Analysis of the Niakhar landscape using satellite imagery

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List of acronyms

CHIRPS: Climate Hazards and Infrared Precipitation Station Data

CV: Coefficient of variation

ESA: European Space Agency

GEE: Google Earth Engine

NIR: Near Infrared

NDVI: Normalized Difference Vegetation Index

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1. INTRODUCTION

Landscape analysis using satellite imagery is now an essential tool for understanding the spatial and temporal dynamics of land use. It allows us to observe, quantify, and analyze changes in land use over long periods of time, highlighting the interactions between natural factors and human activities. In the Sahelian context of the municipality of Niakhar, Senegal, this approach is particularly important due to the high dependence of agricultural systems on climatic conditions and the increasing pressure on natural resources.

This study is part of the AoW2 of the MFL project and aims more specifically to contribute to the development of more efficient and territorialized land use planning. It is intended to be closely linked to the work currently underway on updating local land use management agreements, with the aim of promoting the emergence of new, more integrated and more operational forms of territorial governance.

The municipality of Niakhar has been selected as a pilot site, with the aim of quickly capitalizing on the lessons learned in order to consider extending them to other municipalities and then to the entire department. In this perspective, satellite analysis is a key tool: it allows for a detailed characterization of landscape diversity, identification of land occupation and use dynamics, and a better understanding of the spatial and environmental factors that structure the territory's trajectories.

These elements are essential for informing collective thinking on land use planning and supporting governance choices based on objective diagnoses at the landscape level. Located in the heart of Senegal's peanut-growing region, the municipality of Niakhar is characterized by mainly rain-fed agriculture, which is sensitive to interannual rainfall variability. Satellite imagery thus offers a unique opportunity to analyze landscape transformations linked to climate variability, the intensification of agricultural practices, and the gradual expansion of built-up areas. It also makes it possible to monitor changes in vegetation cover through biophysical indicators such as the normalized difference vegetation index (NDVI).

This study is part of a project to monitor changes in land use over a ten-year period, from 2016 to 2025. This decade has been marked by significant rainfall variations and changes in agricultural practices in the peanut basin, directly influencing the structure and dynamics of local landscapes.

The diachronic analysis of satellite data thus aims to provide a better understanding of the evolution of the Niakhar landscape and to provide information to support the sustainable management of rural areas.

1.1. Objectives

This analysis aims to:

- Quantify changes in the areas of the main land cover classes (crops, bare soil, buildings, water)
- Identify correlations between biophysical variables (rainfall, NDVI) and landscape classes
- Characterize the spatio-temporal dynamics of vegetation during the dry season and rainy season
- Assess interactions between different landscape components

1.2. Study area

The study area is located in the municipality of Niakhar, in the heart of Senegal's peanut basin (14°21'N - 14°31'N; 16°19'W - 16°27'W).

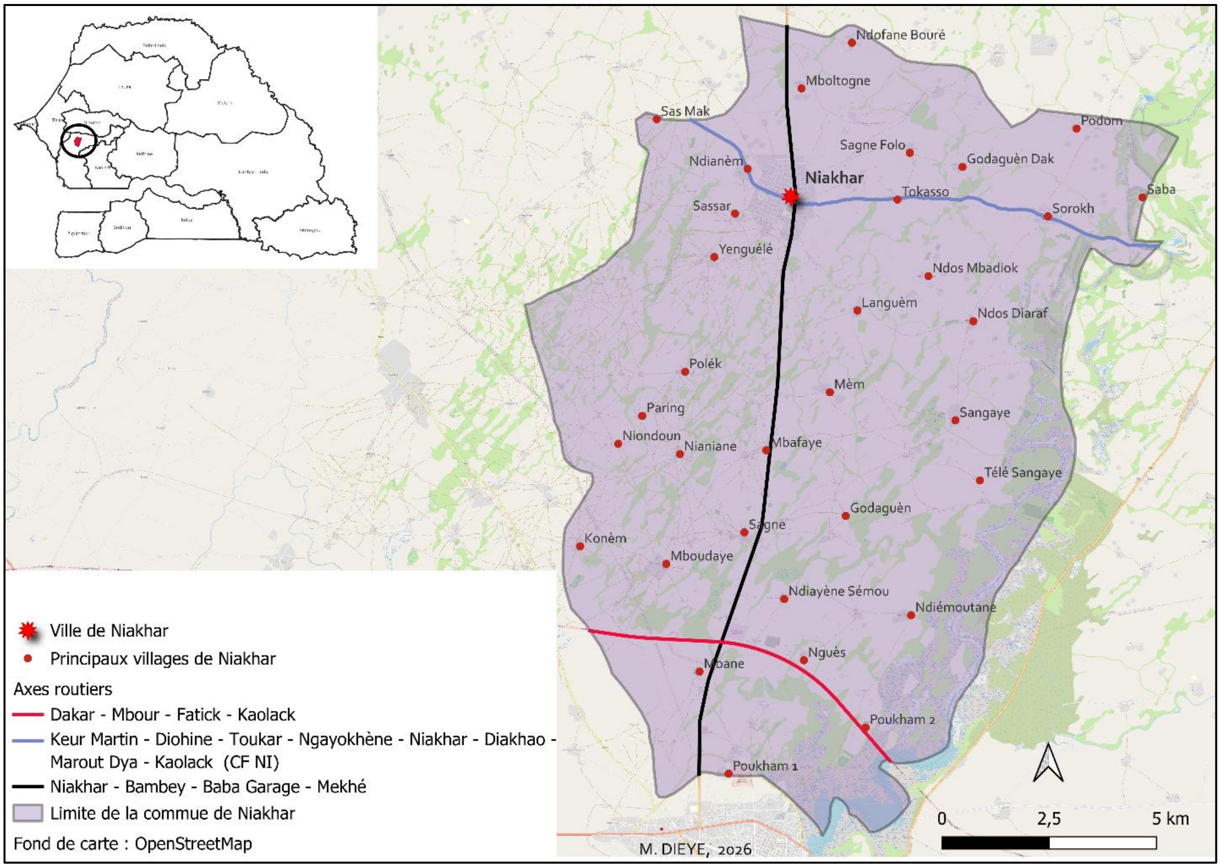

Figure1 : Map showing the location of the municipality of Niakhar .

This region is characterized by a Sahel-Sudanese climate with a rainy season concentrated between June and October (average rainfall: 500-700 mm) and a long dry season.

