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Remote Sensing Assessment Of Pastoral Plantation Efficiency In Combating Desertification: Analysis Of NDVI Evolution, Rainfall Correlation And Pastoral Management Impact In Djelfa Steppe (2005-2025)

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Abstract
The steppe ecosystems of Djelfa province are experiencing critical environmental degradation of their vegetation biomass, compromising essential ecosystem services including water regulation, carbon sequestration, and biodiversity conservation. This deterioration results from complex interactions between anthropogenic factors (overgrazing, unsustainable resource exploitation) and climatic disturbances (rainfall variability, warming, extreme events). Since 2005, the High Commission for Steppe Development (HCDS) has implemented an integrated ecological restoration approach across 20 million hectares of steppe ecosystems. Pastoral plantations constitute the priority intervention, designed as nature-based solutions to mitigate land degradation and promote adaptation to environmental changes.
The case study covers the period 2005-2025 and exploits GPS coordinates of areas planted by the HCDS in 2005, according to data provided by technical services and available synoptic sheets. Of the 16 projects identified, five projects were selected in potential areas with optimal characteristics for this research.
This study develops an advanced remote sensing assessment approach, integrating multitemporal analysis of the Normalized Difference Vegetation Index (NDVI) over two decades (2005-2025), exploitation of LandTrend satellite data, quantification of environmental trajectories of restored ecosystems, and establishment of correlations between vegetation dynamics and hydroclimatic variability. The methodology enables continuous monitoring of key ecological indicators (vegetation index, vegetation cover, primary productivity), near real-time surveillance of degradation/restoration processes, early detection of areas at high environmental risk, and objective evaluation of ecological management performance.
The analyses reveal the critical importance of adaptive management in maintaining the environmental integrity of steppe formations. NDVI spectral signatures accurately identify regeneration/exploitation cycles, critical thresholds beyond which ecological recovery capacity is compromised, zones of optimal resilience to recurrent climatic stress, and sectors requiring urgent environmental interventions. This pioneering research, integrating high-resolution remote sensing, hydroclimatic data, and landscape ecology, constitutes a methodological framework for evaluating ecological restoration programs. It provides innovative tools to optimize the sustainability of anti-desertification interventions and strengthen the environmental resilience of steppe ecosystems facing global climate change challenges. The recommendations aim to improve the efficiency of future strategies and contribute significantly to environmental sciences applied to sustainable management of Mediterranean semi-arid ecosystems.
Keywords: *Remote sensing, NDVI, pastoral plantations, desertification, steppe ecosystems, climate change.*

1. INTRODUCTION

Desertification constitutes one of the major environmental challenges of the 21st century, manifesting as a land degradation process characterized by a drastic reduction in soil biological productivity and alteration of ecosystem equilibrium. This multifactorial phenomenon results from the combination of anthropogenic factors (resource overexploitation, intensive overgrazing, inappropriate agricultural practices) and extreme bioclimatic disturbances, notably recurrent drought episodes. [1], [2]
Steppe formations, characterized by vast grassland expanses in arid and semi-arid environments, hold major ecological and socio-economic importance. These fragile geosystems support traditional agropastoral activities essential for the subsistence of millions of rural populations, while providing crucial ecosystem services: climate regulation, carbon sequestration, biodiversity conservation, and erosion protection. [2]

Algeria, with its 20 million hectares of steppe formations, harbors one of the most extensive pastoral ecosystems in the Mediterranean basin. Facing the alarming regressive dynamics of these territories, the High Commission for Steppe Development (HCDS) has developed since the 2000s an ambitious territorial strategy for ecological restoration, including pastoral plantation as a central strategic pilot project. [3]
Rigorous evaluation of these programs' effectiveness remains a major methodological challenge, constrained by limitations of conventional approaches: high cost of field campaigns, restricted geographical coverage, and subjectivity of in situ observations. Facing these limitations, satellite remote sensing emerges as a revolutionary technology, offering unparalleled capabilities for continuous monitoring and objective evaluation of vegetation dynamics. The Normalized Difference Vegetation Index (NDVI) constitutes a robust biophysical proxy for quantifying vegetation biomass and assessing ecosystem health. [4], [5]
Djelfa province, located in north-central Algeria, constitutes an exceptional natural laboratory for evaluating anti-desertification strategies, where desertification affects approximately 60% of steppe lands. [6], [7]
This research develops an innovative evaluation approach for pastoral plantation programs through satellite remote sensing, based on multitemporal NDVI analysis over a two-decade chronosequence (2005-2025), exploiting archives from the LandTrend platform. [8] This methodology synergistically integrates satellite time series with regional rainfall chronicles and pastoral management protocols.
The central problematic articulates around two fundamental questions: How can remote sensing contribute to objective evaluation of pastoral plantation effectiveness in combating desertification? What is the influence of pastoral management cycles and rainfall variability on regeneration dynamics of restored formations?
Research hypotheses postulate that: (H1) NDVI remote sensing constitutes a reliable and economically viable tool for continuous evaluation of pastoral restoration programs; (H2) pastoral plantation effectiveness is significantly correlated with pastoral management modalities; (H3) resilience of restored formations to climate variability is superior to that of unmanaged natural rangelands.
This study aims to demonstrate the exceptional potential of remote sensing as an operational monitoring tool, enabling early detection of degradation zones, continuous monitoring of vegetation regeneration, and objective evaluation of intervention effectiveness. The objective is to establish a methodological framework for optimizing restoration strategies in steppe geosystems, providing operational recommendations to consolidate pastoral plantation program sustainability and improve efficiency of future anti-desertification interventions.

