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Research Article

Spatio-temporal Dynamics of the Standardized Precipitation Index (SPI) and the Normalized Difference Vegetation Index (NDVI) for the Characterization of Drought in Côte d'Ivoire

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Abstract This study aims to use the potential of satellite imagery for monitoring and characterization of drought conditions based on the Standardized Precipitation Index (SPI) and the Normalized Difference Vegetation Index (NDVI) in the Côte d'Ivoire from 2010-2015 during the season from November to March. These indexes were obtained from two types of data, namely rainfall data from the Tropical Rainfall Measuring Mission (TRMM) and NDVI data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the Earth Observation System (EOS) Terra satellite and the EOS-Aqua platform. They were combined to perform a spatio-temporal analysis of the Drought Index (DI) to determine the driest months. Analyzes and digital processing of the data using the ArgGis 10.2.1 software showed that the months of December and January are the most critical months according to the SPI analysis. On the other hand, according to the NDVI, the critical months are January and February. As for the integrated Drought Index (DI), it indicates that the moderately humid months observed in November, December and March are respectively the mark of the end and the beginning of the rainy season in Côte d'Ivoire. Clearly, the months of January and February are the least rained and therefore the driest and the month most affected by drought is that of January ($-0.46 \leq DI \leq -0.18$) in Côte d'Ivoire during the study period.
Keywords *DI; Drought; Ivory Coast; NDVI; SPI*

1. Introduction

Of all the climatic extremes that affect communities and the natural environment, drought is the most devastating. Throughout history, many regions of the world have experienced drought, with varying consequences (World Meteorological Organization (WMO), 2005). In recent decades, major droughts have affected large areas of every continent, underlining the importance of this phenomenon, Beaudin (2007). Both developing and industrialized countries are affected. In recent years, several studies have focused on climate change, some of which have focused on droughts (Sorokoby and al., 2013; Soro and al. (2014); N'Go et al. (2017). There are a multitude of tools for characterizing the state of the environment, and several of these have been specially developed to characterize drought situations (rainfall, temperature, soil water reserve etc.).

For these reasons, the WMO has adopted a number of indices including the Normalized Precipitation Index (SPI) as a universal drought index and the Normalized Vegetation Index (NDVI), WMO (2016). The development of the Standardized Precipitation Index (SPI) is based on rainfall data provided by meteorological networks. However, meteorological stations are sometimes unrepresentative because they are too small and often difficult to access. It is therefore important to find new methods for describing climatic and environmental conditions, in order to continue characterizing and monitoring drought situations. Thus, efforts have recently been made to take advantage of very high-resolution satellite data. To compensate for the lack of rainfall data in certain regions or regions with difficult access, some studies, such as those by Mohammad (2016); Tarek (2020); Slimani (2016); Kogan (1997), have demonstrated the possibility of using remote sensing for drought monitoring. To achieve this, a study combining NDVI and SPI values has been initiated to characterize drought in Côte d'Ivoire, which is prone to drought and highly vulnerable to this hazard, Dje (2006). It will enable us to monitor the spatio-temporal evolution of drought conditions in Côte d'Ivoire in order to propose ecologically sustainable solutions to minimize the risks associated with this climatic hazard.

2. Study Area

Côte d'Ivoire is located in West Africa, between latitudes 4° and 11° North and longitudes 2° and 9° West with an area of 322,462 km^2. It is bordered to the west by Liberia and Guinea, to the north by Mali and Burkina Faso, to the east by Ghana, and to the south by the Gulf of Guinea (Atlantic Ocean) (Figure 1). The study area has two rainfall regimes. Up to the 9th parallel, the rainfall regime is bimodal. Four (4) seasons can be identified, N'Guessan and Djè (2012):

- March to June: the main rainy season;
- July to August: the rainy inter-season, marked by low rainfall;
- September to October: the short rainy season;
- November to February: the long dry season.

Beyond the 9th parallel, the regime is unimodal, with two seasons:

- May - September: the rainy season;
- November to April: the dry season, characterized by a drop in rainfall.

Average temperatures in Côte d'Ivoire have risen sharply over the past four decades. This rise in temperature is at the root of the persistence of dry seasons, Brou (2005).

