Mitigating Desertification through Solar Infrastructure: Spatiotemporal Analysis of Thermal and Vegetation Resilience in the Kubuqi Desert

Executive Summary

This project presents an integrated remote sensing and climate data analysis to evaluate vegetation dynamics, soil temperature, and precipitation patterns in an arid region of China, specifically the Kubuqi Desert, between 2015 and 2024. The study aims to investigate environmental changes associated with the implementation of large-scale solar power infrastructure and its potential role as a complementary tool in desertification mitigation strategies.

Vegetation spectral indices — NDVI, EVI, and SAVI — derived from satellite imagery were used to identify spatial and temporal patterns of vegetation gain and loss throughout the study period. Temporal variation was calculated by comparing baseline (2015) and final year (2024) conditions, enabling the identification of recovery or degradation trends.

Additionally, climate data from the ERA5-Land reanalysis dataset were employed to analyze annual mean soil temperature and total annual precipitation. These datasets were integrated within a GIS environment and comparatively assessed between areas containing photovoltaic infrastructure and adjacent exposed zones without direct intervention. Zonal statistics were applied to quantify average differences between the defined areas of interest.

Results indicate that, during the analyzed period, areas associated with solar panel installations exhibited lower mean soil temperature increase and a tendency toward vegetation growth when compared to surrounding non-protected zones. A relative increase in accumulated precipitation was also observed within the solar park area; however, the climatic analysis is considered exploratory, as the primary focus of this project lies in geospatial methodologies and environmental monitoring through remote sensing techniques.

This study is presented as a hybrid technical prototype with both academic and practical applicability. It may support environmental policy development, land restoration initiatives, territorial planning, and sustainable energy transition strategies in arid and semi-arid regions. The adopted methodology is replicable, scalable, and adaptable to other geographic contexts.

Introduction

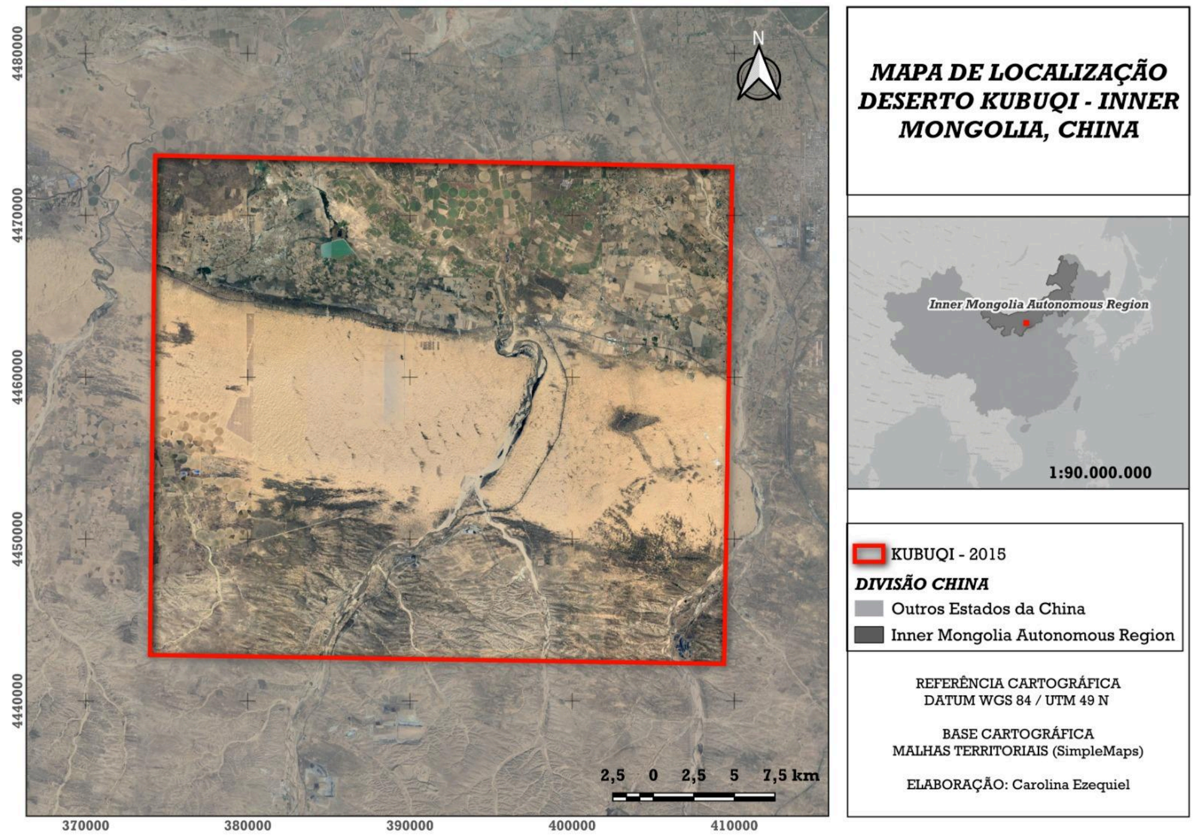
Desertification is one of the major global environmental challenges, affecting arid, semi-arid, and dry sub-humid ecosystems. The process results from the interaction between climate variability and anthropogenic pressures, leading to soil degradation, vegetation loss, and reduced ecological productivity. According to the United Nations Convention to Combat Desertification, millions of hectares of productive land are degraded annually, directly impacting food security, socioeconomic stability, and ecosystem services.

Simultaneously, the global energy transition has accelerated the expansion of large-scale solar power infrastructure in arid regions, where solar radiation is high and population density is relatively low. This strategy, aligned with the climate mitigation goals outlined by the Intergovernmental Panel on Climate Change, positions desert environments as strategic territories for renewable energy generation. However, knowledge gaps remain regarding the localized environmental effects of such infrastructure in fragile ecosystems.

In this context, remote sensing and Geographic Information Systems (GIS) have become essential tools for large-scale environmental monitoring. Vegetation spectral indices, climate reanalysis datasets, and spatial analysis techniques enable the assessment of temporal trends and spatial patterns with methodological consistency and replicability.

Given this framework, the central research question of this study is:
Is the implementation of photovoltaic infrastructure in a desert environment associated with detectable changes in vegetation dynamics, soil temperature, and precipitation over time?

The analysis covers the period from 2015 to 2024, using vegetation indices (NDVI, EVI, and SAVI) and climate data derived from the ERA5-Land reanalysis dataset, applying a comparative approach between areas containing solar panels and adjacent exposed zones.



The study area is located in the Kubuqi Desert, Inner Mongolia Autonomous Region, northern China. Kubuqi is one of the largest deserts in the country and is part of the Ordos Plateau, characterized by arid to semi-arid climatic conditions, low annual precipitation, and high thermal amplitude.

The regional climate presents limited annual rainfall, mainly concentrated during the summer months, with extended dry periods throughout the year. Temperatures vary significantly between seasons, with cold winters and hot summers. Vegetation cover is sparse and predominantly composed of drought-adapted species, with areas subject to land degradation and dune mobility.