2. MATERIALS AND METHODS

2.1 Study area and characterization of intervention sites

Djelfa province (34°41'N, 3°15'E), located in the High Plateaus of north-central Algeria, constitutes the study territory of this research. This steppe region extends over an area of 32,256 km², characterized by a semi-arid continental climate with average annual precipitation ranging between 200 and 400 mm and average temperatures oscillating between 2°C in January and 35°C in July. [7]The dominant vegetation formations belong to associations of Artemisia herba-alba, Stipa tenacissima, and Lygeum spartum, typical of North African steppe ecosystems. [3]

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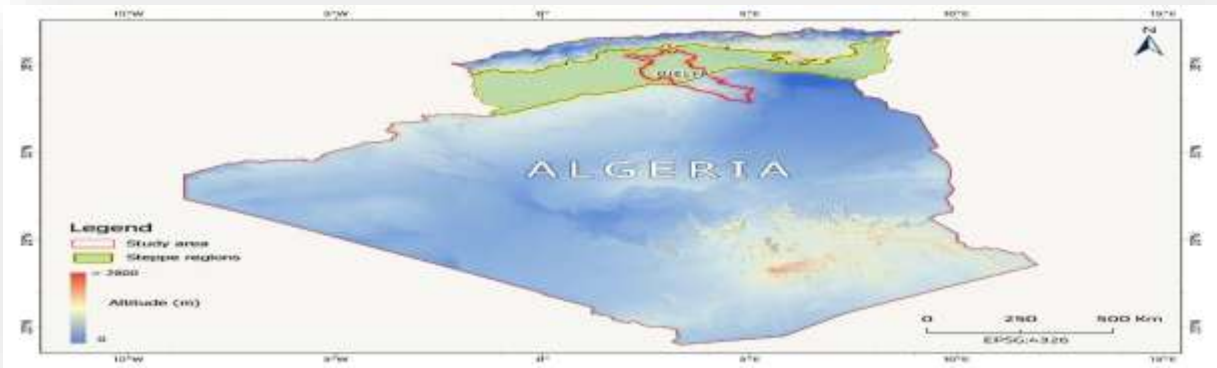

Figure1. Study area: Djelfa Province

The pastoral plantation sites studied were selected according to HCDS intervention criteria: areas showing advanced signs of degradation (vegetation cover rate < 30%), technical accessibility for management operations, and geomorphological representativeness of regional steppe formations. [9] These sites cover a cumulative area of 15,420 hectares, distributed across 12 municipalities of the province, and integrate different types of management: fodder shrub plantation (Atriplex spp.), perennial grass seeding (Medicago sativa, Phalaris tuberosa), and implementation of soil and water conservation structures.

2.2 Collection and processing of institutional data

2.2.1 HCDS data sources

Data collection relies exclusively on institutional archives of the High Commission for Steppe Development (HCDS), the national reference organization for monitoring and evaluating steppe development projects in Algeria. [10] This methodological approach is justified by the quality, completeness, and temporal coherence of data held by this institution, which has centralized since 2005 all technical, socio-economic, and environmental information related to pastoral restoration programs.

The compiled institutional data include:

- Technical data: georeferenced site location, managed areas, types of planted species, installation techniques, intervention schedules;
- Management data: enclosure protocols, authorized exploitation periods, recommended pastoral loads, pastoral monitoring modalities;
- Socio-economic data: number of beneficiaries, impacts on pastoral incomes;
- Environmental data: pedoclimatic characteristics, initial degradation state, vegetation cover evolution.

2.2.2 Periodization and study temporality

The evaluation covers an exceptional 20-year chronosequence (2005-2025), allowing analysis of long-term ecological trajectories of pastoral plantations and assessment of their resilience to interannual climate variations. This extended temporality is essential in steppe ecosystems, where vegetation regeneration processes operate on multi-annual temporal scales and where management effects only stabilize after several climatic cycles. [11], [12]

2.3 Satellite remote sensing methodology

2.3.1 Landsat data acquisition and preprocessing

The spatio-temporal analysis is based on Landsat satellite image time series (TM, ETM+, OLI/TIRS) acquired between 2005 and 2025, with a spatial resolution of 30 meters and a temporal frequency of 16 days. These data were downloaded via the Google Earth Engine platform [13], enabling access to the complete archive of Landsat images preprocessed at the atmospheric correction level (Collection 2 Surface Reflectance).

Image preprocessing includes:

- Atmospheric correction: use of the LaSRC (Landsat Surface Reflectance Code) algorithm for atmospheric effects elimination [14];

- Cloud masking: application of the CFMask (C Function of Mask) for automatic exclusion of cloudy pixels and shadows [15];
- Temporal filtering: selection of images acquired during optimal vegetation growth period (March-June) to minimize phenological variations [16];
- Compositing: creation of temporal mosaics by calculating median NDVI values for each year.

2.3.2 Calculation and analysis of the Normalized Difference Vegetation Index (NDVI)

NDVI constitutes the main biophysical indicator of this study, calculated according to the classical formula [17]: NDVI = (NIR - RED) / (NIR + RED) where NIR represents reflectance in the near-infrared (band 4 for TM/ETM+, band 5 for OLI) and RED represents reflectance in the red (band 3 for TM/ETM+, band 4 for OLI).