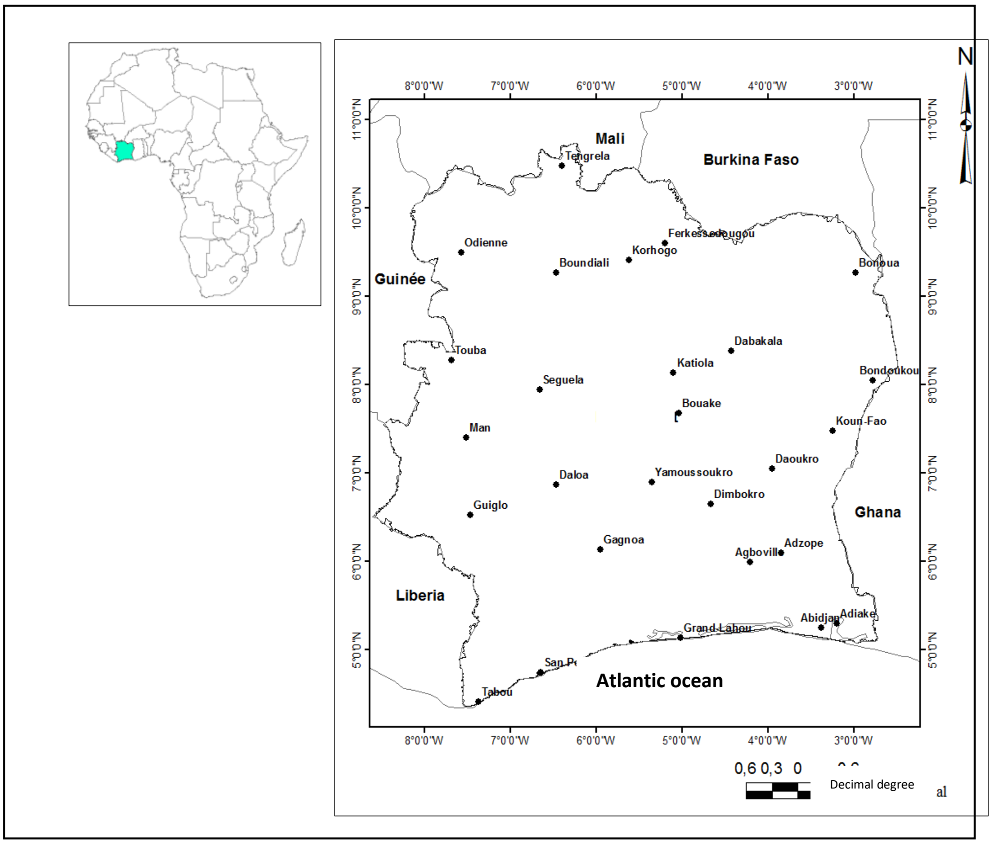


Figure 1: *Presentation of the study area*
(Source: Database, CIGN, 2016)

3. Data Used and Methods

3.1 Data used

3.1.1 Rainfall Data

Rainfall data are provided by the Tropical Rainfall Measuring Mission (TRMM). Daily rainfall estimates are provided with a resolution of 0.25˚×0.25˚. In total, more than 2000 monthly digital data during the season from November to March of the years 1998 to 2019 are collected. They are freely accessible via https://disc.gsfc.nasa.gov/datasets/TRMM_3B43_7/summary .

3.1.2 NDVI data

NDVI data are provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, launched by NASA aboard the Earth Observation System (EOS) Terra satellite and the EOS-Aqua platform. The MODIS VI algorithm operates on a per-pixel basis, using multiple observations over a 16-day period to generate a composite product. The data can be accessed via the link: http://iridl.ldeo.columbia.edu/SOURCES/.USGS/.LandDAAC/.MODIS/.version_005/.WAF/.NDVI/Y . A cumulative total of 1,350 digital data sets were collected during the November to March season from 2010 to 2015. Specialized software was used to carry out the tasks required to complete this work. These include Microsoft Park Office 2013 for ASCII data display and calculation, and Arcgis 10.2.1 for spatial data analysis and map layout.

3.2 Methods for calculating indices and analyzing climate data

3.2.1 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (Mckee and al., 1993) is a powerful, flexible and easy to calculate index. It is determined as follows (eq 1):

$$SPI = (Xi - Xm) / S \quad \text{(eq. 1)}$$

with *Xi*: cumulative monthly rainfall;
Xm: average rainfall for a given series
S: ecartype for a given series.