In recent years, the region has undergone interventions aimed at desertification control and the installation of large-scale solar power complexes, making it a strategic territory for both ecological restoration and renewable energy generation.

The location map displays the spatial delimitation of the analyzed area, including the photovoltaic infrastructure zone and the external comparison area.

Data and Methodology

1. Data Sources

Satellite Imagery
Images from the Sentinel-2 satellite were used, with 10-meter spatial resolution for the visible and near-infrared bands. Images from 2015 and 2024 were selected, prioritizing scenes with low cloud cover.

Climate Data
Climate data were obtained from the ERA5-Land reanalysis dataset. The following variables were used:

- Skin temperature
- Total precipitation (tp)

Study Period
The analysis compares data from 2015 and 2024.

2. Data Processing

2.1 Vegetation Indices

Vegetation indices were calculated using Sentinel-2 spectral bands as follows:

NDVI (Normalized Difference Vegetation Index)
NDVI = (NIR - RED) / (NIR + RED)

EVI (Enhanced Vegetation Index)
EVI = 2.5 × (NIR - RED) / (NIR + 6 × RED - 7.5 × BLUE + 1)

SAVI (Soil Adjusted Vegetation Index)
SAVI = ((NIR - RED) / (NIR + RED + L)) × (1 + L)

Where:
NIR = Band 8
RED = Band 4
BLUE = Band 2
L = 0.5 (soil correction factor)

2.2 Precipitation Conversion (ERA5-Land)

The variable “total precipitation (tp)” in ERA5-Land is provided in meters (m).

The dataset was downloaded as a multiband raster, where each band represents one month of the year (12 bands total).

The processing steps were:

1.**Annual accumulation**

The twelve monthly bands were summed:
$P\ Total = B1 + B2 + \ldots + B12$

2.**Conversion to millimeters**

Since precipitation is provided in meters, the result was multiplied by 1000 to convert to millimeters:

$P_{mm} = P_{total} \times 1000$

If a monthly mean is required:
$P_{mean} = P_{total} / 12$

In this study, annual accumulated precipitation (mm/year) was used.

2.3 **Temperature Conversion**

Temperature in ERA5-Land is provided in Kelvin (K).

Conversion to Celsius was performed as follows:
$T_C = T_K - 273.15$

2.4 **Temporal Difference (Delta)**

The temporal variation between 2015 and 2024 was calculated using:

$Delta\ X = X_{2024} - X_{2015}$

Where X represents:

- Vegetation indices (NDVI, EVI, SAVI)
- Annual mean temperature
- Annual accumulated precipitation

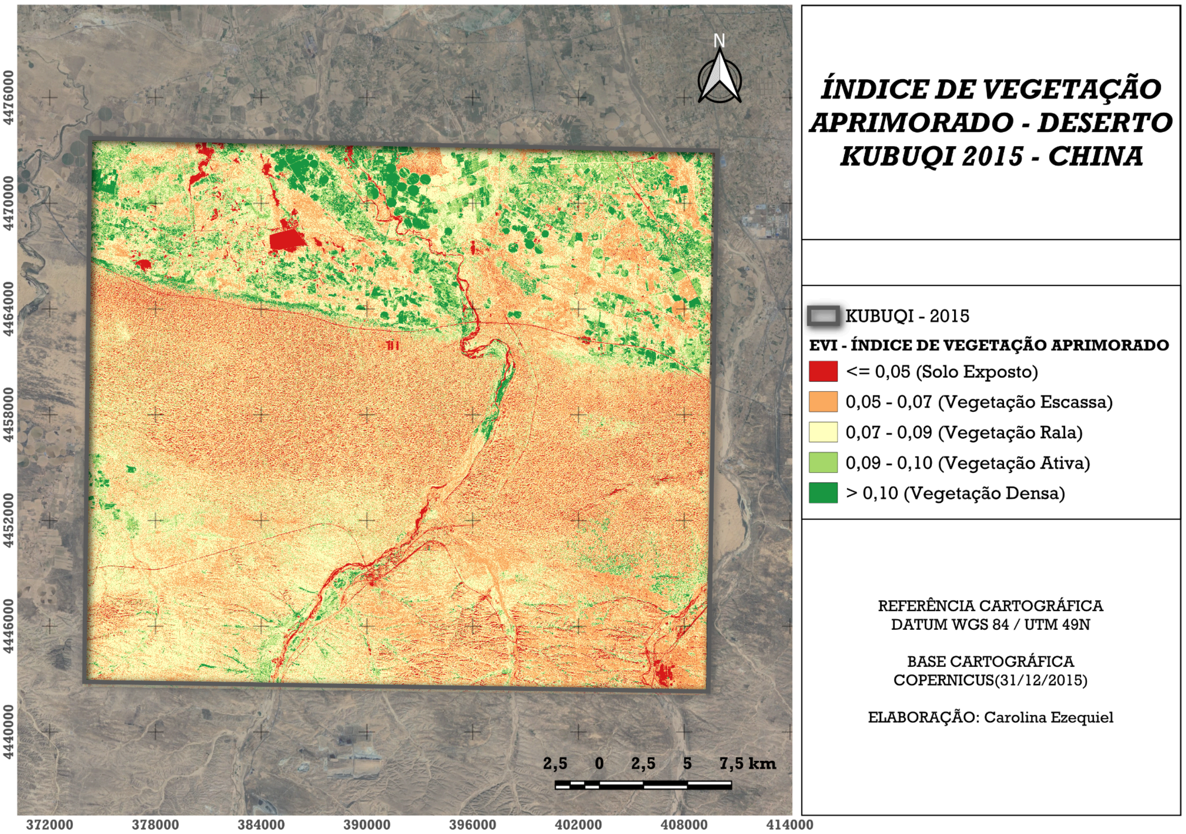
3. **Zonal Statistics**

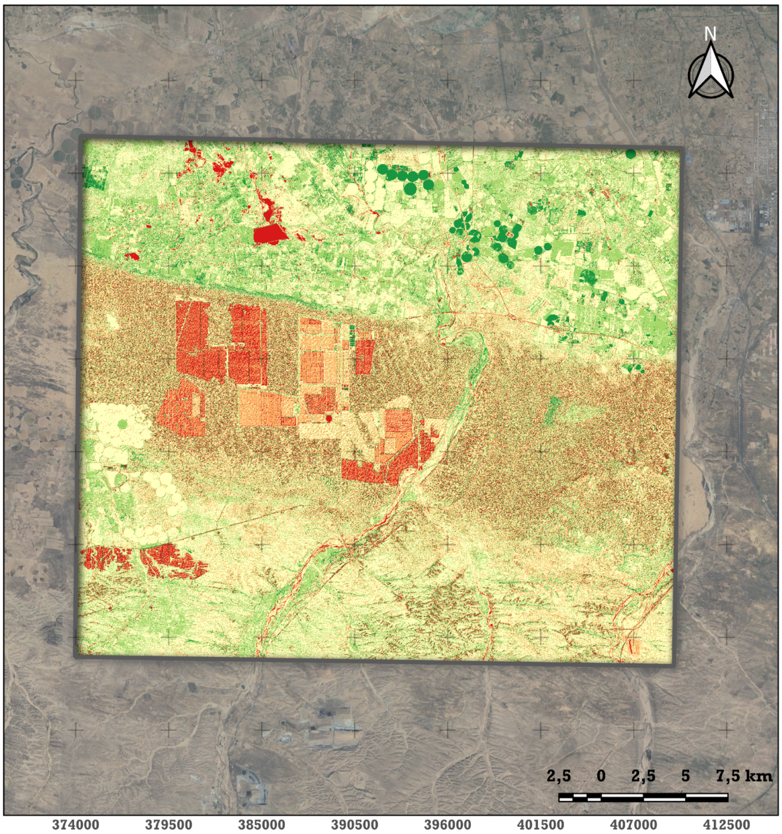
Zonal statistics were applied to compare two spatial zones:

- Area containing photovoltaic infrastructure
- External control area

The mean raster values for each variable were extracted for both zones, enabling quantitative comparison between the solar infrastructure area and the surrounding desert environment.

Vegetation 2015 - 2024





ÍNDICE DE VEGETAÇÃO APRIMORADO - DESERTO KUBUQI 2024 - CHINA

KUBUQI - 2024

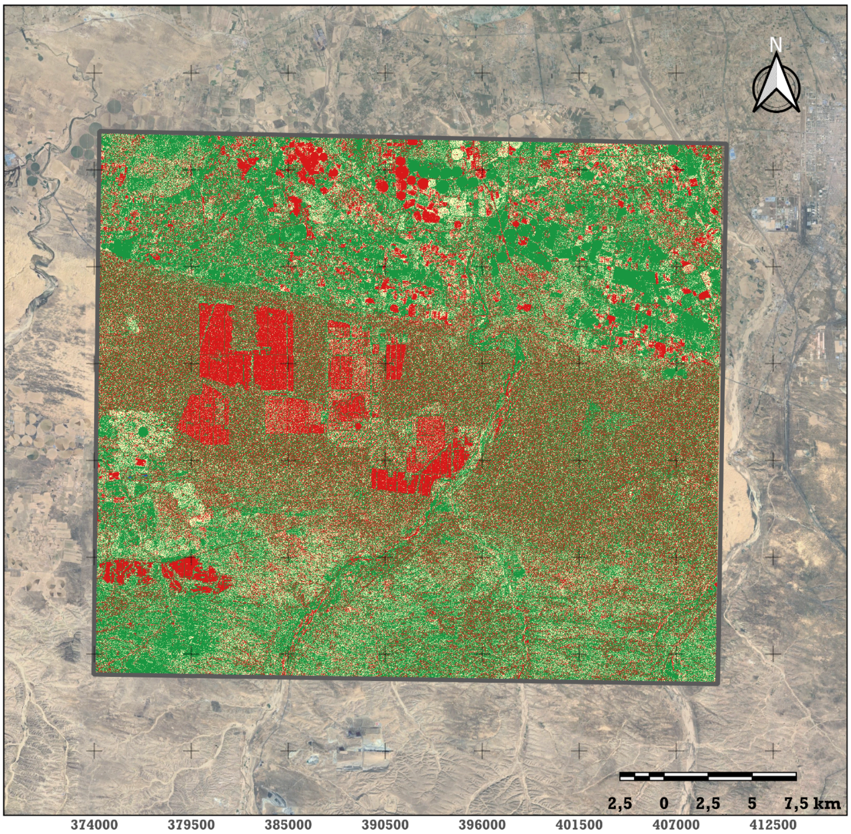
EVI - ÍNDICE DE VEGETAÇÃO APRIMORADO

- <= 0,01 (Solo Exposto)
- 0,01 - 0,06 (Vegetação Escassa)
- 0,06 - 0,10 (Vegetação Rala)
- 0,10 - 0,14 (Vegetação Ativa)
- > 0,14 (Vegetação Densa)

REFERÊNCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
COPERNICUS (13/12/2024)

ELABORAÇÃO: Carolina Ezequiel



DETECÇÃO DE MUDANÇAS NO VIGOR VEGETATIVO (EVI) EM KUBUQI - CHINA (2015 - 2024)

KUBUQI - CONTORNO

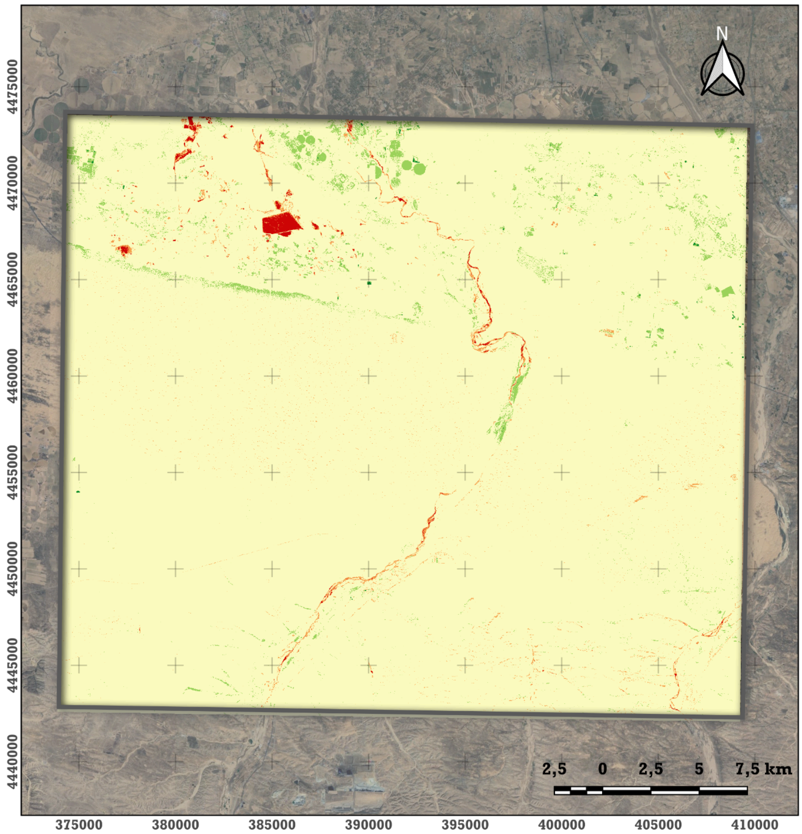
FENÔMENO AMBIENTAL

- -1 - -0,01 (Perda)
- -0,01 - 0,01 (Estável)
- 0,01 - 1 (Ganho)

REFERÊNCIA CARTOGRÁFICA
DATM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
COPERNICUS(31-12-2025/13-12-2024)