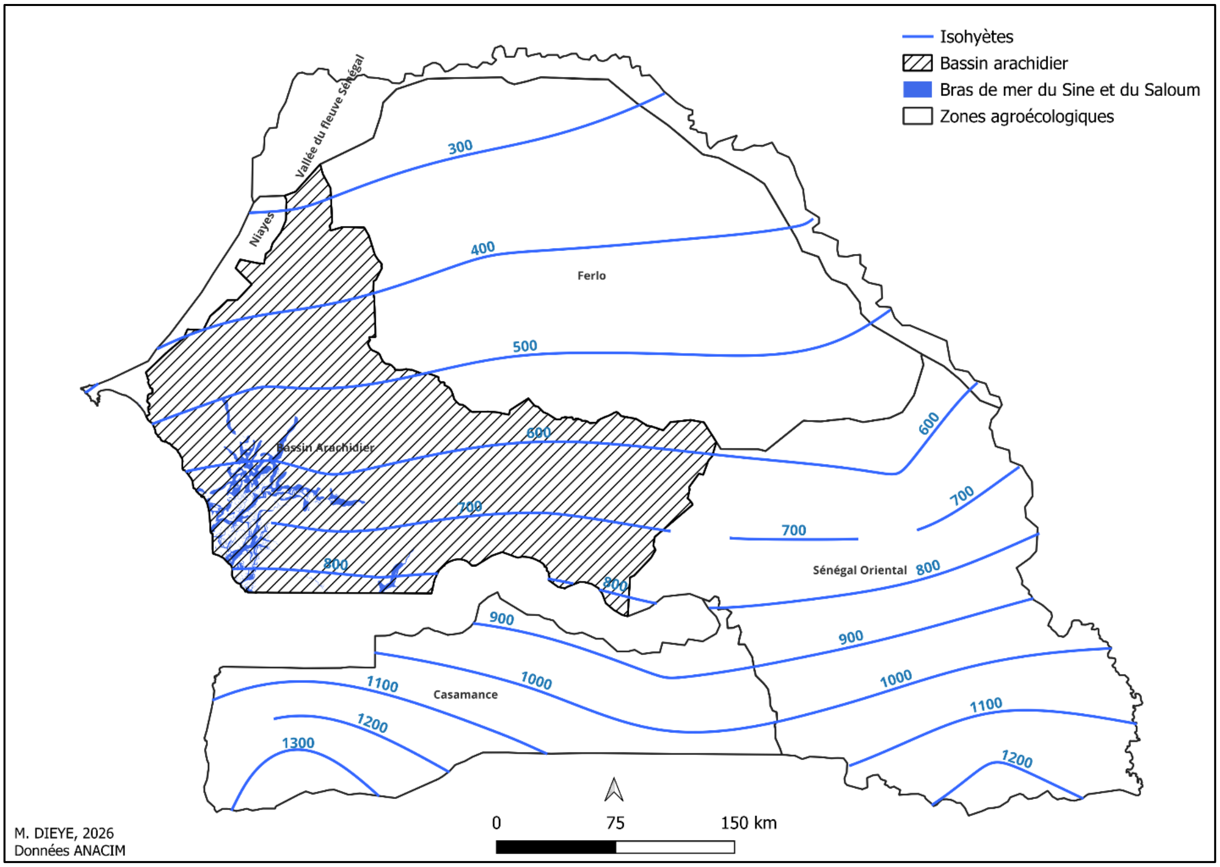

Figure2 : Map of isohyets (precipitation levels in mm/year)

The landscape is dominated by an agro-pastoral mosaic combining rain-fed crops (peanuts, millet, sorghum), fallow land, and sparse shrub vegetation.

2. METHODOLOGY

2.1. Data used

2.1.1. Satellite data

The analysis is based on two main sources of Earth observation data:

Dynamic World (Google Earth Engine): Automatic land cover classification product with 10-meter resolution, generated in near real time from Sentinel-2 images.

Overall accuracy: ~86%. Availability period: 2015-2025. These data were used for the land cover maps.

Sentinel-2 (ESA): Multispectral images with 10-20 meter spatial resolution, used to calculate the NDVI (Normalized Difference Vegetation Index). The data used covers the period 2016-2025, with a revisit frequency of five (5) days.

2.1.2. Rainfall data

Precipitation data comes from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) product, with a spatial resolution of 5 km and daily temporal resolution, covering the period 2016-2025.

2.2. Data processing

2.2.1. Land cover classification

All Sentinel-2 images available for the period 2016–2025 are stacked for each year. For each pixel, Google Earth Engine (GEE) determines the class that appears most frequently over the 12 months: this is the principle of mode reduction. Thus, if a pixel is classified as "Bare ground" for 8 months and "Herbaceous" for 4 months, the annual mode selected will be "Bare ground." This approach has the advantage of being robust to clouds (a cloudy pixel is simply ignored in the calculation), but it erases seasonality and does not allow for the observation of intra-annual dynamics. This is why, when analyzing spatial units, we limited our interpretation to the classes Crops, Bare Ground Buildings, and Water, as the other classes (tree vegetation, herbaceous vegetation) were not sufficiently representative in this context. The latter were replaced by the normalized difference vegetation index (NDVI), calculated separately for the dry season and the rainy season (Figure 5).

However, this methodology has a significant limitation due to the absence of seasonal filtering. As the script covers the entire calendar year (January 1 to December 31), the stark contrast between the dry season (November to June) and the rainy season (July to October) in Niakhar is not taken into account. The dominant class over the year may therefore reflect the length of the dry season rather than the ecological reality of the area.

The Dynamic World classes have been reclassified according to the following nomenclature:

Table1 : Land use classification

Class	Name	Description
0	Water	Water surfaces (ponds, streams)
5	Crops	Crops (peanuts, millet, sorghum, cowpeas)
6	Buildings	Buildings (urban areas, villages)
7	Bare soil	Bare soil (fallow land, bare surfaces)

The "bare soil" class actually includes several states: recent fallow land, land being prepared for cultivation, areas of intensive grazing, and genuinely degraded areas.

2.2.2. NDVI calculation

The NDVI was calculated from the red (B4) and near-infrared (B8) spectral bands of Sentinel-2 using the following formula:

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

Two periods were distinguished: dry season (November-June) and rainy season (July-October), allowing the seasonal dynamics of vegetation to be captured.

2.2.3. Statistical analyses (Pearson correlations)

The analyses include: (a) calculation of areas by class and by year, (b) evaluation of Pearson correlations between variables (rainfall, seasonal NDVI, class areas), and (c) analysis of temporal trends. The statistical significance thresholds are:

$$^{*}p < 0.05,\ ^{**}p < 0.01,\ ^{***}p < 0.001.$$

3. RESULTS

3.1. Analysis of land use dynamics

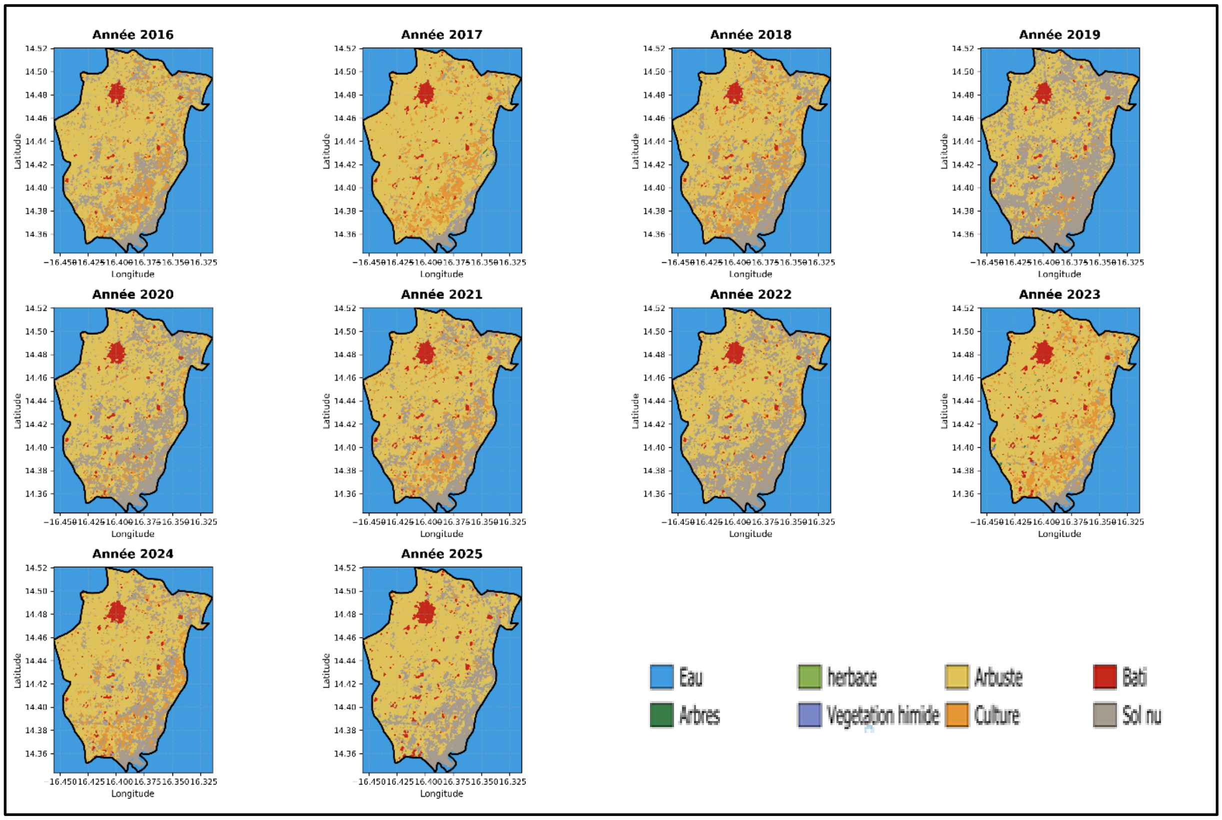

Figure3 : Evolution of land use from 2016 to 2025

3.1.1. Crops

Cultivated areas show significant interannual variability, ranging from 14,583 ha (2019) to 23,070 ha (2017), with an average of 19,581 ha over the period 2016-2025. The overall trend is stable, with fluctuations linked to rainfall conditions. The year 2019 marks a notable low point, coinciding with a rainfall deficit, while 2017 and 2023 recorded the highest levels (23,070 ha and 22,260 ha respectively).