This spectral index, widely validated for vegetation monitoring in arid and semi-arid environments, presents optimal sensitivity to chlorophyll biomass and vegetation cover variations [4], [18]. Its capacity to detect subtle changes in vegetation vigor makes it a reliable proxy for evaluating pastoral plantation effectiveness [19].

2.3.3 Time series analysis with LandTrendr

The LandTrendr algorithm (Landsat-based Detection of Trends in Disturbance and Recovery), implemented on Google Earth Engine, constitutes the main tool for NDVI time series analysis [8],[20]. This temporal segmentation approach enables automatic identification of trend breaks and characterization of vegetation dynamics according to three distinct phases:

- Degradation phase: significant decrease in NDVI values, indicating vegetation stress or anthropogenic disturbances;
- Recovery phase: progressive increase in NDVI, indicating vegetation regeneration post-management;
- Stabilization phase: NDVI values plateau, reflecting ecological equilibrium of restored formations.

LandTrendr configuration parameters were adjusted to steppe ecosystem specificities:

- Change detection threshold: 0.1 NDVI unit ;
- Minimum stabilization duration: 3 years ;
- Inter-annual variation filtering: smoothing by segmented linear regression.

2.4 Integration of climatic and pastoral data

2.4.1 Rainfall data

Monthly precipitation data were extracted from the CHIRPS database (Climate Hazards Group InfraRed Precipitation with Station data), which constitutes a reliable international scientific reference for daily rainfall data analysis. [21] This choice is justified by CHIRPS's high spatial (0.05°) and temporal resolution, as well as its quasi-global coverage and rigorous scientific validation covering the period 2005-2025. These data were spatialized by kriging interpolation to generate precipitation maps at Landsat image resolution (30m), enabling pixel-by-pixel analysis of NDVI-rainfall correlations. [22]

2.4.2 Pastoral management cycles

Information on pastoral management modalities (enclosure periods, exploitation schedules, animal loads) was extracted from HCDS annual reports and georeferenced for each study site. This temporal dimension enables analysis of management practice impacts on NDVI evolution and identification of critical thresholds for pastoral overexploitation.[23]

2.5 Statistical analysis methods

2.5.1 Temporal trend analysis

NDVI trend analysis is based on the Mann-Kendall test, a robust non-parametric method for detecting monotonic trends in environmental time series. [24], [25] Trend magnitude is quantified by Sen's slope estimator [26], expressed in NDVI units per year.

2.5.2 NDVI-rainfall correlations

Relationships between vegetation and precipitation are analyzed by calculating Pearson correlation coefficients, with application of temporal lags (time-lags) of 1 to 6 months to identify delayed vegetation responses to rainfall events. [27], [28]

2.5.3 Spatial comparisons

Pastoral plantation effectiveness is evaluated by comparing NDVI trends between managed areas and non-restored control zones, using Student's t-tests for paired samples and repeated measures analysis of variance (ANOVA). [29]

2.6 Validation and quality control

Validation of satellite results is performed through confrontation with field data collected by HCDS (floristic surveys, coverage measurements, pastoral evaluations) and coherence analysis with previous studies conducted in similar ecological contexts. [30], [7] . A systematic quality control protocol ensures analysis reliability: verification of NDVI time series temporal coherence, detection of satellite artifacts, validation of change detection thresholds.

2.6.1 Methodological process

Considering GPS coordinates of areas planted by HCDS in 2005 according to data provided by technical services and available synoptic sheets from 16 projects, of which five projects were selected in potential zones (Zone no 01 Boumaidouna, Z02 Chebaika, Z03 Doume, Z04 Louibed, Z05 Z'barat M'hamdia), and monitoring NDVI variance over time in relation to climate change and land exploitation, a working methodology was developed to better monitor the evolution of plantations established by HCDS in 2005 in Djelfa steppe. We integrate precise GPS coordinates of each planted zone to extract NDVI index values from satellite images covering the entire study period. Using the LandTrendr tool, we analyze temporal NDVI variance to detect trends and significant changes in pastoral vegetation over the years. This approach enables evaluation of climatic factor impacts, particularly drought linked to climate change, as well as land exploitation practices on vegetation dynamics.

It is important to note that the surface area processed by LandTrendr in NDVI around a GPS point corresponding to a pastoral plantation depends essentially on the spatial resolution of satellite images used and the buffer zone defined around this point. For example, with Landsat images, resolution is generally 30 meters per pixel, meaning each pixel covers approximately 900 m^2. [8]

To analyze a pastoral plantation from a GPS point, an area of interest (buffer zone) is often delimited around this point, which can vary from a few hectares to several tens of hectares depending on plantation extent and study objectives. LandTrendr then processes the NDVI time series for all pixels included in this zone, enabling evaluation of spatialized vegetation dynamics over this area.

It is important to note that when extracting vegetation indices such as NDVI from time series processed by the LandTrendr algorithm, obtained values are often expressed as integers within an extended range, generally between -10,000 and +10,000. This representation corresponds to a coded scale specific to Landsat data, aimed at preserving measurement precision while using an integer format to facilitate storage and computer processing [31].