ELABORAÇÃO: Carolina Ezequiel



ÍNDICE DE VEGETAÇÃO - DESERTO KUBUQI 2015 - CHINA

KUBUQI - 2015

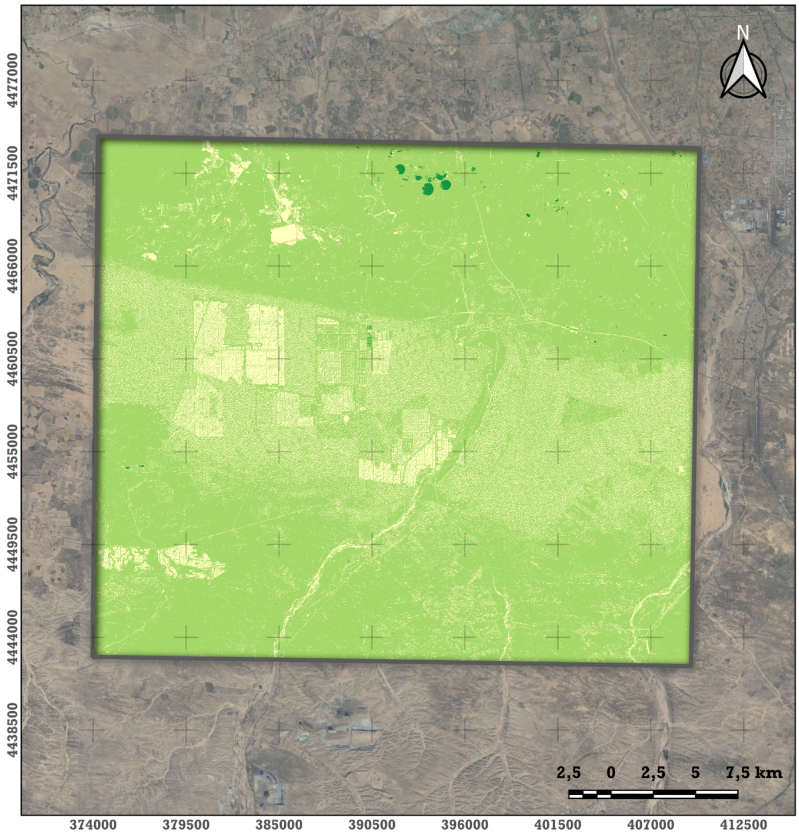
NDVI - ÍNDICE DE VEGETAÇÃO

- <= -0,16 (Água/ Solo não Vegetado)
- -0,16 - 0,02 (Solo Exposto)
- 0,02 - 0,20 (Vegetação Rala)
- 0,20 - 0,38 (Vegetação Moderada)
- > 0,38 (Vegetação Densa)

REFERÊNCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
COPERNICUS (31/12/2015)

ELABORAÇÃO: Carolina Ezequiel



ÍNDICE DE VEGETAÇÃO - DESERTO KUBUQI 2024 - CHINA

KUBUQI - 2024

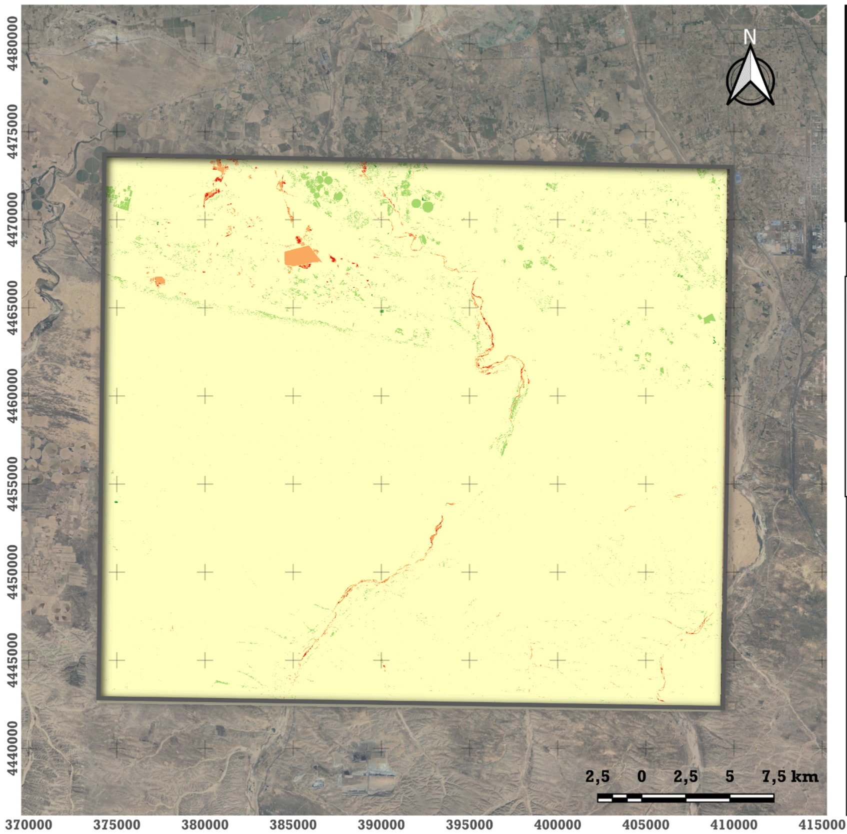
NDVI - ÍNDICE DE VEGETAÇÃO

- <= -0,64 (Água/ Solo não Vegetado)
- -0,64 - -0,29 (Solo Exposto)
- -0,29 - 0,07 (Vegetação Rala)
- 0,07 - 0,42 (Vegetação Moderada)
- > 0,42 (Vegetação Densa)

REFERÊNCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
COPERNICUS (13/12/2024)