3.1.2. Built

Built-up areas are gradually increasing, from 845 ha in 2016 to 1,572 ha in 2025, representing growth of +86% over the decade. This relatively steady expansion (, +7.2% per year on average) reflects the urbanization and densification of villages in the study area.

3.1.3. Bare land

The areas of bare soil show very high interannual variability, with values ranging from 1,932 ha (2023) to 12,735 ha (2019). This dynamic mainly reflects fallow practices and the response of herbaceous vegetation to rainfall conditions. Years with low rainfall (2019) show particularly high areas of bare soil.

3.1.4. Spatio-temporal evolution of land cover

Figure 4 provides a synoptic visualization of the spatio-temporal evolution in the form of a heat map cross-referencing years and land cover classes. The inverse chromatic symmetry observed between the "Built-up areas" and "Bare soil" lines is particularly striking: high values for one correspond systematically to low values for the other, and vice versa. This visual complementarity explicitly confirms the anti-correlation highlighted in the correlation matrix (Appendix 5).

The year 2019 stands out clearly as an atypical configuration, characterized by a maximum value for "Bare ground" (42.7%), which nevertheless remains the dominant class compared to "Built-up areas" (48.9%). This relationship of dominance of bare ground over built-up areas is constant throughout the period 2016-2025: regardless of the year considered, the area of bare ground systematically exceeds that of built-up areas. Furthermore, the "Crops" class shows a regular color gradient, changing from yellow in 2016 (2.8%) to orange in 2025 (5.3%), with no notable breaks or reversals. This continuous progression visually reflects the linear upward trend previously highlighted in Appendix 10.

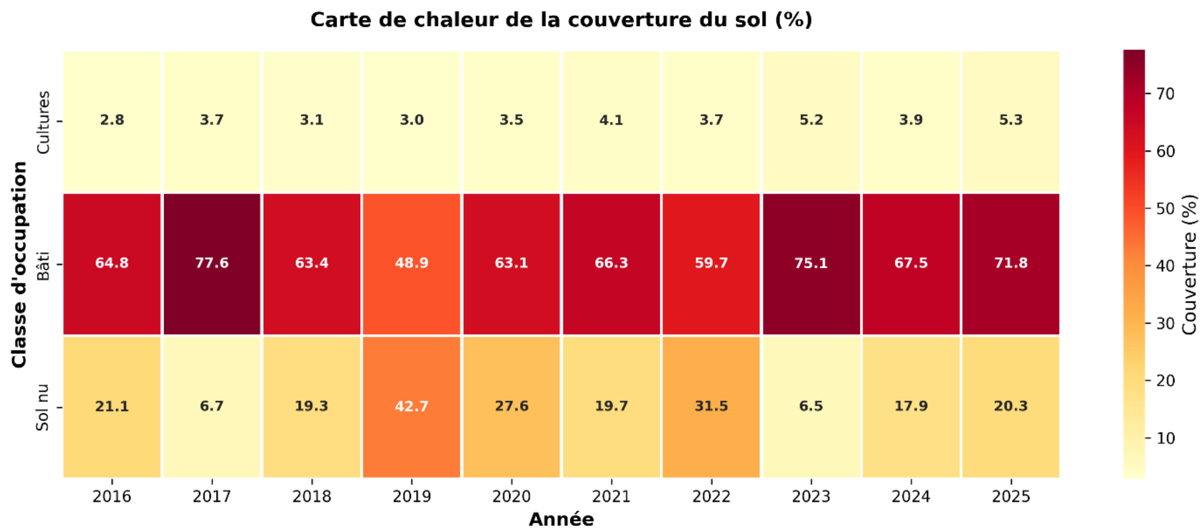

Figure4 : Spatio-temporal evolution of spatial units

3.2. Correlations between variables

3.2.1. Rainfall and vegetation

The results reveal contrasting relationships between rainfall and vegetation depending on the season:

- Rainfall / NDVI dry season: r = +0.59 (moderate positive correlation)
- Rainfall / NDVI rainy season: r = -0.38 (weak negative correlation)

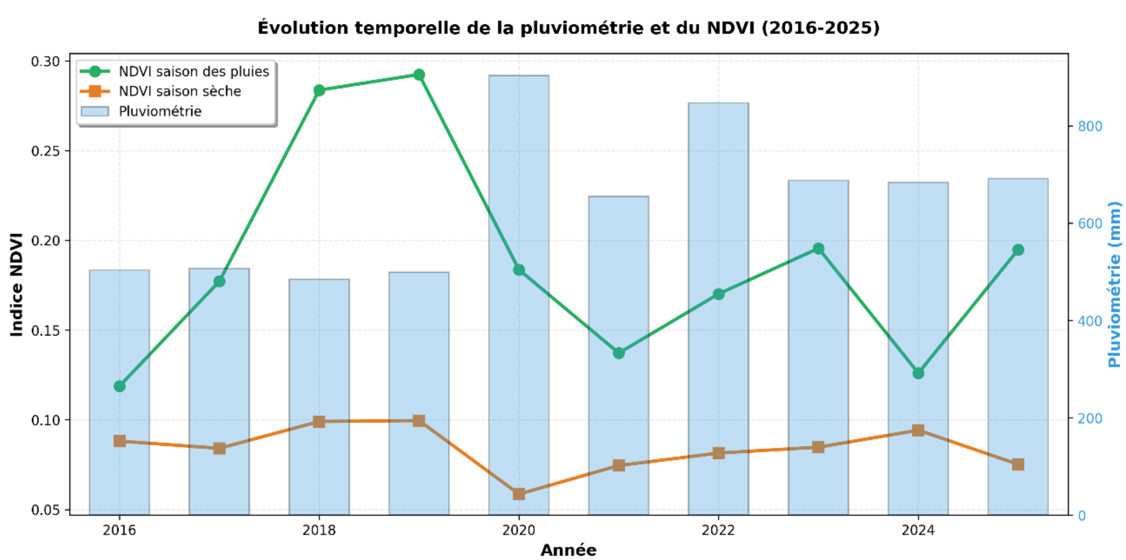

Figure5 : Temporal evolution of rainfall and NDVI (2016–2025)

The positive correlation in the dry season suggests that years with high rainfall maintain more residual vegetation during the dry period. The negative correlation in the rainy season can be explained by a saturation effect: heavy rainfall can temporarily reduce photosynthetic activity (excess water, cloud cover).

3.2.2. NDVI and land cover

NDVI in the rainy season shows significant correlations with several classes:

- Rainy season NDVI / Water: r = -0.65* (significant negative correlation)
- Rainy season NDVI / Bare soil: r = -0.53 (moderate negative correlation)
- Rainy season NDVI / Buildings: r = +0.59 (moderate positive correlation)

These results indicate that high vegetation activity during the rainy season is associated with a reduction in water surfaces (probably due to evapotranspiration) and a decrease in bare soil (herbaceous colonization). The positive correlation with buildings could reflect the presence of peri-urban vegetation.

1.1.1. Interactions between landscape classes

Three major correlations structure landscape interactions (Figure 6):

- **Water/Bare soil: r = +0.79** (strong and significant positive correlation)**

  This correlation suggests that years with a high presence of water surfaces (temporary pools during the rainy season) are also marked by large areas of bare soil, probably in topographical depressions prone to alternating flooding and drying out.

- **Water / Buildings: r = -0.95*** (very strong and highly significant negative correlation)**

  This very marked inverse relationship indicates a strong spatial incompatibility between water areas and built-up areas, consistent with the logic of locating human settlements outside flood zones.