To ensure correct interpretation and comparability with standard NDVI values, which normally vary between -1 and +1, data normalization is necessary by dividing raw values by 10,000. This step is a widely adopted convention in Landsat satellite data processing and is recommended in LandTrendr usage protocols, particularly in technical guides and tutorials associated with the tool. [32], [8].

Although the original publication by Kennedy et al. (2010), which presents the LandTrendr methodology, does not explicitly mention this normalization, it is implicitly integrated in Landsat data processing used by the algorithm. Recent educational resources and operational applications confirm this practice, emphasizing its importance to ensure vegetation indices are expressed within their universal range, thus facilitating analysis, comparison, and integration of results in environmental and ecological studies. [33]

Thus, normalization of LandTrendr values by division by 10,000 is a rigorous scientific step that enables obtaining NDVI indices conforming to international standards, ensuring reliability and relevance of vegetation dynamics analyses within our research framework.

This method constitutes a valuable tool for more precisely evaluating pastoral plantation projects in Djelfa region, providing reliable indicators of their ecological effectiveness. Furthermore, obtained results are highly beneficial economically, environmentally, and ecologically, as they enable optimization of natural resource management, improvement of forage production, and contribution to sustainable desertification control, while supporting local socio-economic development.

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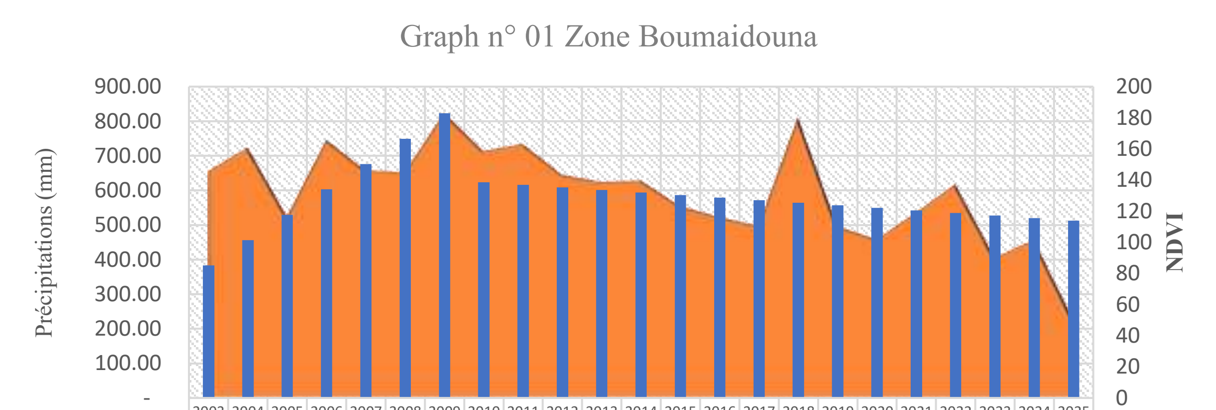
Successful monitoring of these pastoral plantations also ensures sustainability of financial resource diversification for beneficiary municipalities. Indeed, generated revenues come notably from leasing these lands to sheep breeders, who practice controlled grazing over a well-defined period, thus enabling natural regeneration of plantations. This system guarantees balance between exploitation and restoration, favoring sustainability of pastoral resources and sustainable development of concerned territories.

3. RESULTS AND DISCUSSION

Analysis of NDVI (Normalized Difference Vegetation Index) variability over the period 2005-2025 (see graphs below from HCDS projects and based on LandTrendr data) reveals several significant trends. Between 2005 and 2012, NDVI shows relative stability, oscillating around average values between 0.23 and 0.27. This period coincides with a moderate rainfall regime, enabling maintenance of satisfactory vegetation cover.

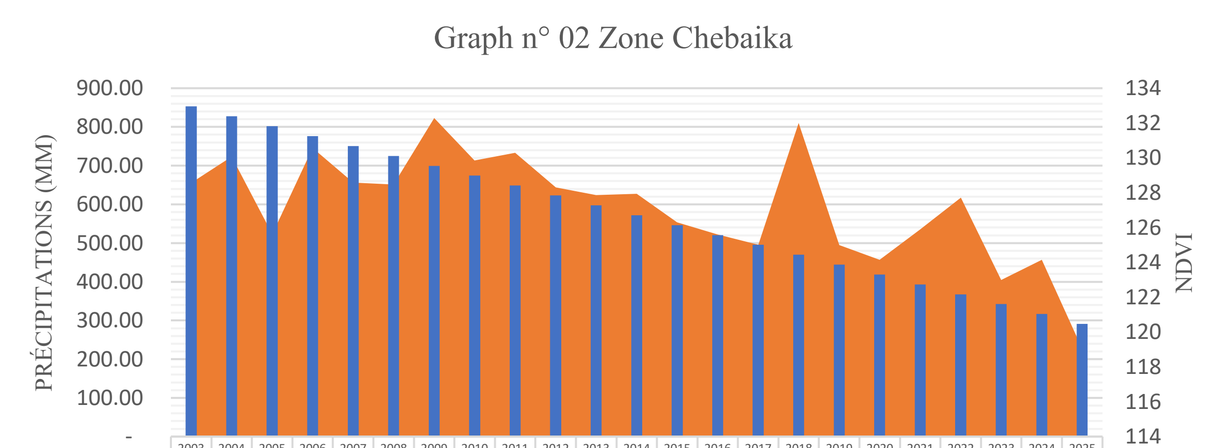
Zone no 01 Boumaidouna, Ain Oussera Municipality



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Precipitation (mm)	655	723	523	745	656	651	822	713	733	643	623	627	553	521	495	810	494	456	535	617	404	456	226
NDVI Index	85.1	101	118	134	150	167	183	139	137	135	134	132	130	129	127	125	124	122	120	119	117	116	114

The correlation between the NDVI index (green bars) and precipitation (blue line) reveals the strong dependence of steppe vegetation on water inputs. Notable observations include:
Favorable years (2008-2009, 2018-2019): Precipitation peaks (>800mm) coincide with high NDVI values, indicating dense and vigorous vegetation. These years represent optimal conditions for the development of the herbaceous layer characteristic of steppes.