ELABORAÇÃO: Carolina Ezequiel



ÍNDICE DE VEGETAÇÃO AJUSTADO AO SOLO - KUBUQI 2015 - CHINA

kubuqi_shape

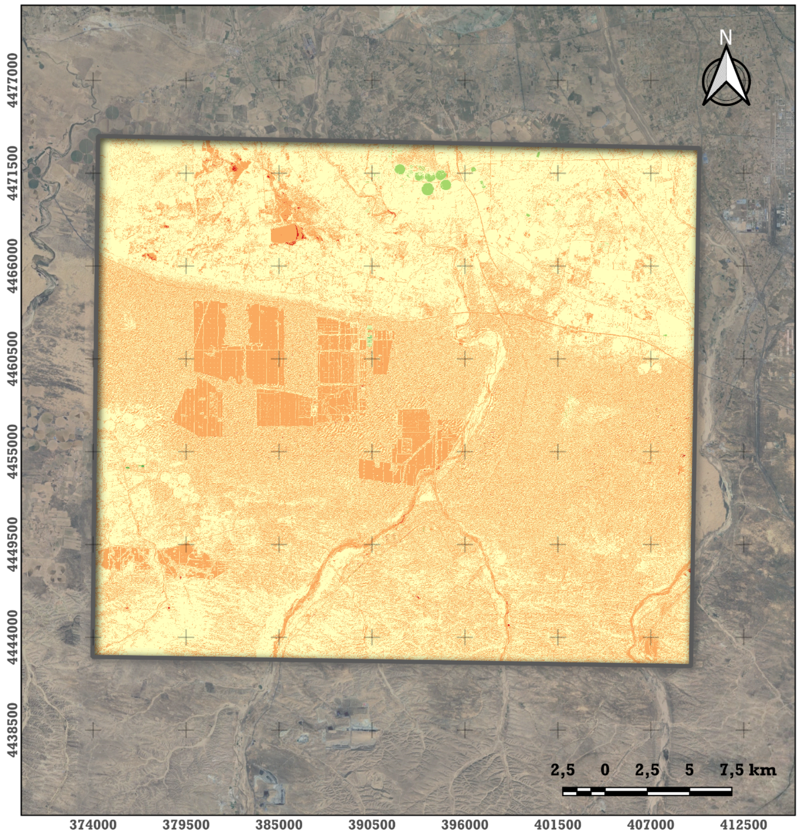
SAVI - AJUSTADO AO SOLO

- <= -0,15 (Água/ Solo Degradado)
- -0,15 - -0,01 (Solo exposto)
- -0,01 - 0,13 (Vegetação Rala)
- 0,13 - 0,28 (Vegetação Moderada)
- > 0,28 (Vegetação Densa)

REFERÊNCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
COPERNICUS(31/12/2015)

ELABORAÇÃO: Carolina Ezequiel



ÍNDICE DE VEGETAÇÃO AJUSTADO AO SOLO - DESERTO KUBUQI 2024 - CHINA

KUBUQI - 2024

SAVI - AJUSTADO AO SOLO

- <= -0,12 (Água/Solo Degradado)
- -0,12 - 0,08 (Solo Exposto)
- 0,08 - 0,27 (Vegetação Rala)
- 0,27 - 0,47 (Vegetação Moderada)
- > 0,47 (Vegetação Densa)

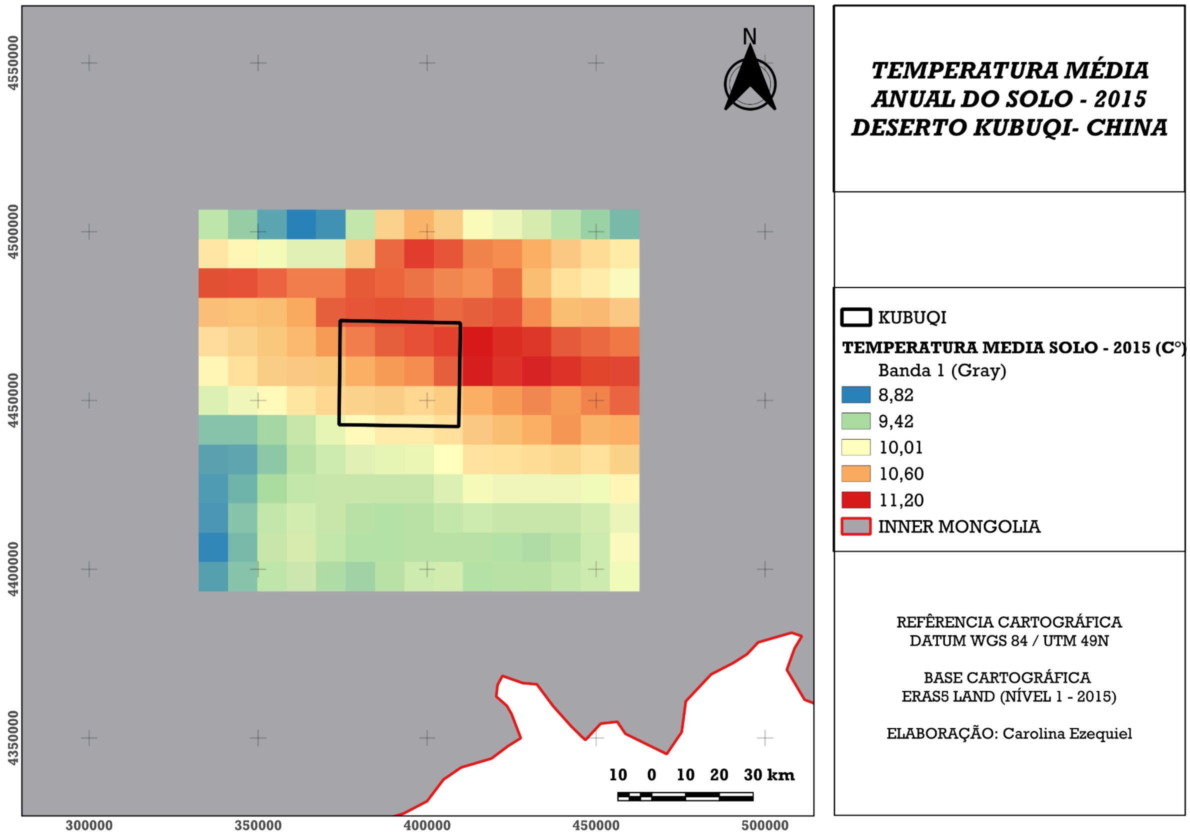
REFERÊNCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

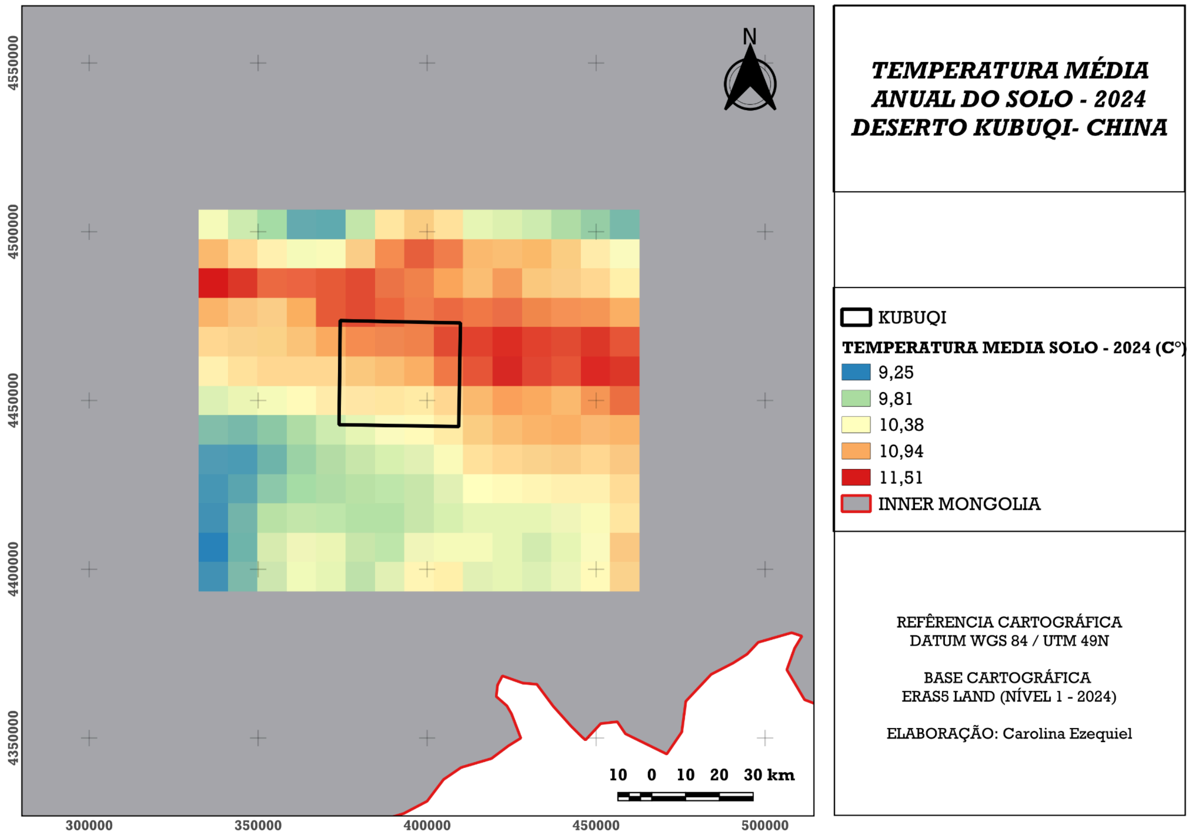
BASE CARTOGRÁFICA
COPERNICUS (13/12/2024)