• **Bare ground/built-up area: r = -0.84** (strong and significant negative correlation)**

The expansion of built-up areas is accompanied by a reduction in bare ground, suggesting either peri-urban vegetation densification (gardens, trees) or the conversion of marginal land into built-up areas.

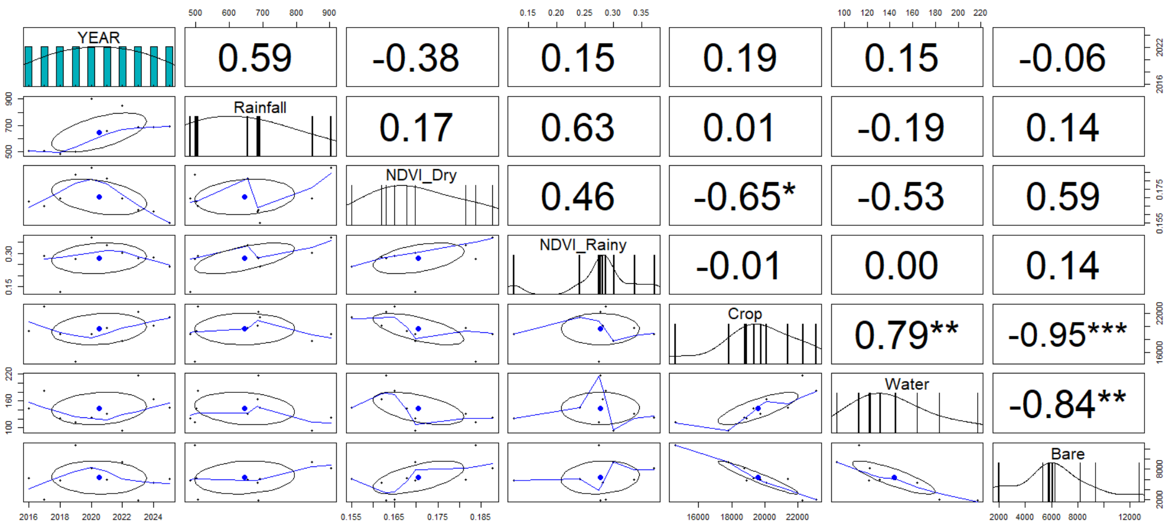

Figure6 : Pearson correlation matrix between landscape units (2016-2025)

1.2. Quantitative summary

Table 2 summarizes the results for the different soil classes.

Table2 : Quantitative summary of the different soil classes studied

Class	Average (ha)	Min - Max (ha)	Change 2016-2025
Crop	19,581	14,583 - 23,070	+10.6% (+2,056 ha)
Built	1,141	845 - 1,572	+86.1% (+727 ha)
Bare	6,352	1,932 - 12,735	-3.5% (-218 ha)

4. DISCUSSION

4.1. Agricultural dynamics and climate variability

The high interannual variability in cultivated areas (coefficient of variation: 13.6%) reflects the adaptation of agricultural practices to rainfall constraints in the Sahelian context. The collapse in cultivated areas in 2019 (14,583 ha, or -37% compared to the average) coincides with a year of low rainfall, illustrating the vulnerability of rain-fed agriculture. Conversely, 2017 and 2023 benefited from favorable water conditions, allowing for an expansion in planted areas.

This flexibility in cultivated areas also reflects farmers' risk management strategies: reducing sowing at the beginning of the season in the event of delayed or irregular rainfall, abandoning plots in the event of prolonged water stress. The overall stable trend over the decade (+10.6%) therefore masks significant intra-decadal variability, which is more related to climate than to a net expansion of agricultural land.

4.2. Urbanization and landscape transformation

The steady expansion of built-up areas (+86% in 10 years) is the most striking and irreversible trend observed. Although modest in absolute terms (+73 ha per year on average), this urbanization process reflects sustained demographic growth and densification of housing in the villages in the study area.

The very strong negative correlation between built-up areas and water surfaces ($r = -0.95^{***}$) confirms the principle of rational settlement planning, with human settlements systematically located away from flood zones. This inherited spatial structure ensures the sustainability of residential areas in the face of climate hazards.

The negative relationship between buildings and bare soil ($r = -0.84^{**}$) suggests that urban expansion is paradoxically accompanied by a relative increase in vegetation cover, probably through the development of peri-urban vegetable gardens and fruit plantations. This phenomenon, which is well documented in Sahelian urban systems, contributes to local changes in the microclimate and biomass availability.

4.3. Bare soil and degradation: a nuanced interpretation

Although highly variable (CV: 66.2%), bare soil areas do not show a clear upward trend over the decade (-3.5%). This observation qualifies the hypothesis of widespread land degradation. The "bare soil" class actually includes several states: recent fallow land, land being prepared for cultivation, areas of intensive grazing, and genuinely degraded areas.

The strong correlation between bare soil and water surfaces ($r = +0.79^{**}$) points to a hydrological interpretation: years with high rainfall generate temporary flooded areas which, once dry, appear as bare soil in dry season images. Far from being degraded, these areas are fertile lowlands used for market gardening.

4.4. Seasonal NDVI: an indicator of resilience

The positive correlation between rainfall and NDVI in the dry season ($r = +0.59$) is a relevant indicator of the resilience of Sahelian vegetation cover. Years with high rainfall allow for deep soil water recharge, maintaining residual vegetative activity (trees, shrubs) during the following dry season.

Conversely, the negative correlation between rainfall and NDVI during the rainy season ($r = -0.38$), although counterintuitive, can be explained by secondary effects: excess water causing temporary root anoxia, persistent cloud cover reducing photosynthetically active radiation, or preferential development of herbaceous cover with lower NDVI than woody crops under optimal water conditions.

4.5. Cultivated areas and pastoralism

The cultivated areas identified by remote sensing are not monofunctional but are part of complex farming cycles combining agriculture and livestock farming. During the dry season (November-May), the plots become grazing areas, where livestock make use of crop residues (millet stalks, peanut leaves) while fertilizing the soil. This practice of "fallow grazing" provides nutritional complementarity for livestock and agronomic complementarity for the soil (restitution of organic matter).

The well-fed market gardens and temporary ponds (ndiawling), identified in the "Crops" category, serve a strategic multifunctional purpose in Niakhar. These areas, developed around wells 3 to 15 m deep, enable off-season crops (tomatoes, onions, eggplants, peppers) to be grown during the lean season (April-July). Although they cannot be accurately quantified at the municipal level due to a lack of available data, these market gardening areas are small (generally 3 to 10 ha per site according to PARIIS/Fatick data), and their aggregate area remains marginal in relation to the total cultivated area (19,581 ha). This activity, mainly practiced by women and young people, generates monetary income and improves food security.

Temporary ponds play a crucial role during and after the rainy season (July-October): they provide watering points for livestock, encourage the growth of forage vegetation around them, and allow for small-scale opportunistic crops (watermelon, cowpea) to be grown once they have dried up.

This multifunctionality makes these areas strategic elements in the agro-pastoral economy of Niakhar, where rain-fed peanut production allows for only one production season. They fill food and fodder deficits in the dry season while integrating into local commercial circuits (markets in Toucar, Ngayokhème, and central Niakhar).

The growing importance of these areas explains their intensification (new wells, fenced perimeters, drainage equipment) and the land pressures that generate conflicts of use between market gardeners, herders, and farmers.

4.6. Limitations and prospects

Several methodological limitations should be highlighted:

- The availability of Dynamic World only from 2015 onwards limits the temporal consistency of the classification
- Potential confusion between grassland fallow and rainy season crops (similar spectral signature)
- The lack of systematic field validation to confirm the accuracy of the classification
- The temporal resolution (point images) may miss transitional states of the landscape

Future developments could include: (1) the integration of radar data (Sentinel-1) to better discriminate between crops during the rainy season, (2) the use of dense time series to capture intra-annual trajectories, and (3) coupling with field surveys to validate and refine the classification.