3.2.2 Normalized Difference Vegetation Index (NDVI)

The NDVI is calculated according to the following equation (eq 2):

$$NDVI = (PIR-R) / (PIR+R) \quad \text{(eq. 2)}$$

with PIR: Proche InfraRed band;

R: Red band.

Data is obtained per 15-day period. An average is calculated to have the monthly value.

3.2.3 Composite Drought Index (DI)

Developed by Sepulcre-Canto and colleagues at the European Drought Observatory, they have combined multiple Indices (SPI, soil moisture and vegetation condition), to detect droughts that impact agriculture, Sepulcre-Canto and al. (2012). In our study, we combined SPI and NDVI to characterize drought.

It corresponds to the formula (eq 3):

$$DI = 0.6*SPI + 0.4*NDVI \quad \text{(eq. 3)}$$

with *DI*: Drought Index;
SPI: Standardized Precipitation Index;
NDVI: Normalized Difference Vegetation Index.

3.2.4 Climate data analysis

The method used was based on the analysis of graphs derived from monthly mean SPI, NDVI and DI data. The study was done on a monthly scale to detect the propitious period of drought over the study period and analyze the variability of drought occurrence. To achieve this, indices were spatialized according to the months of the dry period studied. The kriging method was used to interpolate index values in order to better assess thresholds by month and year.