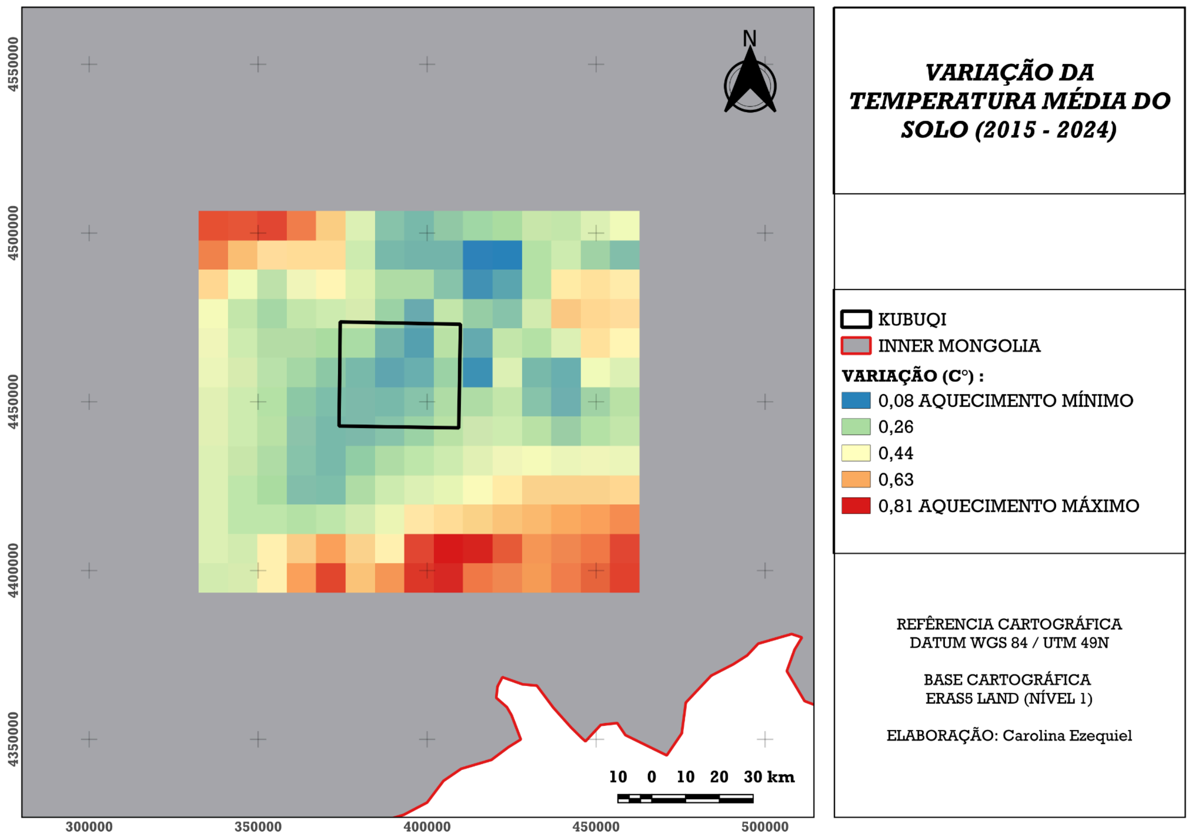
ELABORAÇÃO: Carolina Ezequiel

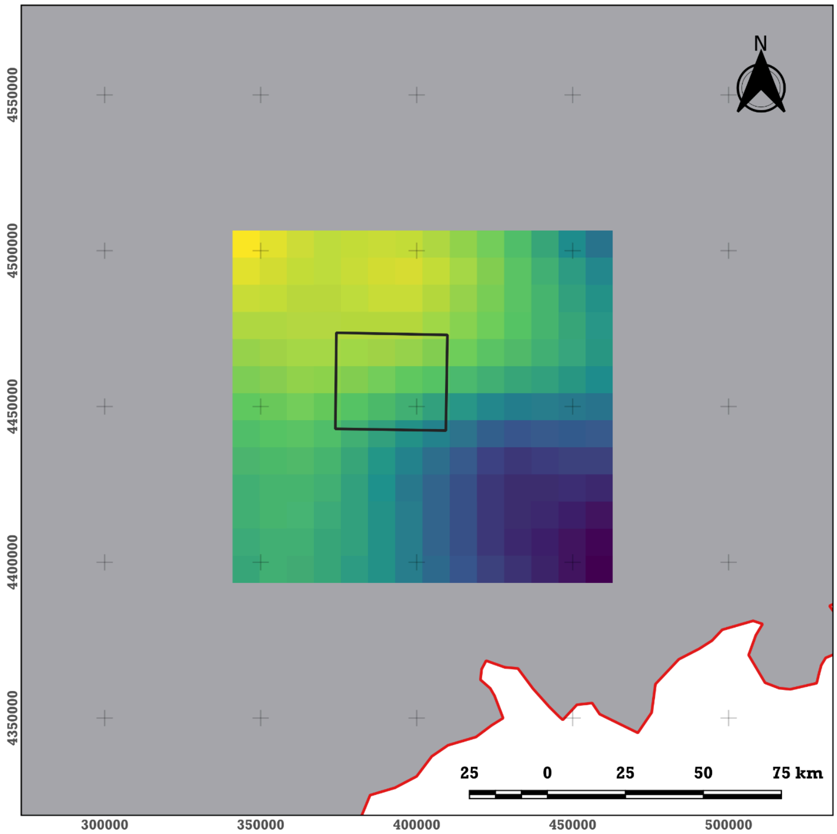
DINÂMICA DIFERENÇA (2015 - 2024)		
CLASSES/ FENÔMENO	DIFERENÇA (HA)	MUDANÇA (%)
1- PERDA/ DEGRADAÇÃO	31078.84	27.61
2- ESTABILIDADE	22467.21	19.96
3- GANHO/ RECUPERAÇÃO	54641.14	48.55
TOTAL:	108.187,19	96,12 (3,88 NODATA)

