Q1, Q2, Q3, Q4) of each year from 1990 to 2024, and NDVI1 is the first 16-days NDVI composite to NDVIn which is the last 16-days NDVI composite (Landsat revisit cycle) during the fourth trimester of each year. After computing the NDVImean_i, the overall mean NDVI from 1990 to 2023 was then computed using the formula (Equation (4)).

$$\boldsymbol{\overline{NDVI} = \sum_{i=n}^{n} \frac{NDVI_{mean\_i}}{n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{4})$$

Where n is the number of years (1990-2023) which is equal to 33.The NDVI anomaly for the quarterly trimester of 2024 was derived using the formula (Equation (5)) for each grid cell in the study area (Anyamba et al. 2001, in Nanzad et al. 2019).

$$\boldsymbol{NDVI_{anomaly\_i} = \left(\frac{NDVI_{mean} - \overline{NDVI}}{\overline{NDVI}}\right) \times 100\,\%} \ldots\ldots\ldots\ldots\ldots (\mathbf{5})$$

Where NDVIanomaly_i is the anomaly percentage for each trimester of 2024, NDVImean is the mean NDVI for each trimester of 2024.

Anomalies above zero are considered gain, and below zero shows vegetation loss. NDVI calculations, time series, and anomalies analysis focused on Sharaan NP (fenced) and Gharameel NR (unfenced) rangelands during the second trimester of the year and the whole AlUla for a larger context.

3. Results and Discussion

3.1 Perennial Grass and Forb Biomass

An analysis of variance (ANOVA) was conducted to compare the mean dry biomass of perennial grasses and forbs across the study sites (Sharaan NP and Gharameel NR), Figure 2. The ANOVA results revealed a significant difference in perennial grass dry biomass among the sites ($p = 0.0175$)). Tukey HSD post-hoc test indicated a significant difference in perennial grass dry biomass between Sharaan and Gharameel ($p = 0.0369$). Moreover, no significant difference was observed in the dry biomass of forbs across the sites ($p = 0.585$). These results suggest that the dry biomass of perennial grasses is significantly higher at Sharaan compared to Gharameel, reflecting the positive impact of livestock grazing exclusion.

3.2 Land Coverture from NDVI and NDVI Anomaly

Based on NDVI for the four trimesters of 2024, Land Coverture was assigned to represent the vegetation state (Figure 3), and NDVI anomaly was calculated from 1990 to 2024 to show the spatial distribution of vegetation changes along each quarter of 2024 (Figure 4). Finally, Land Cover detailed maps highlighting areas with permanent vegetation along the year were produced for Sharaan NP (Figure 5) and Gharameel NR (Figure 6).

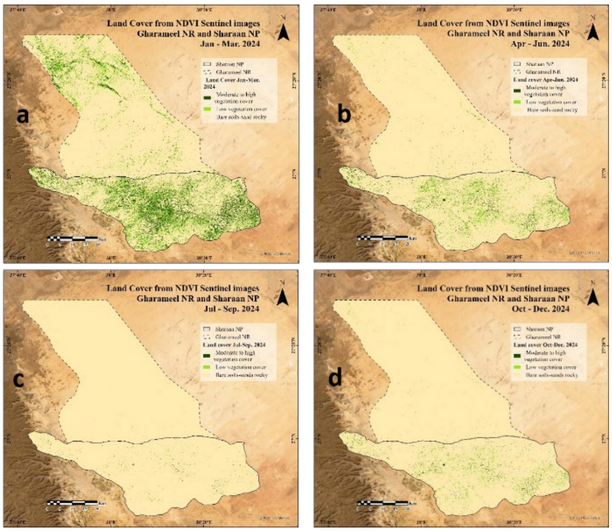

Figure 3. Land Cover from NDVI Sentinel images for Sharaan NP and Gharameel NR for each quarter of 2024. a: Jan-Mar, b: Apr-Jun, c: Jul-Sep, d: Oct-Dec.