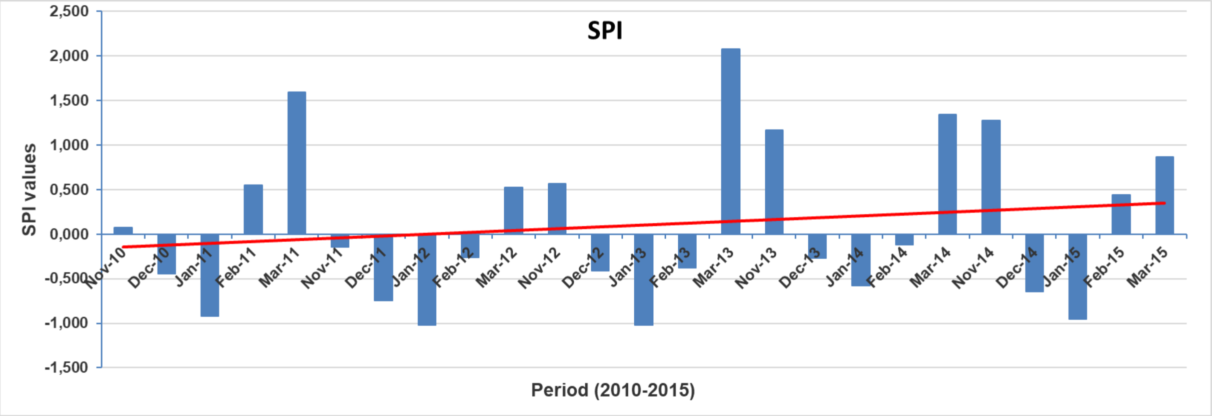
4. Results and Discussion

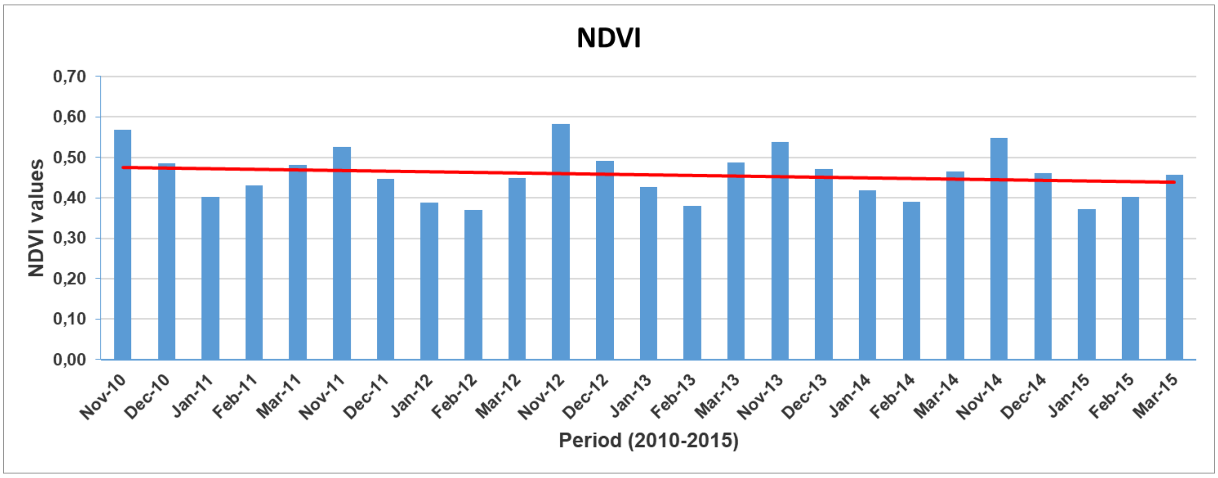
4.1 Monthly variations of indices

Figure 2 illustrates the monthly time series of SPI, NDVI and DI from 2010 to 2015. The three drought indices deliver relatively similar results related to drought variability and trends in Côte d'Ivoire. In particular, the results indicate that the time series show positive and negative indices that exist at the

SPI and DI levels. Drought intensities are highly variable, becoming negative on several occasions. Drought intensities are very variable and become negative several times.

However, SPI and DI show a positive trend reflecting a relatively wet period overall. But we register a longer sequence of negative index from November 2011 to February 2012 (-1.02≤ SPI ≤ -0.15; -0.46 ≤ DI ≤ 0.12) and from December 2011 to February 2013 (-1.02≤ SPI ≤ -0.38; -0.45 ≤ DI ≤ -0.05). The most critical month in the series is January in general, and in particular January 2012 (SPI= -1.02; DI= -0.46) and January 2013 (SPI= -1.02; DI= -0.45). NDVI, on the other hand, gives positive values but with a negative trend. This indicates a deterioration in vegetation condition over the period. It also reflects crop stress influencing crop growth. The highest values are recorded in November, and the lowest in January and February. The lowest NDVI is recorded in February 2012 and January 2015 (NDVI=0.37) and the highest in November 2012 (NDVI=0.37). It should be noted that the seasons from November 2011 to February 2012 and December 2012 to February 2013 appears to be the lees humid compared with the other seasons.





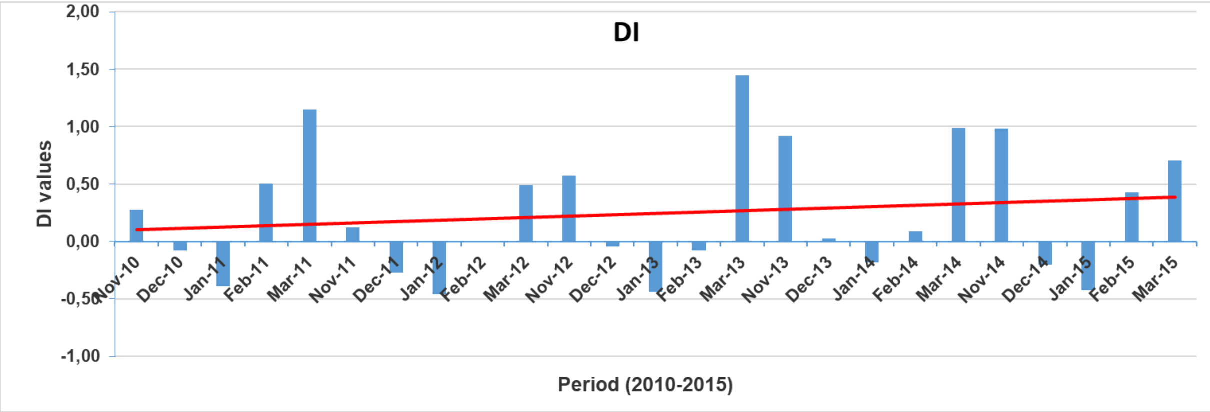


***Figure 2**: Monthly evolution of the SPI, NDVI and DI from November to March 2010 to 2015*

(Source: Dje, May 2024)

4.2. Monthly average index mapping

4.2.1 SPI mapping

Figure 3 shows the average monthly spatio-temporal variability of rainfall in Côte d'Ivoire. It covers the period from November to March from 2010 to 2015. By comparing the maps obtained by spatial interpolation, it is easier to see the differences and similarities. With regard to SPI variability, Figure 3 shows that there are two types of months (November and March: humid, and December to February: moderately dry).