Temperature and Precipitation 2015 - 2024




TEMPERATURA MÉDIA ANUAL DO SOLO - 2024 DESERTO KUBUQI- CHINA
KUBUQI
TEMPERATURA MEDIA SOLO - 2024 (C°)
9,25
9,81
10,38
10,94
11,51
INNER MONGOLIA
REFÊRENCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N
BASE CARTOGRÁFICA
ERA5 LAND (NÍVEL 1 - 2024)
ELABORAÇÃO: Carolina Ezequiel
N
10 0 10 20 30 km
300000
350000
400000
450000
500000
4550000
4500000
4450000
4400000
4350000


VARIAÇÃO DA TEMPERATURA MÉDIA DO SOLO (2015 - 2024)
KUBUQI
INNER MONGOLIA
VARIAÇÃO (C°) :
0,08 AQUECIMENTO MÍNIMO
0,26
0,44
0,63
0,81 AQUECIMENTO MÁXIMO
REFÊRENCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N
BASE CARTOGRÁFICA
ERA5 LAND (NÍVEL 1)
ELABORAÇÃO: Carolina Ezequiel
N
10 0 10 20 30 km
300000
350000
400000
450000
500000
4550000
4500000
4450000
4400000
4350000



PRECIPITAÇÃO MÉDIA ANUAL - 2015 DESERTO KUBUQI - CHINA

KUBUQI
INNER MONGOLIA

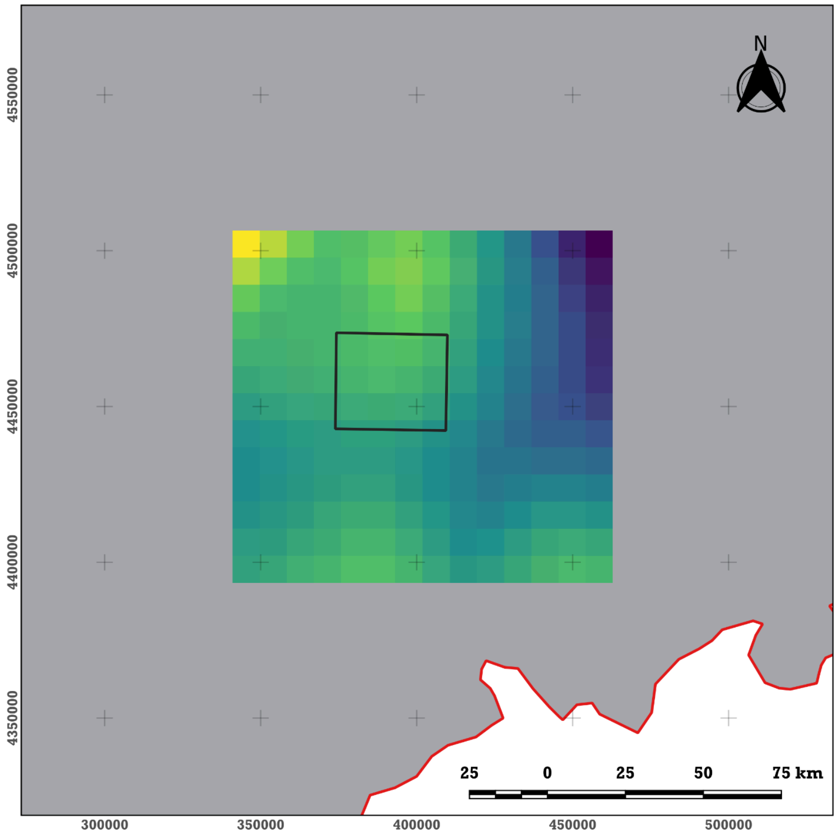
MÉDIA DE PRECIPITAÇÃO - 2015 (MM)

237,50
285,15
332,81
380,46
428,11

REFÊRENCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
ERAS5 LAND (PRECIPITAÇÃO TOTAL - 2015)

ELABORAÇÃO: Carolina Ezequiel



PRECIPITAÇÃO MÉDIA ANUAL - 2024 DESERTO KUBUQI - CHINA

KUBUQI
INNER MONGOLIA

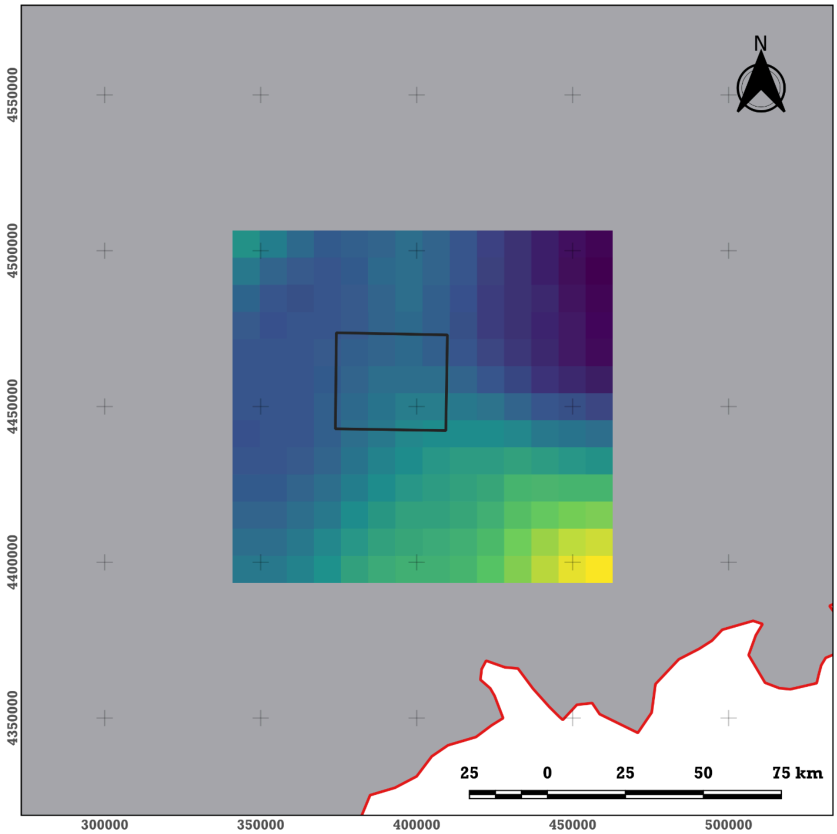
MÉDIA DE PRECIPITAÇÃO - 2024 (MM)

509,25
566,80
624,36
681,92
739,47

REFÊRENCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
ERAS5 LAND (PRECIPITAÇÃO TOTAL - 2024)