Zone no 02 Chebaika, Djelfa Municipality



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Precipitations (mm)	655.2	723.2	523.2	745.7	656.5	651.5	822.8	713.5	733.0	643.6	623.7	627.2	553.2	521.8	495.8	810.2	494.7	456.7	535.1	617.2	404.9	456.5	226.5
NDVI Index	132.95	132.39	131.82	131.25	130.68	130.12	129.55	128.98	128.41	127.85	127.28	126.71	126.14	125.58	125.01	124.44	123.87	123.31	122.74	122.17	121.6	121.04	120.47

This graph reveals particularly interesting environmental dynamics for this chott zone, characterized by specific edaphic and climatic conditions.

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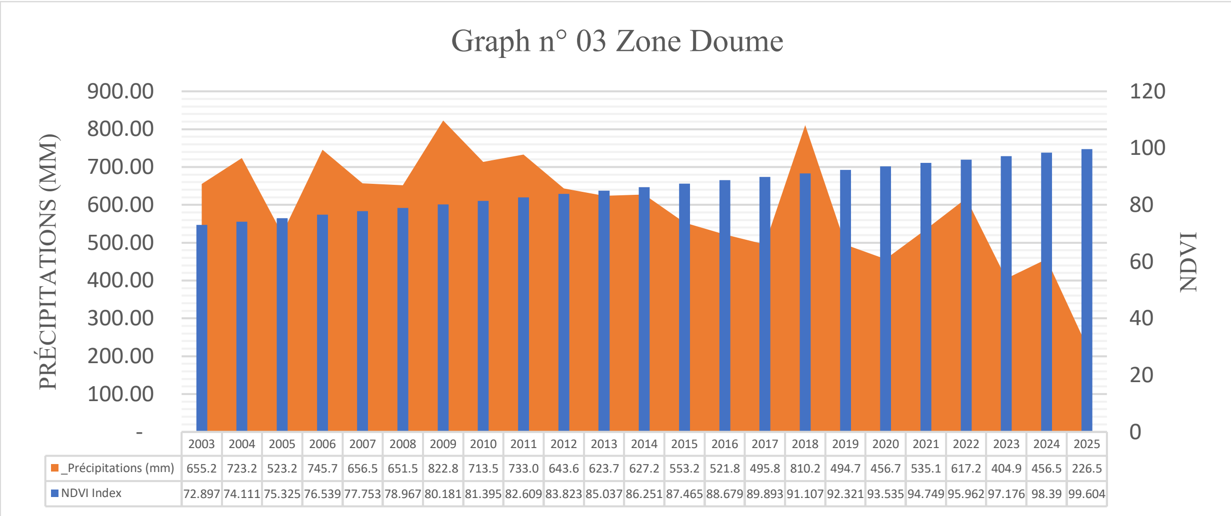
Progressive NDVI decline: A constant decrease in vegetation index is observed from 2003 (133.95) to 2025 (120.47), representing nearly a 10% decline over 22 years. This trend is particularly marked after 2010.
Rainfall variability: Precipitation shows strong interannual irregularity typical of semi-arid zones, with notable peaks in 2004 (723mm), 2009 (822mm), and 2018 (810mm).
Delayed response: Contrary to expectations, precipitation peaks do not immediately translate into proportional NDVI increases. For example, heavy rainfall in 2018 (810mm) only allows partial NDVI recovery.
Recovery threshold: NDVI values for 2020-2025 remain low (120-124) despite variable precipitation, suggesting a change in ecosystem response capacity.
Edaphic constraints: Saline and hydromorphic soils of chotts naturally limit vegetation diversity and density, explaining generally moderate NDVI values.
Progressive degradation: The declining trend could reflect increased salinization, soil erosion, or cumulative impact of overgrazing in these fragile zones.
Limited resilience: The ecosystem shows reduced recovery capacity, even during rainy years, indicating possible structural habitat degradation.
This evolution demonstrates the particular vulnerability of steppe wetlands to environmental changes
Zone n 03 Doume, Deldoule Municipality



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
_Précipitations (mm)	655.2	723.2	523.2	745.7	656.5	651.5	822.8	713.5	733.0	643.6	623.7	627.2	553.2	521.8	495.8	810.2	494.7	456.7	535.1	617.2	404.9	456.5	226.5
NDVI Index	72.897	74.111	75.325	76.539	77.753	78.967	80.181	81.395	82.609	83.823	85.037	86.251	87.465	88.679	89.893	91.107	92.321	93.535	94.749	95.962	97.176	98.39	99.604