In general, NDVI values range between -0.4 and 0.1. Land Coverture was assigned based on the vegetation status: Topaz color represents Bare soils, sands, and rocks (NDVI values ≤ 0.115), Light green represents Low vegetation cover like sparse vegetation, shrubs and grasses (NDVI values 0.115-0.128), and Dark green represent Moderate to high vegetation cover (NDVI values ≥ 0.128). The NDVI anomaly maps are shown in percentage, and the colors range from white (0%), representing no changes, to dark green (above 0 to 100%), representing normal to good vegetation conditions, and to dark brown (below 0 to -100%) representing negative changes or lost in vegetation conditions.

Land coverture states shows variations along the year going from large areas of Moderate to High vegetation cover during the first quarter of 2024 to mainly bare land sands ad rocks in the third quarter and fourth quarter of 2024 (Figure 3). These changes are more remarkable in Gharameel NR where Moderate to High vegetation cover is seen in the northern areas only during the first quarter (Figure 3-top right), to mainly bare lands for the remainder of the year, while for Sharaan NP, the change is less accentuated and more gradual showing signs of vegetation growth by the last trimester (Figure 3- d). NDVI anomaly map shows the state of vegetation during the four trimesters of 2024 compared to the same trimester of the previous years (1990 - 2023). We can see that the whole region presents normal to good conditions despite the harsh seasonal transitions. The first two quarters of the year show better vegetation conditions and more positive anomalies than the last two quarters (Figure 4). Higher positive anomalies shifts from areas north in the first quarter (Figure 4-a) to southeast in the second quarter of 2024 for Gharameel NR (Figure 4-b), and for Sharaan NP these positive conditions are consistent in the central valley throughout the year.

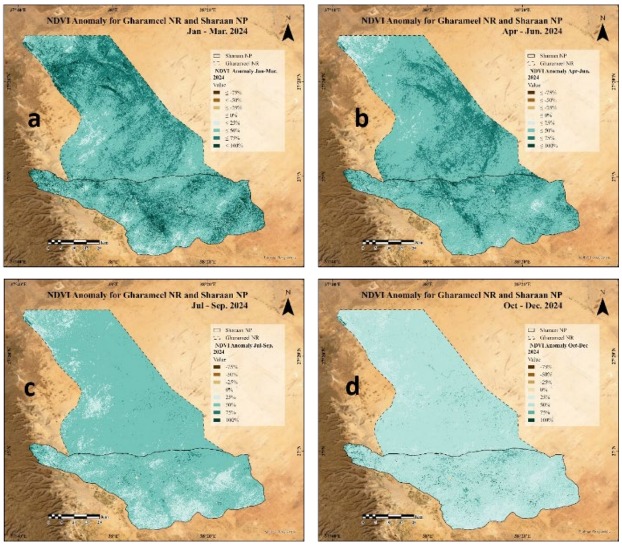

Figure 4. NDVI Anomaly for Sharaan NP and Gharameel NR for each quarter of 2024. a: Jan-Mar, b: Apr-Jun, c: Jul-Sep, d: Oct-Dec.

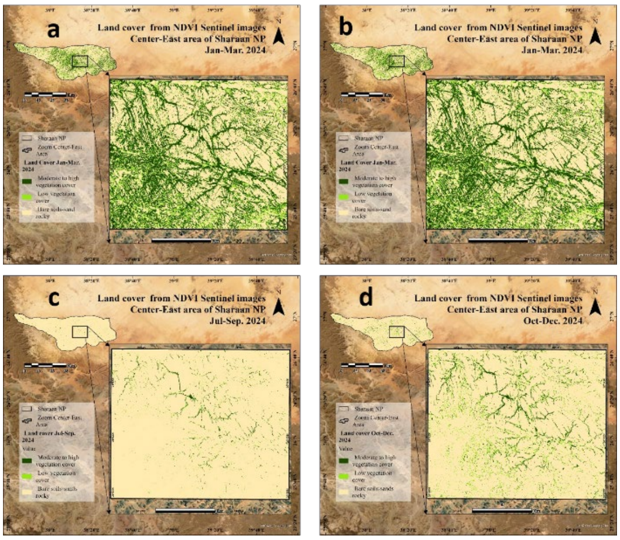

Figure 5. Land Cover from NDVI Sentinel images for the Center-East areas of Sharaan NP for each quarter of 2024. a: Jan-Mar, b: Apr-Jun, c Jul-Sep, d: Oct-Dec.