5. CONCLUSION

This multi-temporal analysis of land use in the Niakhar area, based on the joint use of Dynamic World and Sentinel-2, reveals a Sahelian landscape characterized by high adaptability to climatic constraints and gradual transformation under the effect of demographic pressure.

Three major dynamics emerge over the 2016-2025 period:

1. High interannual variability in cultivated areas (CV: 13.6%), directly driven by rainfall conditions. Rain-fed agriculture remains extremely vulnerable to climatic hazards, with occasional collapses of up to -37% (2019).

2. Sustained and steady expansion of built-up areas (+86%), reflecting an irreversible urbanization trend. Paradoxically, this growth is accompanied by peri-urban greening, illustrated by the negative correlation between built-up areas and bare soil ($r = -0.84^{**}$).

3. Relative stability in bare land (-3.5%), tempering alarmist rhetoric about land degradation. The strong correlation between bare soil and water surfaces ($r = +0.79^{**}$) points to a hydrological rather than a pedological interpretation: the variations observed reflect the dynamics of flooding/drying of lowlands rather than irreversible degradation processes.

The correlations identified between seasonal NDVI, rainfall, and landscape classes offer avenues for predictive modeling of land cover based on climate scenarios. In particular, the positive relationship between rainfall and dry season NDVI ($r = +0.59$) is a relevant indicator of the resilience of Sahelian ecosystems to water variability.

Operationally, these results call for: (1) the development of early warning systems based on satellite monitoring of vegetation dynamics, (2) support for agricultural intensification to stabilize cultivated areas in the face of climate shocks, and (3) spatial planning of urbanization to preserve quality agricultural land and functional wetlands.

This study thus demonstrates the relevance of high temporal and spatial resolution satellite imagery for documenting and understanding landscape transformations in Sahelian environments. Free and open access to products such as Dynamic World and Sentinel-2 opens up considerable prospects for environmental monitoring at the regional and local levels. Beyond global monitoring, the high spatial resolution makes it possible to characterize the intra-municipal diversity of landscapes, enabling the identification of homogeneous landscape units within the municipality of Niakhar. Such an approach could provide operational cartographic support for the development and implementation of local natural resource management agreements, offering local stakeholders a spatialized and updatable representation of the territories they administer.

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APPENDICES

Appendix 1: Table of annual land areas

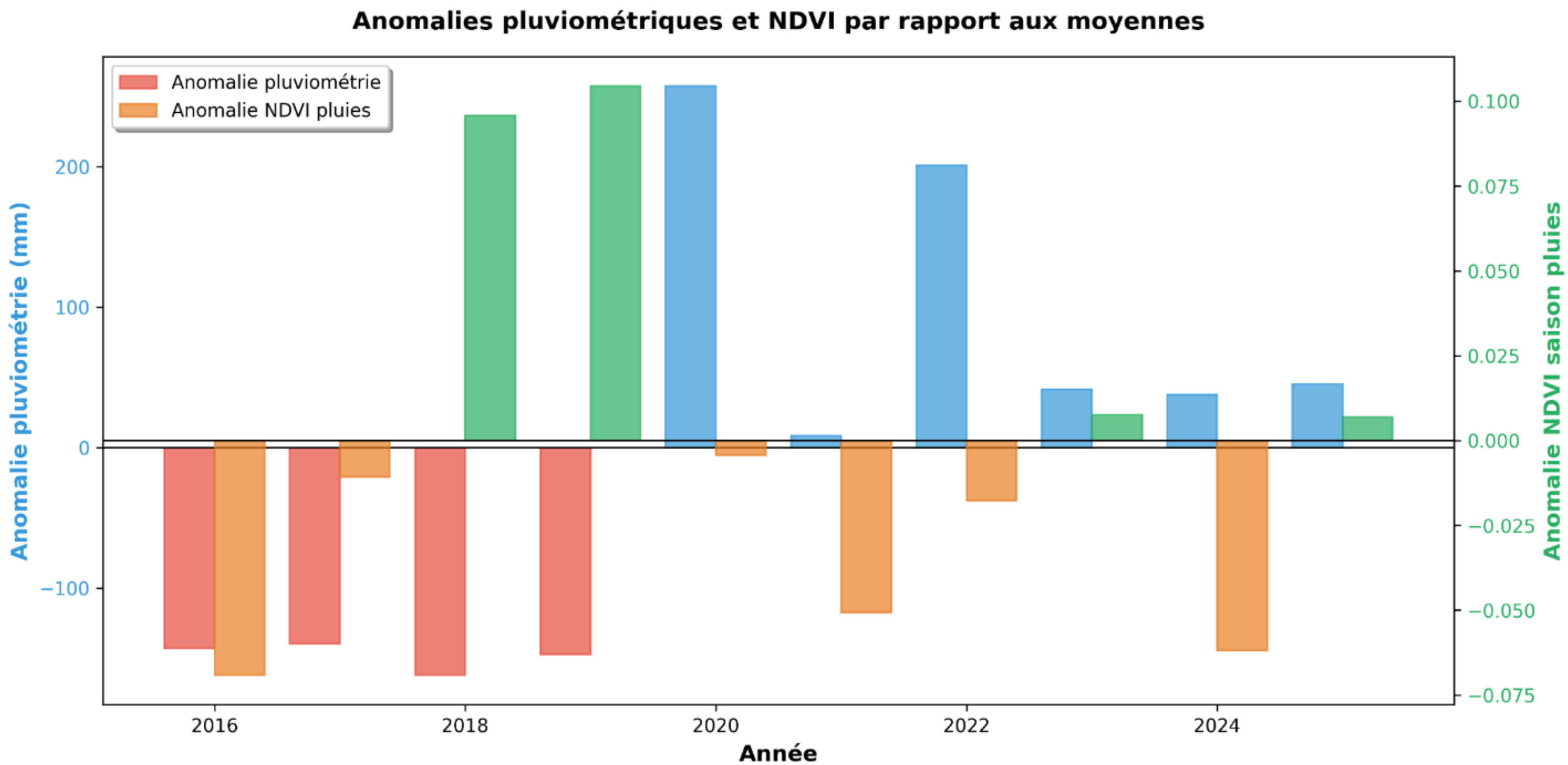
Year	Crop (ha)	Built (ha)	Bare (ha)
2016	19,306.25	844.59	6,266.72
2017	23,069.89	1087.27	1,986.93
2018	18,866.46	937.06	5,759.75
2019	14,583.14	905.31	12,734.73
2020	18,768.59	1050.37	8,204.42
2021	19,727.47	1225.94	5868.09
2022	17,784.26	1094.54	9385.74
2023	22,259.51	1532.05	1931.74
2024	20,083.08	1157.29	5328.78
2025	21,362.18	1,571.89	6049.16

Appendix 2: Correlation matrix (selection)