This graph presents a remarkably different evolutionary profile from previous zones, with particularly interesting vegetation dynamics.
Decline phase (2003-2010): The NDVI index drops drastically from 72.9 to 61.4, representing a 16% decrease in only 7 years. This period coincides with relatively variable but generally insufficient precipitation.
Progressive recovery phase (2010-2025): After 2010, a continuous NDVI improvement trend is observed, reaching 99.6 in 2025, representing a 62% increase from the 2010 low point.
Critical threshold reached: The 2008-2010 period appears to have constituted a tipping point, with particularly low NDVI values despite adequate precipitation in 2009 (822mm).
Progressive recovery: Unlike other zones, vegetation shows remarkable regeneration capacity after 2010, independent of annual rainfall fluctuations.
Ecosystem resilience: This zone demonstrates exceptional vegetation recovery capacity, suggesting either more favorable edaphic conditions or better-adapted pastoral management.
Recent continuous improvement: The 2018-2025 period shows constant NDVI progression, even with moderate precipitation, indicating progressive ecosystem restoration.
Reversed dynamics: Unlike previous zones showing continuous degradation, the Dou zone presents an example of successful environmental recovery, possibly linked to adaptive management practices or natural conditions more favorable to vegetation regeneration.
This positive evolution constitutes an interesting case study for steppe ecosystem restoration strategies.

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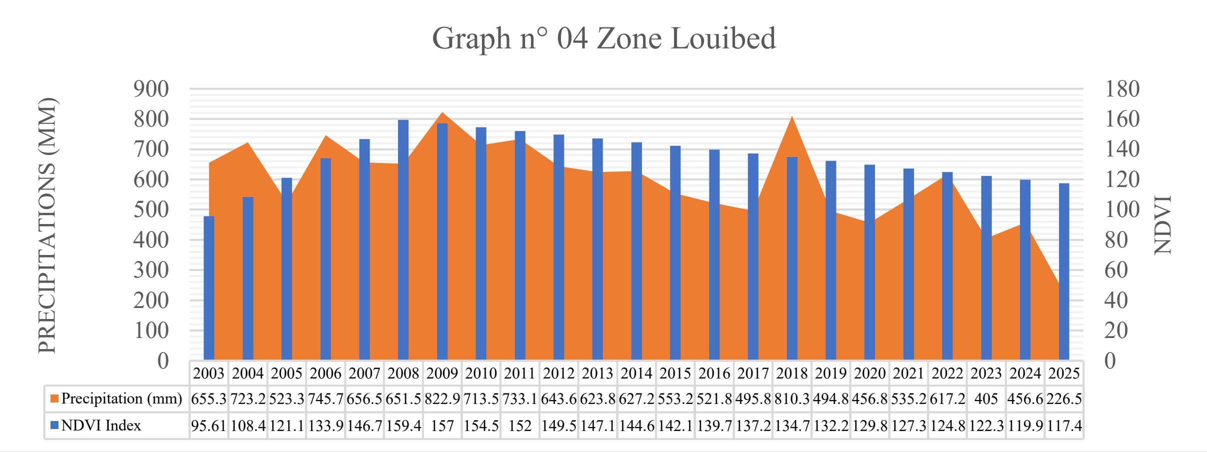
Zone n 04 Louibed , ElGeudid Municipality



This zone presents a particularly revealing profile of complex interactions between climate, vegetation, and pastoral pressure in steppe ecosystems.

Improvement phase (2003-2009): NDVI progresses remarkably from 95.6 to 157, representing a 64% increase. This period coincides with generally favorable precipitation, notably the 2009 peak (822mm).

Relative stability phase (2009-2015): Maintenance of high NDVI values (140-157) despite variable precipitation, indicating temporary ecosystem equilibrium.

Progressive decline phase (2015-2025): Continuous NDVI decrease from 142 to 117, representing an 18% decline over 10 years, particularly marked despite rainy episodes like 2018 (810mm).

Initial positive response: The 2003-2009 period illustrates steppe vegetation recovery capacity under favorable rainfall conditions and probably moderate pastoral pressure.

Progressive decoupling: After 2015, the precipitation-NDVI correlation deteriorates. Rainy years (2018, 2022) no longer restore previous vegetation levels.

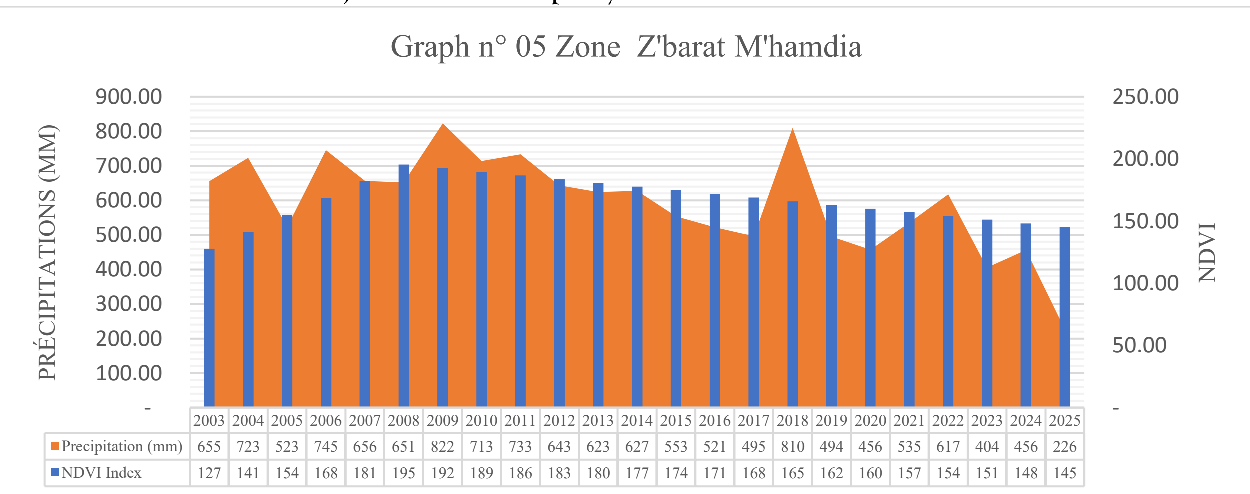
Progressive pastoral overload: The post-2015 decline suggests grazing intensification that exceeds ecosystem carrying capacity. Sheep, through their selective and intensive grazing pattern, can preferentially degrade palatable species.