ELABORAÇÃO: Carolina Ezequiel



VARIAÇÃO DA PRECIPITAÇÃO MÉDIA ANUAL (2024 - 2015) DESERTO KUBUQI - CHINA

KUBUQI
INNER MONGOLIA

VARIAÇÃO DE PRECIPITAÇÃO - (MM)

158,81
216,14
273,46
330,79
388,11

REFÊRENCIA CARTOGRÁFICA
DATUM WGS 84 / UTM 49N

BASE CARTOGRÁFICA
ERAS5 LAND (PRECIPITAÇÃO TOTAL)

ELABORAÇÃO: Carolina Ezequiel

VARIAÇÃO DE TEMPERATURA		MÉDIA PRECIPITAÇÃO	
Área Protegida	0.20°	2015	237 mm - 428 mm
Área Externa	0.38°	2024	509 mm - 739 mm
(0,38 - 0,20) / 0,38 = ~47%		AUMENTO MÉDIO - VARIAÇÃO	158 mm - 388 mm

Integrated Discussion

The integrated analysis of vegetation indices, temperature, and precipitation between 2015 and 2024 indicates measurable environmental changes in the study area.

NDVI, EVI, and SAVI showed an overall increase in the analyzed area, indicating intensification of vegetation cover over the period. The consistent behavior among the three indices suggests that the increase is not solely due to soil exposure effects (as could occur with NDVI alone), but also reflects structural and vigor improvements in vegetation (supported by EVI and SAVI).

Mean temperature presented spatial variation between the photovoltaic infrastructure area and the external control zone. A tendency toward lower temperature increase or localized cooling effects was observed within the solar panel area compared to the surrounding environment, suggesting possible microclimatic modification associated with panel coverage.

Annual precipitation showed a regional increase during the analyzed period. Visually, the area containing solar panels followed the same regional precipitation pattern, without significant divergence from the control area. This suggests that the observed precipitation change is linked to broader climatic variability rather than a localized infrastructure-driven effect.

Integrated interpretation indicates that:

• Vegetation cover increased over the study period.
• Precipitation showed regional growth.
• The solar infrastructure area followed the regional precipitation trend.
• Temperature variation in the photovoltaic zone showed slightly distinct behavior compared to the surrounding area.

The findings suggest that vegetation expansion may be associated with both regional precipitation increase and potential localized shading effects that reduce thermal stress. However, direct causality cannot be established based solely on the spatial comparative analysis conducted.

Applicability

The applied methodology demonstrates strong potential for continuous environmental monitoring in arid and semi-arid regions. The integration of Sentinel-2 imagery and ERA5-Land climate data enables low-cost, scalable, and replicable temporal analyses across different geographic contexts.

The combined use of NDVI, EVI, and SAVI allows for sensitive monitoring of vegetation dynamics, accounting for both vegetation density and soil background effects — a crucial factor in dryland environments. The inclusion of meteorological variables strengthens interpretation by contextualizing spectral changes within broader climatic patterns.

This approach is directly applicable to Brazilian semi-arid regions such as the Caatinga biome, where the expansion of solar and wind energy projects requires systematic environmental monitoring. The methodology allows for:

- Assessment of environmental conditions before and after renewable infrastructure installation
- Identification of potential microclimatic modifications linked to large-scale energy projects
- Monitoring of vegetation recovery or degradation trends
- Integration of climatic variability into sustainability assessments

Furthermore, the method provides technical support for decision-making in renewable energy projects by contributing to:

- Environmental impact assessments
- Sustainable land-use planning
- Long-term monitoring of sensitive ecosystems
- Evaluation of compatibility between energy transition and environmental conservation

Because it relies on open-access data and standard GIS-based workflows, the methodology is fully replicable by public agencies, environmental consultancies, and energy planning teams.

Limitations

Despite the consistency of the results, several methodological limitations must be acknowledged.

First, the comparative analysis was based on two specific years (2015 and 2024). Although the temporal interval spans nine years, the absence of a continuous time series limits the ability to detect interannual trends, detailed seasonal variability, or intermediate extreme climatic events that may have influenced the observed patterns.

Second, the climate data were derived from reanalysis products (ERA5-Land) rather than local meteorological stations. Although widely used in scientific research, reanalysis data are model-based estimates and may contain uncertainties, particularly in arid regions where precipitation events are sparse and spatially heterogeneous.

Furthermore, no field validation (ground truthing) was conducted to directly confirm the vegetation index variations or microclimatic differences identified through remote sensing. The lack of in situ measurements restricts the ability to verify localized ecological processes potentially associated with photovoltaic infrastructure.

Finally, the study identifies spatial and temporal associations but does not establish direct causality between the presence of solar panels and the environmental changes observed.

Conclusion

The integrated analysis conducted between 2015 and 2024 demonstrates that remote sensing combined with reanalysis climate data represents a robust tool for environmental assessment in arid regions undergoing renewable energy expansion.

The results indicate increased vegetation cover over the analyzed period, accompanied by regional precipitation growth and spatially differentiated thermal variations. The photovoltaic infrastructure area followed the regional precipitation pattern without significant divergence, while presenting slight thermal distinctions compared to surrounding areas.

Although direct causality between solar panel installation and observed environmental changes cannot be established, the findings highlight the value of integrating spectral and meteorological variables to identify spatial patterns relevant to territorial planning.

From a strategic perspective, this study demonstrates that:

• Environmental impacts of renewable energy projects can be monitored using open-access data and replicable methodologies
• The integration of vegetation indices and climatic variables enhances environmental assessments in sensitive regions
• Remote sensing provides technical support for sustainable energy transition planning

The applied approach reinforces the role of geospatial analysis as a technical instrument for balancing energy development and environmental conservation, particularly in vulnerable ecosystems.

Future Perspectives

The continuation of this study may significantly strengthen analytical robustness and practical applicability.

A key next step would be the development of a continuous time series from 2015 to 2024, incorporating all intermediate years. This would allow for the assessment of interannual trends, seasonality, and extreme events, enhancing the interpretation of observed patterns.

Another important direction involves integrating local meteorological station data, when available, for cross-validation with reanalysis datasets. The combination of modeled and in situ measurements would increase the reliability of the findings.

From a methodological standpoint, future research may include:

• Surface albedo and energy balance analysis
• Land Surface Temperature (LST) assessment
• Statistical modeling or correlation analysis between spectral and climatic variables
• Expansion to multiple photovoltaic sites for regional comparison

There is also potential to apply machine learning techniques to detect more complex spatial patterns and improve environmental change assessment.

Finally, replicating this methodology in Brazilian semi-arid biomes such as the Caatinga could support the development of national monitoring protocols linked to renewable energy expansion. This study contributes to the understanding of environmental dynamics in arid regions undergoing energy transition, reinforcing the strategic role of remote sensing as a monitoring tool.

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Tools: QGIS • Sentinel-2 • ERA5-Land • Raster Analysis • Zonal Statistics