November saw a generally humid situation throughout the country (1 ≤ SPI ≤1.49). From December onwards, dry conditions prevail (-1.49 ≤ SPI ≤ -1) and persist throughout the country in January and February. On the other hand, in February, the south-east of the country shows normal conditions (-0.99 ≤ SPI ≤ 0.99). This situation continues in March, when the entire territory becomes wet again (1≤SPI≤ 1.49).

November and March are considered humid, as rainfall indices are mostly above 1 throughout the country. On the other hand, the months most affected by drought are December and January (-1.49 ≤ SPI ≤ -1), when we observe a moderately dry state over the whole country.

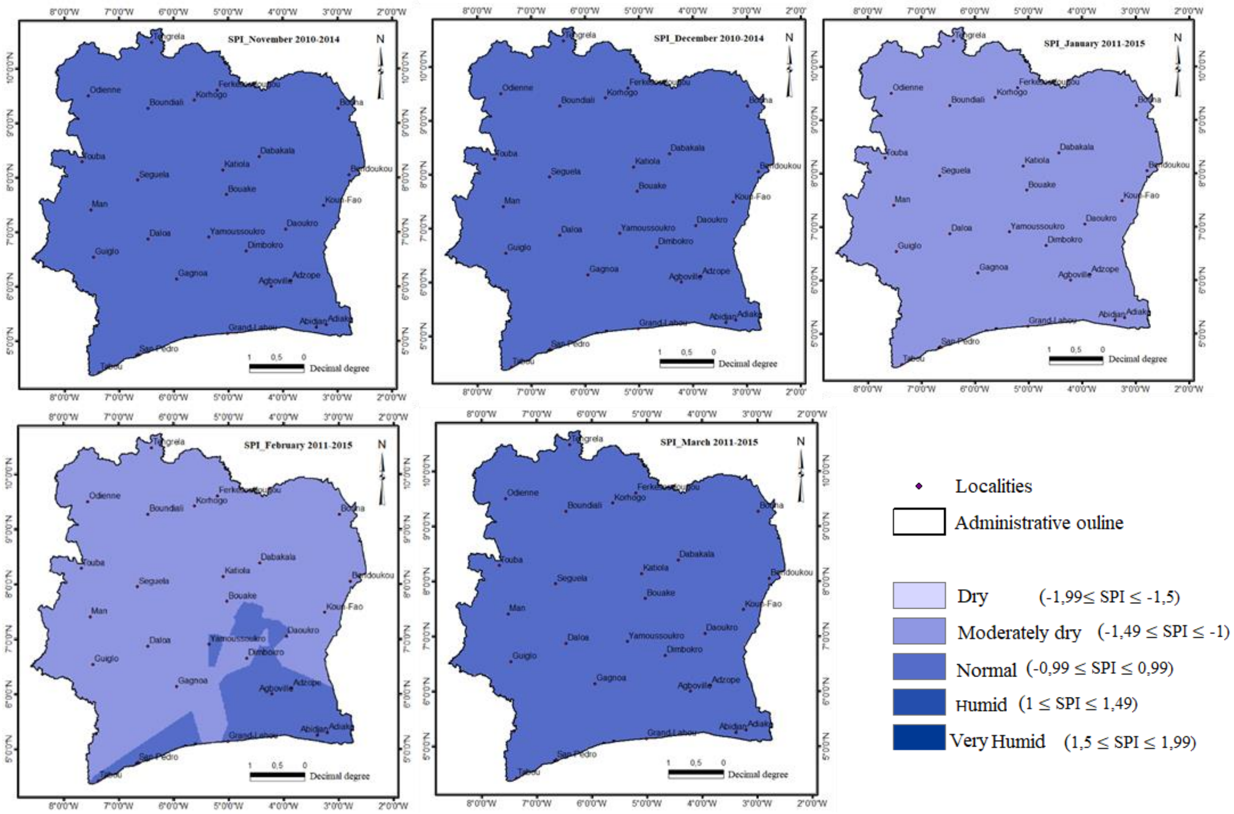


Figure 3: *Spatio-temporal variability of the monthly average of the SPI*
(Source: Dje, May 2024)