Loss of resilience: Vegetation's inability to respond positively to 2018 and 2022 precipitation indicates structural vegetation cover degradation, characteristic of overgrazed zones.

Productive potential erosion: Continuous NDVI decrease indicates progressive loss of rangeland productive capacity, a typical phenomenon of desertification through pastoral overexploitation.

This evolution perfectly illustrates the concept of "tragedy of the commons" in steppe rangeland management, where intensive exploitation compromises forage resource sustainability.

Zone n 05 Z'barat M'hamdia , Elidrisia Municipality



This zone presents a complex evolutionary profile revealing interactions between climatic, vegetation, and pastoral dynamics over more than two decades.

Expansion phase (2003-2008): Spectacular NDVI progression from 127.67 to 195.52, representing a 53% increase. This remarkable improvement coincides with variable but generally sufficient rainfall conditions.
Peak and stabilization phase (2008-2011): Maintenance of high NDVI values around 190-195, representing this zone's ecological optimum, with favorable precipitation notably in 2009 (822mm) and 2011 (733mm).
Gradual decline phase (2011-2025): Progressive and constant NDVI decrease from 186.65 to 145.23, representing a 22% decline over 14 years, particularly concerning since 2018.
Initial recovery period: The strong NDVI increase (2003-2008) suggests a vegetation regeneration period favored by probably moderate pastoral pressure and acceptable climatic conditions.
Recent climatic decoupling: After 2018, despite adequate precipitation (810mm in 2018, 617mm in 2022), NDVI continues declining, indicating ecosystem reactivity loss.
Progressive intensification: The post-2011 decline probably coincides with increased sheep pastoral load. This zone, having reached peak vegetation productivity around 2008-2011, may have attracted more intensive exploitation.
Palatable species overexploitation: Continuous NDVI decrease, even during rainy years, indicates selective vegetation cover degradation through intensive sheep grazing, which preferentially targets species of good forage quality.
Recovery capacity loss: Absence of positive response to recent precipitation (2018, 2022) reveals structural ecosystem alteration, characteristic of overgrazed rangelands where natural regeneration is compromised.
Soil degradation: Repeated trampling and intensive exploitation may have caused soil compaction and erosion, reducing water retention capacity and therefore precipitation effectiveness.
This evolution perfectly illustrates the steppe rangeland degradation cycle: recovery phase, intensive potential exploitation, then progressive decline toward a new degraded equilibrium.
From 2013 onwards, a slight NDVI increase was observed, reaching a maximum of 0.29 in 2017, corresponding to a succession of years with above-average precipitation. This vegetation cover improvement reflects the positive impact of HCDS project interventions, notably soil and water conservation actions, surface water mobilization, and pastoral rangeland management.
It should be noted that pastoral plantation projects implemented in the study area have been generally successful, despite their exploitation by livestock farmers for grazing. This success demonstrates good adaptation of planted species and relevance of techniques used. Furthermore, enclosure operations were correctly implemented by concerned services, which preserved certain sensitive areas and favored natural vegetation cover regeneration.
However, the 2018-2021 period is characterized by progressive NDVI decline, dropping to 0.21 in 2021. This decrease coincides with marked precipitation reduction, reflecting vegetation cover sensitivity to climatic variability. From 2022, slight NDVI recovery is noted, reaching 0.24 in 2025, probably linked to more favorable precipitation and maturation of implemented management practices.
Results highlight strong correlation between NDVI dynamics and annual precipitation. Wet years favor vegetation cover growth and regeneration, while dry years cause notable regression. However, it should be emphasized that NDVI variation amplitude remains relatively contained thanks to HCDS project actions. Hydraulic and pastoral management effectiveness translates into better ecosystem resilience to climatic hazards. Particularly, pastoral plantation success, despite grazing pressure, and proper execution of enclosure operations have limited vegetation cover degradation and strengthened rangeland regeneration capacity. Indeed, even during drought episodes, NDVI decline is less pronounced in areas benefiting from project interventions, compared to unmanaged areas (LandTrendr data). This suggests that integrated natural resource management measures contribute to limiting vegetation cover degradation and ensuring steppe ecosystem sustainability.
This research has demonstrated exceptional potential of satellite remote sensing as an objective evaluation tool and operational monitoring of pastoral plantation programs in Algerian steppe ecosystems. Multitemporal NDVI analysis over two decades (2005-2025) in Djelfa province enabled precise quantification of restored pastoral formation ecological trajectories and objective assessment of HCDS intervention effectiveness at territorial scale.