Detailed maps of Land Coverture were produced based on consistent positive vegetation conditions from the NDVI Anomalies in the South-East areas of Gharameel NR and in the Central areas of Sharaan NP (Figure 5 & Figure 6).

For Sharaan NP Moderate to High vegetation coverture remains throughout the year shrinking inside the valleys in patterns that are probably due to groundwater reservoirs or remaining seasonal drainages (Figure 5). In Gharameel NR scattered patches of vegetation appear to be randomly distributed in the zoomed South-East area (Figure 6).

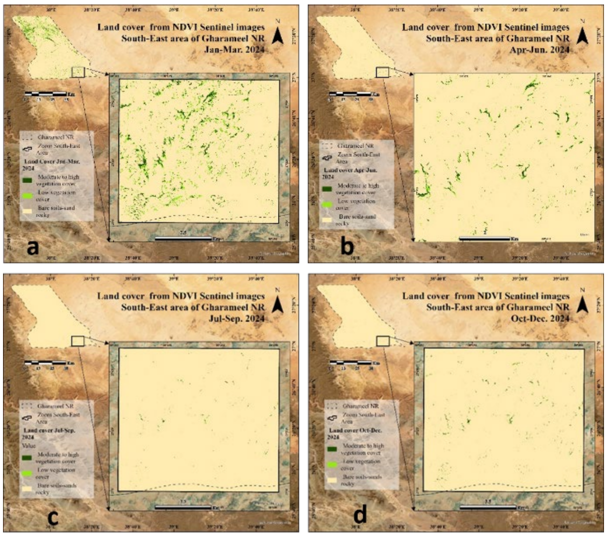

Figure 6. Land Cover from NDVI Sentinel images for the South-East areas of Gharameel NR for each quarter of 2024. a: Jan-Mar, b: Apr-Jun, c: Jul-Sep, d: Oct-Dec.

In general, areas with low vegetation coverture do not show anomalies during the different trimesters of 2024, and areas with Moderate to High Vegetation coverture also presented normal anomalies, the changes in vegetation coverture along the year respond mainly to seasonal weather conditions.

3.3 Temporal Change of NDVI

Temporal change in NDVI average trimestral values from 1990 to 2023 compared with the same trimester of 2024 is shown in Figure 7. NDVI values for the four quartiles of 2024 are higher than the average values for the same trimester from 1990 to 2023. These temporal changes in NDVI also suggest that vegetation coverture during 2024 is higher than in previous years; in general, higher values of NDVI can be seen in Sharaan NP, compared with Gharameel, and the whole region. These results are supported by the NDVI anomaly maps (Figure 2).

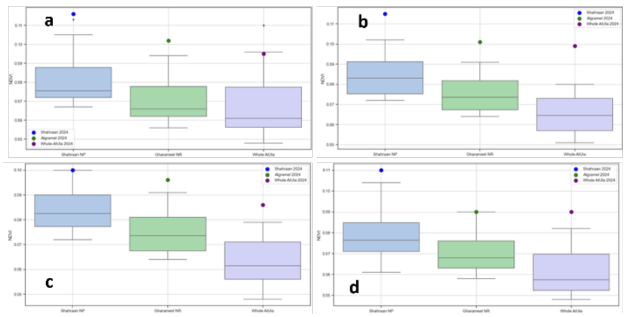

Figure 7: NDVI distribution by regions (Gharameel NR, Sharaan NP and whole AlUla), comparing data from 1990 to 2023 against the year 2024. Box plots represent the median, and quartiles, of NDVI values for the years 1990-2023, while individual points for 2024 highlight the NDVI values for that year. a: Jan-Mar, b: Apr-Jun, c: Jul-Sep, d: Oct-Dec.

As has been exposed, there are visible variations in the rangeland's vegetation coverture in both reserves, as well as its changes in response to seasonal variations, being the flat landscapes in Gharameel NR more susceptible to such changes, while the hill, slopes and valleys of Sharaan NR landscapes offers places with potential benevolent microclimatic conditions were humidity and water can remain during most part of the year.