4.2.2 NDVI mapping

The monthly mean NDVI over the period November to March for the years 2010 to 2015 reveals an increasing regression in the state da vegetation from November to March (Figure 4). During November, strong vegetation (0.5 ≤ NDVI ≤ 0.6) is more predominant throughout the territory. From December to February, there is a pronounced deterioration in vegetation (0.1≤ NDVI ≤ 0.5) generally throughout the territory. Except in the south-west and south-east, where we observe normal vegetation conditions. In the months of January and February, the north and south of the country are essentially covered with sparse vegetation (0.1 ≤ NDVI ≤ 0.4). And the month most affected by drought is February, when we observe very low vegetation in the northwest (0.1≤ NDVI ≤ 0.3) of the country. In March, vegetation gradually picks up again in the southwest, southeast and center, giving way to heavy vegetation. The south and north also gain in vegetation.

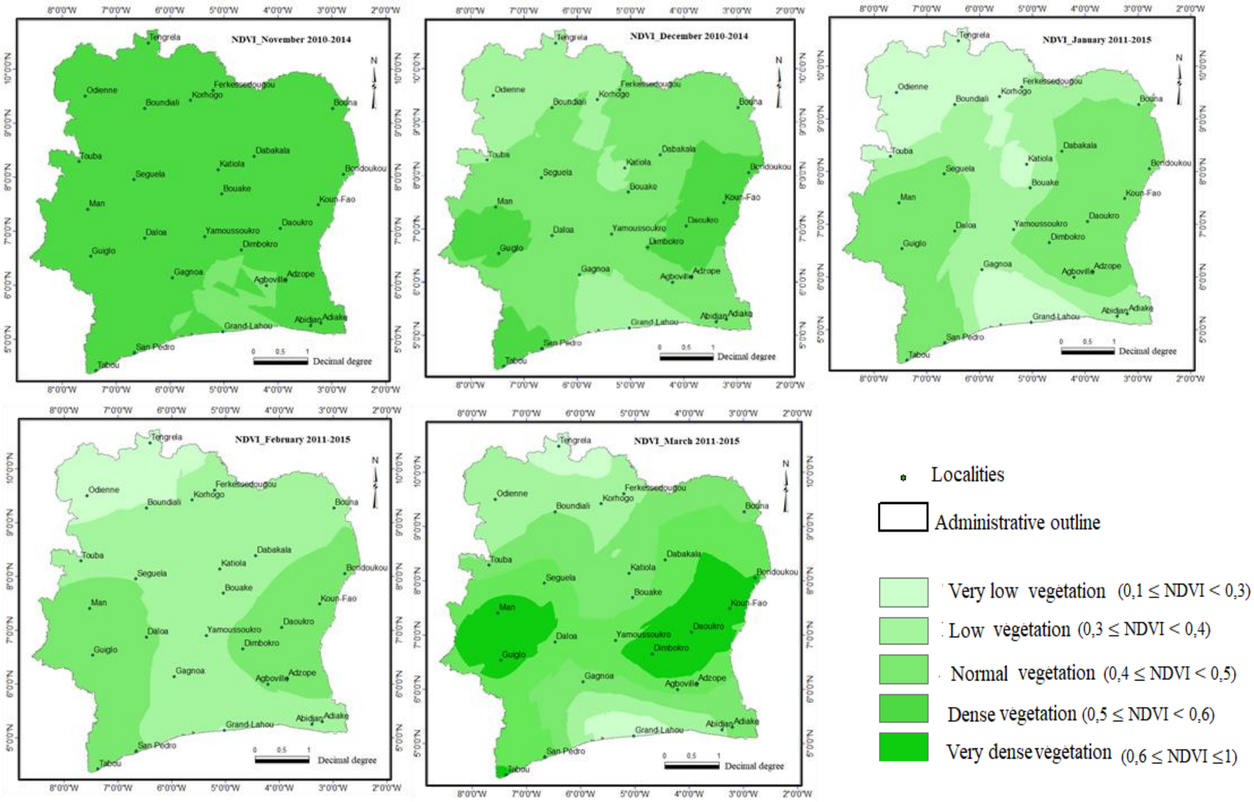


Figure 4: *Spatio-temporal variability of the monthly average NDVI*
(Source: Dje, May 2024)

4.2.3 DI mapping

The monthly mean of the compound Drought Index (DI) over the period November to March from 2010 to 2015 reveals a gradual regression in the state of drought (Figure 5). There are two types of months (November, December and March: humid, and January to February: moderately dry).