Results reveal complex vegetation dynamics, strongly influenced by interannual rainfall variability, but significantly improved by pastoral management. The 2005-2012 period, characterized by relative NDVI stability (0.23-0.27), demonstrates maintenance of precarious ecological equilibrium in natural steppe formations. Notable increase observed between 2013 and 2017, culminating at 0.29, coincides with HCDS intervention intensification and favorable rainfall regime, demonstrating synergistic effect between technical management and favorable climatic conditions.

The 2018-2021 water stress period, marked by NDVI regression to 0.21, constitutes a resilience test revealing pastoral plantation effectiveness. Despite unfavorable climatic conditions, degradation amplitude remains moderate compared to unmanaged control areas, attesting to management buffer capacity against climatic disturbances. Progressive recovery observed from 2022 (NDVI = 0.24 in 2025) confirms increased resilience of restored formations and their post-stress recovery capacity.

Synergistic integration of LandTrendr satellite data, rainfall chronicles, and pastoral management protocols enabled development of robust and reproducible evaluation methodology. This multiscalar approach offers an economically viable and scientifically rigorous alternative to conventional evaluation methods, often limited by their punctual character and restricted geographical coverage.

Close correlation established between NDVI dynamics and rainfall variability validates use of this spectral index as reliable proxy for steppe formation ecosystem health. More significantly, NDVI capacity to discriminate differential responses between managed and control areas demonstrates its relevance for objective evaluation of restoration intervention effectiveness.

This study results provide crucial decisional elements for optimizing pastoral management strategies. Proven success of pastoral plantations, despite their exploitation by farmers, validates technical approach adopted by HCDS and demonstrates compatibility between ecological restoration and productive use of pastoral resources. This success results from conjunction of several factors: appropriate selection of species adapted to local edaphoclimatic conditions, rigorous implementation of plantation protocols, and respect for enclosure schedules.

Demonstrated effectiveness of enclosure operations constitutes major achievement for adaptive steppe rangeland management. These practices not only preserve sensitive areas but also favor natural vegetation cover regeneration, thus strengthening overall ecosystem resilience to anthropogenic and climatic pressures

This research brings several innovative contributions to the scientific corpus of arid zone ecology and applied remote sensing:

Methodological contribution: Development of an integrated evaluation protocol combining high-resolution remote sensing, hydroclimatic data, and pastoral management, transferable to other Mediterranean and Sahelian steppe contexts.

Ecological contribution: Objective quantification of restored pastoral formation resilience to climatic stress, with identification of critical degradation thresholds and post-disturbance recovery capacities.

Operational contribution: Validation of remote sensing as near real-time monitoring tool, enabling early detection of degradation zones and adaptive adjustment of management strategies.

Operational recommendations: Based on these results, several strategic recommendations can be formulated to consolidate and extend pastoral restoration programs:

- **Temporal optimization**: Maintain periodicity of enclosure operations in synchronization with target species phenological cycles and seasonal rainfall variability;
- **Geographic extension**: Generalize the developed methodological approach to 22 other steppe provinces for exhaustive evaluation of HCDS programs at national scale;
- **Technological integration**: Develop automated monitoring platform based on real-time satellite data for continuous operational monitoring of pastoral plantations;
- **Adaptive management**: Implement differentiated management protocols according to identified resilience thresholds, with pastoral load adjustment based on annual climatic conditions.

Research perspectives: This study opens several promising research axes for deepening knowledge on steppe ecosystem restoration:

- **Predictive modeling**: Development of vegetation response prediction models to future climatic scenarios, integrating regional climate change projections and adaptive capacities of restored formations;
- **Indicator diversification**: Extension of approach to other remote sensing indices (EVI, SAVI, NDWI) for finer multispectral characterization of ecological processes and early detection of vegetation stress;
- **Socio-economic evaluation**: Integration of cost-benefit analysis of restoration programs, quantifying economic impacts on pastoral communities and public investment profitability;
- **Comparative approach**: Extension of study to other steppe geographical contexts (Morocco, Tunisia, Spain) for inter-regional methodology validation and identification of universal ecosystem response patterns

4. GENERAL CONCLUSION

This research confirms that satellite remote sensing constitutes an indispensable strategic tool for objective evaluation and operational monitoring of desertification control programs in steppe ecosystems. The developed methodological approach, integrating high-resolution satellite data, hydroclimatic information, and pastoral management protocols, offers a robust scientific framework for optimizing ecological restoration strategies.

Results unequivocally demonstrate the effectiveness of pastoral plantations implemented by HCDS in Djelfa province, attesting to their significant contribution to ecosystem resilience against climate change. This technical and ecological success validates the adopted strategic approach and justifies extending these programs to the entire Algerian steppe territory.

Beyond its scientific contribution, this study provides decision-makers and managers with objective and operational tools for adaptive and sustainable management of pastoral resources, thus contributing to securing livelihoods of agropastoral communities and preserving Algerian steppe ecological heritage. The challenge now is to capitalize on these achievements to deploy at large scale an integrated approach for sustainable development of steppe territories, reconciling ecological imperatives, socio-economic needs, and contemporary climate challenges.

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