This relation between moisture conditions and landscape in Saudi Arabian dessert has been discussed by Schulz and Whitney (1986) who described the vegetation in north-central Saudi Arabia as a sparse but diffuse permanent vegetation with annual vegetation occurring along *wadis,* and concluded that local environmental factors such as topography, sediment type, and local moisture conditions are the dominant influence on vegetation distribution.

Mohammed and Algarni (2020) analyzed spatiotemporal drought variations in northern Asir using remote sensing indexes like NDVI. They found that changes in the NDVI were associated with the changes in precipitation and evapotranspiration, thus changes in vegetation cover tend to be driven by humidity and drought transitions events.

Therefore, the relationship between vegetation coverture and landscape variability is attributed to the potential of moisture retention in valleys, hills and sloppy landscapes. Water harvesting restoration practices in rangelands relays on this correlation for re-establishing of herbaceous and woody vegetation, maximizing the retention of water on hillslopes landscapes (Stavi et al., 2020, Al-Shamiri & Ziadat, 2012).

In conclusion, monitoring vegetation cover in relation to landscape variability serves as a valuable tool for guiding targeted restoration efforts. Future research should focus on analyzing seasonal responses, particularly the dynamics of perennial grass growth and moisture availability across the study area, to refine restoration strategies. Special attention should be given to flat landscapes, such as those in Gharameel NR, to ensure the development of effective and context-specific approaches for rangeland management and ecosystem recovery.

4. Conclusion

The spatiotemporal changes in NDVI for the year 2024 show a historical increase compared with previous years (1990-2023), trimestral changes in vegetation coverture are mainly due to seasonal climatic variations. Higher positive NDVI Anomalies are related to Moderate to High vegetation covertures that remain throughout the year despite the harsh weather conditions.

Sharaan NP shows better vegetation conditions compared with Gharameel NR and the whole region, as has been exposed before the fencing management in the NP might contribute positively to improving vegetation coverture due to restoration practices, control of logging, camel grassing and off-roading.

The landscape plays a crucial role in vegetation cover and its seasonal variations. For instance, the sloped and hilly terrain of Sharaan NR supports a consistently moderate to high vegetation cover, whereas the vast, flat landscape of Gharameel NR is more associated with bare sand, rocks, and sparse, low vegetation. These findings reinforce the importance of aligning restoration efforts with landscape variability. Integrating passive restoration strategies, such as water harvesting, can significantly enhance survival rates and overall vegetation cover, leading to more effective and sustainable ecological restoration practices.

5. References

Al-Bukhari, A., Hallett, S., & Brewer, T. A. (2018). Review of potential methods for monitoring rangeland degradation in

Libya. Pastoralism, 8(13). https://doi.org/10.1186/s13570-018-0118-4

Al-Gaadi, K. A., Samdani, M. S., & Patil, V. C. (2011). Assessment of temporal land cover changes in Saudi Arabia using remotely sensed data. Middle-East Journal of Scientific Research, 9(6), 711-717.

Al-Shamiri, A., & Ziadat, F. M. (2012). Soil-landscape modeling and land suitability evaluation: The case of rainwater harvesting in a dry rangeland environment. *International Journal of Applied Earth Observation and Geoinformation, 18*, 157–164. https://doi.org/10.1016/j.jag.2012.01.005

Anyamba, A., & Tucker, C. J. (2012). *Historical perspectives on AVHRR NDVI and vegetation drought monitoring*. NASA Publications. http://digitalcommons.unl.edu/nasapub/217

Booth, D. T., & Tueller, P. T. (2003). Rangeland Monitoring Using Remote Sensing. Arid Land Research and Management, 17(4), 455–467. https://doi.org/10.1080/713936105

Canfield, R. H. (1941). Application of the line interception method in sampling range vegetation. Journal of Forestry, 38, 388–394.

Chandola, V., Banerjee, A., & Kumar, V. (2009). Anomaly detection: A survey. ACM computing surveys (CSUR), 41(3), 1-58.