In November and December, drought conditions are normal (0 ≤ DI ≤ 0.5) throughout the country. From January to February, there is a pronounced deterioration in drought conditions across the whole country. We are observing a moderately dry drought (-0.5 ≤ DI ≤ 1) these two months. Except in certain localities in the south, south-east and center, where we are observing a normal state of drought (0 ≤ DI ≤ 0.5). In March, the situation gradually returned to normal throughout the country. However, the north-east and south of the country remain subject to a state of drought that is still moderately dry (-0.5 ≤ DI ≤ 1). And the month most affected by drought is January (-0.5 ≤ DI ≤ 1) where we observe a moderately dry state throughout the country with a more pronounced situation in the locality of Katiola (-1 ≤ DI ≤ -0.5).

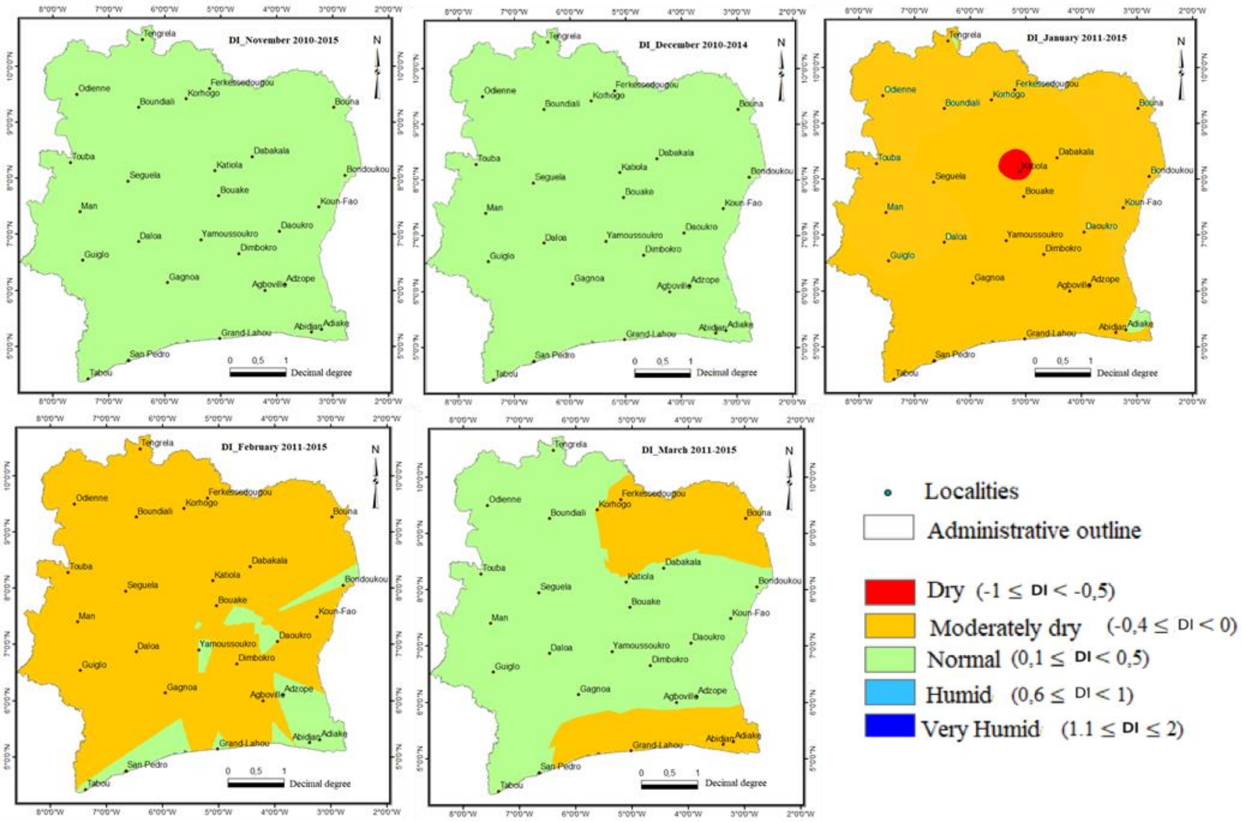


Figure 5: *Spatio-temporal variability of the monthly average of the DI*
(Source: Dje, May 2024)