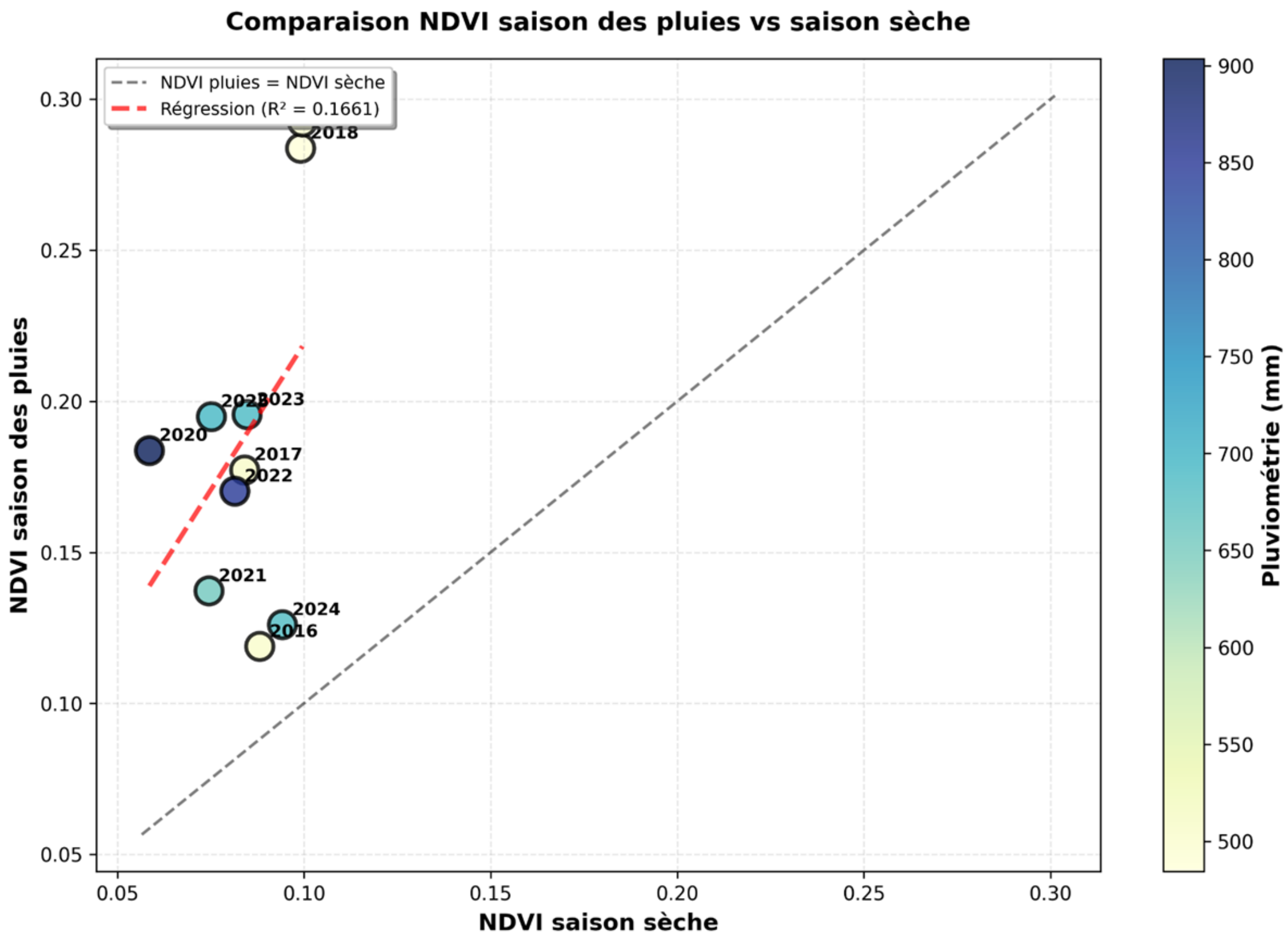
Variables	Correlation coefficient (r)
Rainfall / NDVI dry season	+0.59
Rainfall / NDVI rainy season	-0.38
NDVI rainy season / Water	-0.65*
Water / Bare	+0.79**
Water / Built	-0.95***
Bare / Built	-0.84

*Significance thresholds: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$*

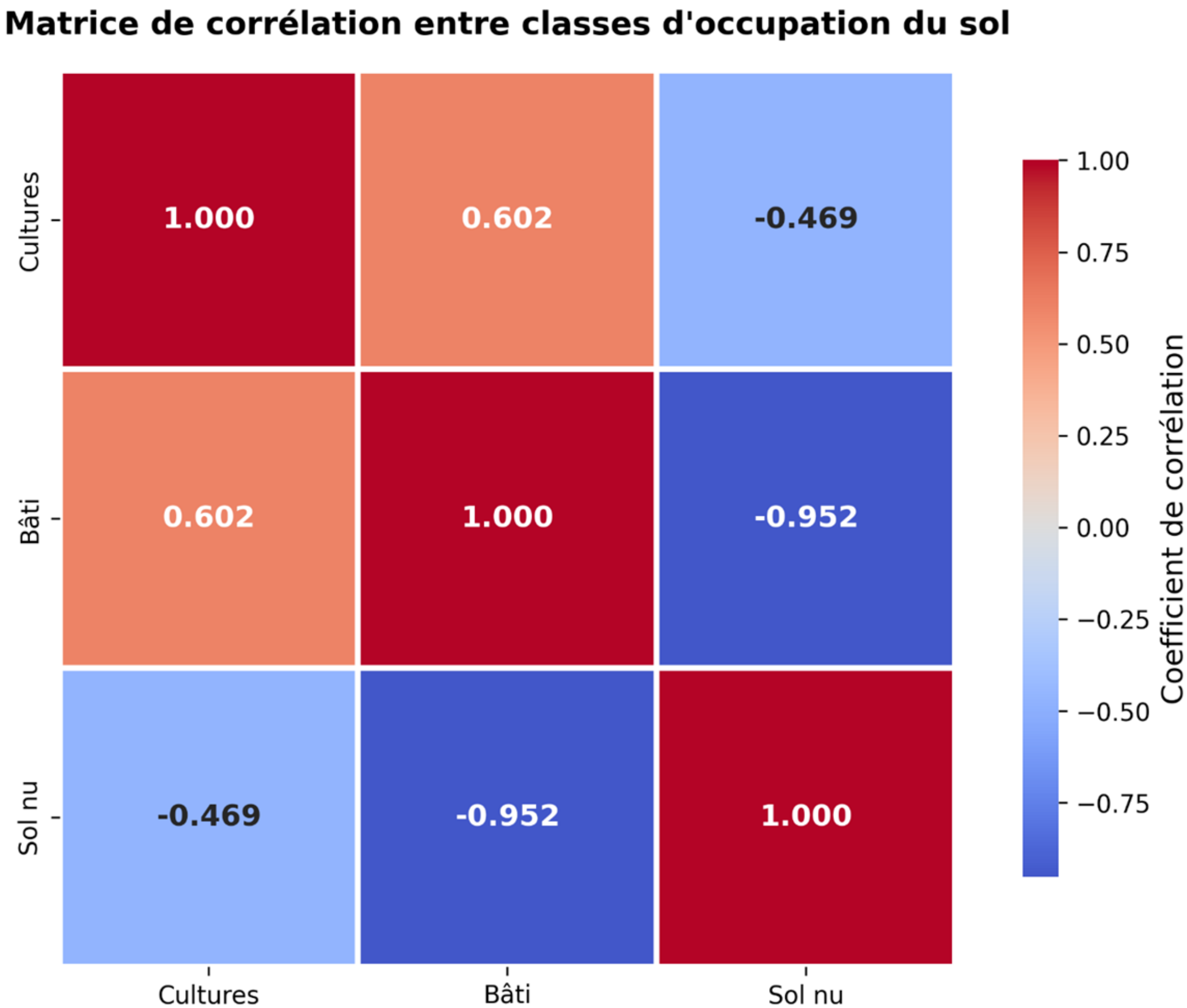
Appendix 3: Rainfall anomalies and NDVI compared to averages