D'Allestro, P., & Parente, C. (2015). GIS application for NDVI calculation using Landsat 8 OLI images. International Journal of Applied Engineering Research, 10(21), 42099-102.

European Space Agency (ESA) team. (2023). *Data Quality Report - MSI L2A* (Filename: OMPC.CS.DQR.002.06-2023 - i63r0 - MSI L2A DQR July 2023.docx). Copernicus Space Component Sentinel Optical Imaging Mission Performance Cluster Service. Approved by S. Enache & S. Clerc, authorized by F. Poustomis, and accepted by V. Boccia & S. Dransfeld. Distributed by ESA, published in Sentinel Online.

Google Earth Engine. (n.d.). Image morphological operations. Google. Retrieved May 27, 2024, from https://developers.google.com/earth- ngine/guides/image_morph

Hassan, M. M., Smith, A. C., Walker, K., Rahman, M. K., & Southworth, J. (2018). Rohingya refugee crisis and forest cover change in Teknaf, Bangladesh. Remote Sensing, 10(5), 689.

Hemati, MohammadAli, Mahdi Hasanlou, Masoud Mahdianpari, and Fariba Mohammadimanesh. (2021). "A Systematic Review of Landsat Data for Change Detection Applications: 50 Years of Monitoring the Earth" Remote Sensing 13, no. 15: 2869. https://doi.org/10.3390/rs13152869

Li, Jian, and David P. Roy. (2017). "A Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring" Remote Sensing 9, no. 9: 902. https://doi.org/10.3390/rs9090902

Mallick, J., AlMesfer, M. K., Singh, V. P., Falqi, I. I., Singh, C. K., Alsubih, M., & Kahla, N. B. (2021). Evaluating the NDVI–Rainfall Relationship in Bisha Watershed, Saudi Arabia Using Non-Stationary Modeling Technique. Atmosphere, 12(5), 593. https://doi.org/10.3390/atmos12050593

Mohammed, W. E., & Algarni, S. (2020). A remote sensing study of spatiotemporal variations in drought conditions in northern Asir, Saudi Arabia. *Environmental Monitoring and Assessment, 192*, 784. https://doi.org/10.1007/s10661-020-08771-8

Nanzad, L., Zhang, J., Tuvdendorj, B., Nabil, M., Zhang, S., & Bai, Y. (2019). NDVI anomaly for drought monitoring and its correlation with climate factors over Mongolia from 2000 to 2016. Journal of Arid Environments, 164, 69-77. https://doi.org/10.1016/j.jaridenv.2019.01.019

NDVI anomaly patterns over Africa during the 1997/98 ENSO warm event. (2001). International Journal of Remote Sensing, 22(10), 1847–1859. https://doi.org/10.1080/01431160010029156

R Core Team. (2024). R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.R-project.org/

Schulz, E., & Whitney, J. W. (1986). Vegetation in north-central Saudi Arabia. *Journal of Arid Environments, 10*(3), 175–186. https://doi.org/10.1016/S0140-1963(18)31237-0

Stavi, I., Siad, S. M., Kyriazopoulos, A. P., & Halbac-Cotoara-Zamfir, R. (2020). Water runoff harvesting systems for restoration of degraded rangelands: A review of challenges and opportunities. *Journal of Environmental Management, 255*, 109823. https://doi.org/10.1016/j.jenvman.2019.109823

U.S. Geological Survey. (n.d.). Landsat 7. U.S. Department of the Interior. Retrieved May 27, 2024, from https://www.usgs.gov/landsat-missions/landsat-7

Yeganeh, H., Khajedein, S. J., Amiri, F., & Shariff, A. R. B. M. (2014). Monitoring rangeland ground cover vegetation using multitemporal MODIS data. Arabian Journal of Geosciences, 7, 287-298.

Yengoh, G. T., Dent, D., Olsson, L., Tengberg, A. E., Tucker, C. J. (2016). Limits to the use of NDVI in land degradation assessment. In Use of the Normalized Difference Vegetation Index (NDVI) to Assess Land Degradation at Multiple Scales: Current Status, Future Trends, and Practical Considerations (pp. 27-30).