4.3 Discussion

Our study focuses on the temporal variability of drought indices and the spatio-temporal analysis of drought conditions in Côte d'Ivoire from November to March over the period 2010 to 2015. According to SPI, the critical months from 2010 to 2015 are December and January. On the other hand, according to NDVI, the critical months are January and February. These drought sequences, which do not occur simultaneously, reveal that the drought indicators (SPI and NDVI) generally vary by time lag over the study period. In fact, rainfall is still not linked to plant cover, since there are critical periods, corresponding to certain vegetative stages, during which a certain amount of rain is required by the plants. The SPI does not take into account other climatic parameters such as temperature, light intensity and evapotranspiration. However, several plant mechanisms can potentially increase membrane stability at high temperatures in plants subjected to drought, Cornic (2007). The results appear to be in line with previous studies. Indeed, many studies conducted in different spatio-temporal contexts have revealed that the SPI/NDVI relationship is not linear and not necessarily significant, Ji and Peters (2003); Beaudin (2007). Brou (2010), however, indicated a close link between changes in vegetation cover dynamics and climate variability in Côte d'Ivoire.

The moderately humid months (DI) observed in November, December and March respectively mark the end and start of the rainy season in Côte d'Ivoire. This is remarkable throughout the country. In fact, November marks the end of the short rainy season below the 9th parallel, and north of this limit, above the 9th parallel, rainfall levels remain acceptable. March marks the start of the main rainy season. Although rainfall is limited in the far north, the month as a whole has a normal drought index. The moderately dry months of January and February are the least rainy in Côte d'Ivoire. In most cases, rainfall levels are very low. The lowest values were recorded in January. For the most part, the climate is moderately dry throughout the country during this month. This situation continues into February, with the exception of the southern zone. Even if the DI in February is normal in the southern part of the country, it is mainly very light rain.

Also, the general trend for the SPI and DI is also positive. This explains why Côte d'Ivoire does not undergo repeated, large-scale droughts. There is a clear correlation between these three indices (SPI, NDVI, DI), as revealed by the studies of Bhukya and al., 2023 in India. Similar results were also obtained by other authors such as Ali and Lebel (2009), who showed the persistence of drought throughout West Africa during the 1970s. However, they indicate that since the 2000s, only a few years have been rainfall deficient, and agree with some authors who believe that the drought is over, Sene and Ozer (2002) and Niang and al. (2008). However, the return to normal must be nuanced. It is essential to bear in mind the temporal and spatial variation of the dry period, caused by pronounced climatic variability, Kouassi and al. (2010). Vegetation, whose photosynthetic activity is strongly linked to rainfall in semi-arid Africa, Martiny and al. (2006), finds itself weakened by climatic variability. The generalized drop in rainfall observed in West African monsoon zones is of the order of 5 to 20%, depending on the country, L'Hôte and al. (2002).

According to a UNESCO report published in 2003, the associated impacts on food security, public health and ecosystem equilibrium are the most urgent problem to be tackled by the 1st half of the 21st century. In this study, droughts were characterized using satellite data (rainfall and NDVI). In Morocco, Jouilil and al. (2013), in additional to rainfall data, used temperature and evaporation data to characterize droughts in the Oum Erbia hydraulic basin over recent decades.

5. Conclusion

Analysis of satellite data on droughts provides essential information on their spatio-temporal distribution, the relationship between them and the spatio-temporal distribution of their combination. The results revealed a gap in response between the two selected indices over the study period. In fact, NDVI values were most prevalent in January and February, whereas cumulative rainfall was observed on the SPI from December to January, due to the delayed response of photosynthetic activity to precipitation. This hypothesis, confirmed by other studies, provides a basis for this research. The combination of SPI and NDVI yielded the DI, which indicates that January and February are the less rainy and therefore driest months in Côte d'Ivoire over the study period. The analysis highlights that the moderately humid months (DI) observed in November, December and March are respectively the end and beginning of the rainy season in Côte d'Ivoire. There still seems to be a need to improve our results, in particular by selecting quality data and conducting more in-depth methodological research. As part of this initiative, it makes sense to test the relevance of other indices and indicators that touch on the issue of drought sensitivity. At the same time, it should be borne in mind that there is no single definition of drought, or indicator or index that is suitable for all types of drought. Finally, a better mapping of drought risk can take into account the size of useful soil reserves to determine the stock of water available to plants.

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