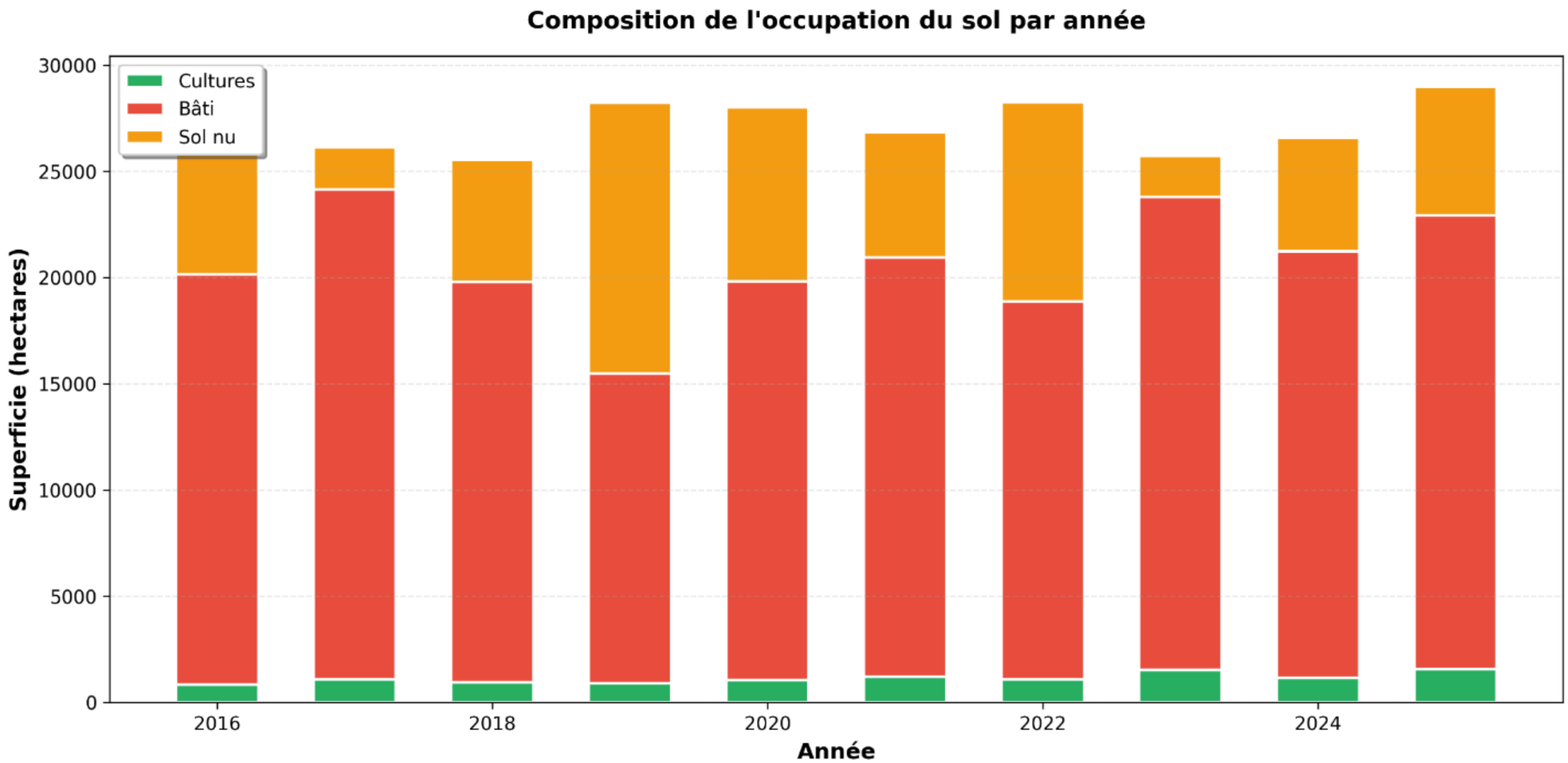
Appendix 4: Comparison of NDVI during the rainy season vs. the dry season



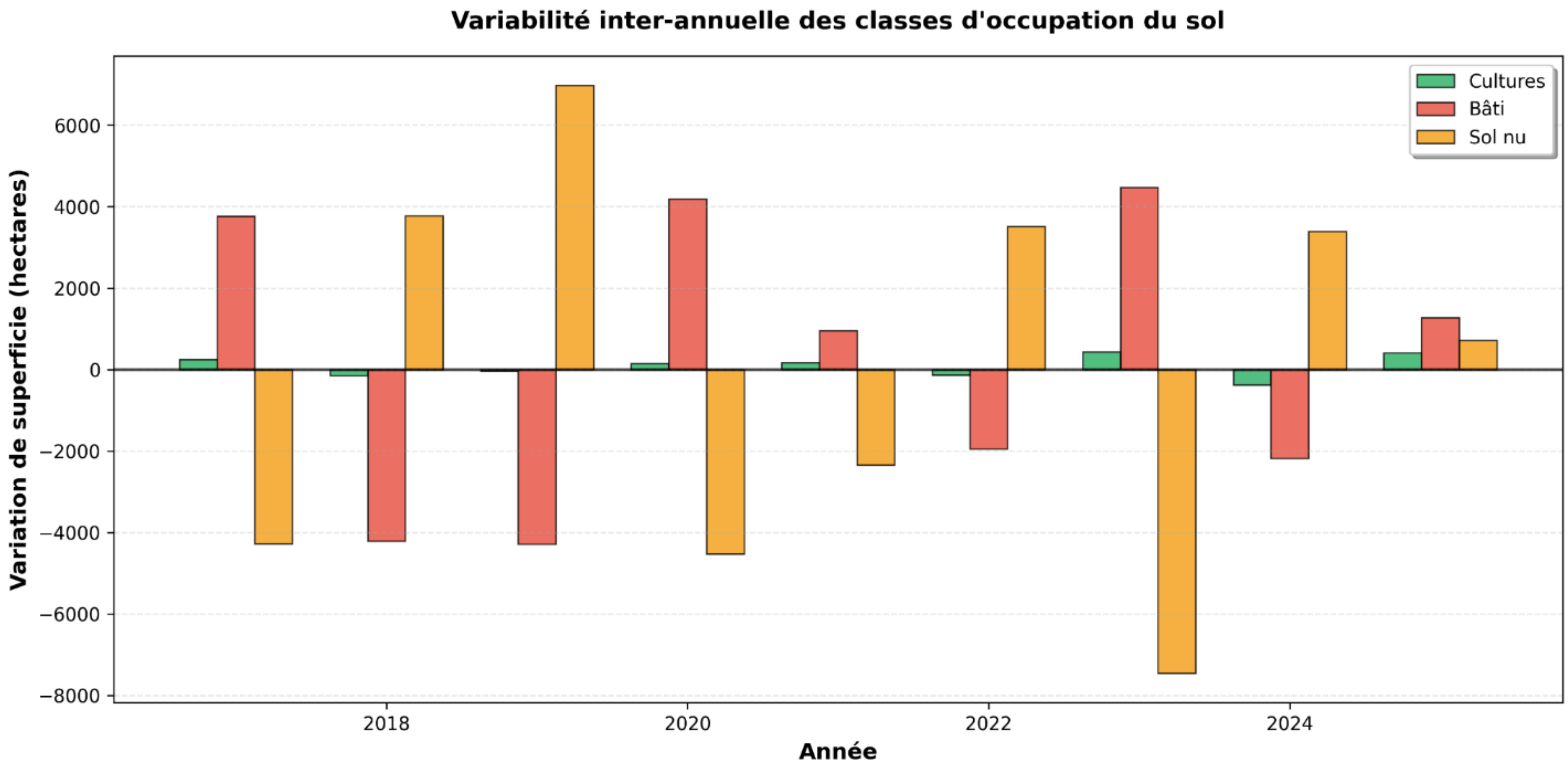
Appendix 5: Correlation matrix between land use classes



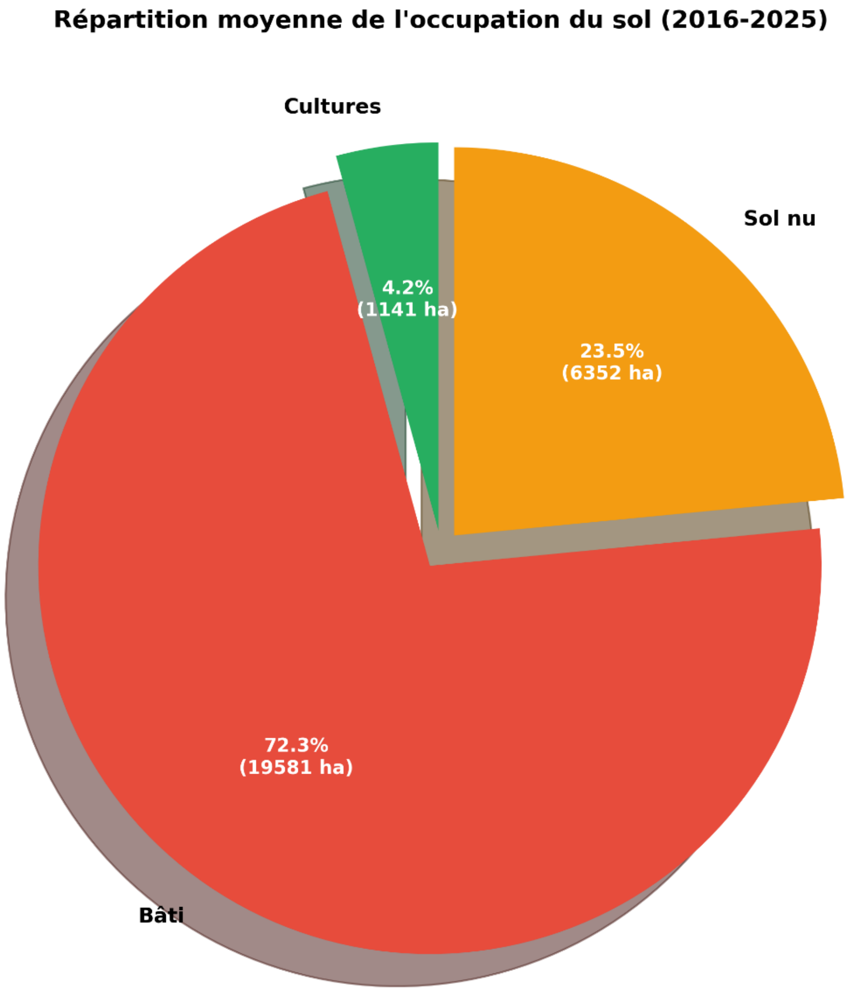
Appendix 6: Land use composition by year



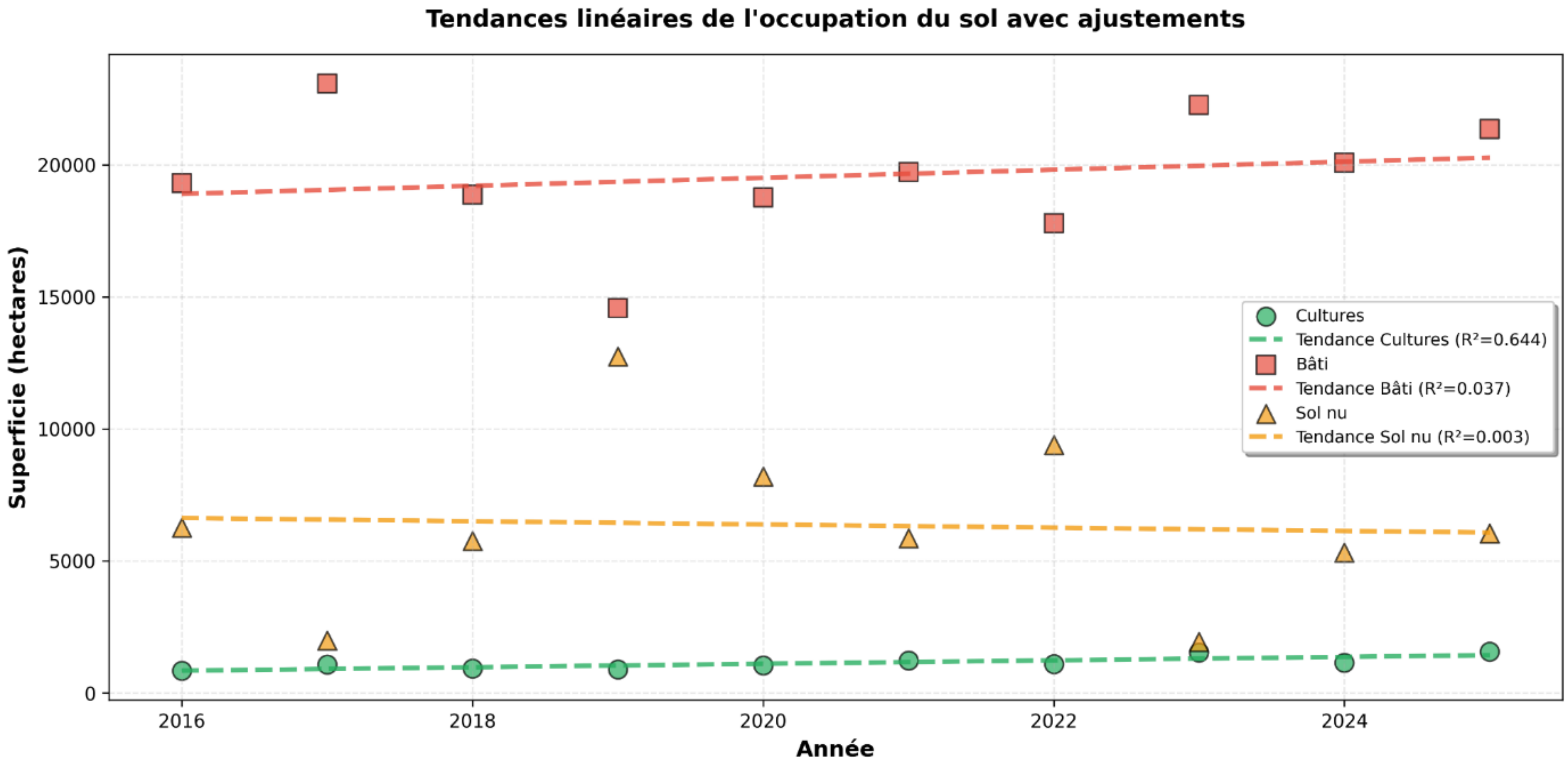
Appendix 7: Interannual variability of land cover classes



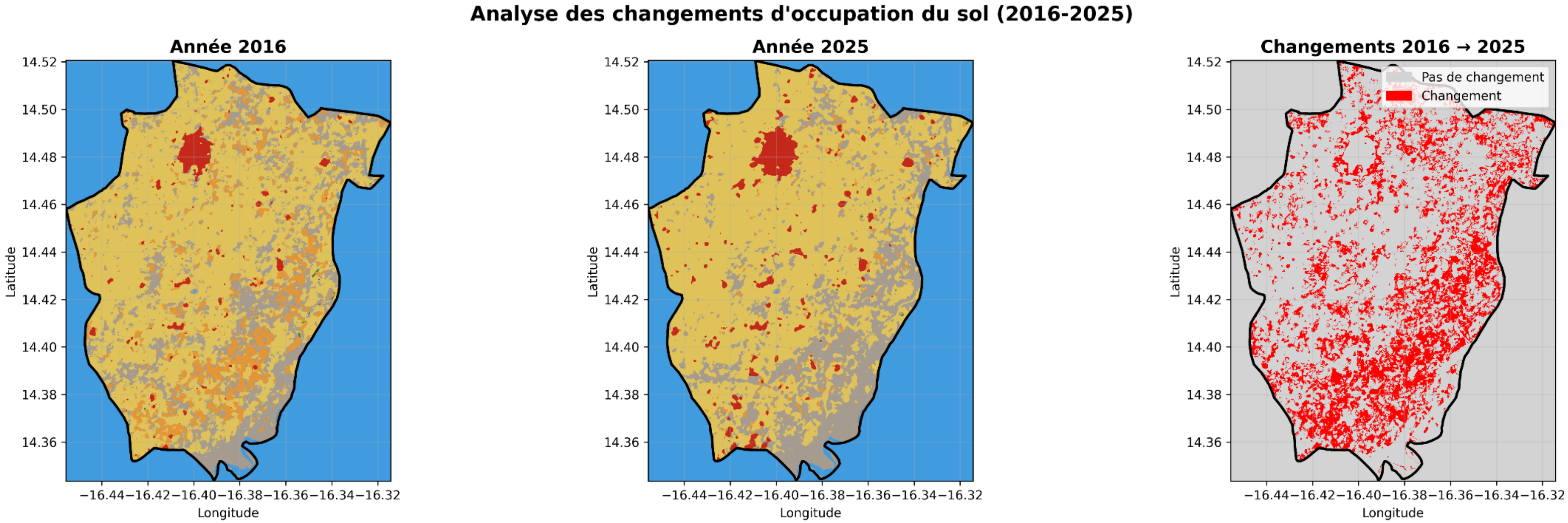
Appendix 8: Average land use distribution (2016–2025)



Appendix 9: Linear trends in land cover with adjustments



Appendix 10: Analysis of land use changes (2016–2025)



Analysis of the Niakhar landscape using satellite imagery