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# INFLUENCE OF THE RAINFALL SEASONAL VARIABILITY IN THE CAATINGA VEGETATION OF NE BRAZIL BY THE USE OF TIME-SERIES

Jorge Alberto Bustamante-Becerra*, Suzana Carvalho* e Jean Pierre Ometto*

* National Institute for Space Research -INPE, Center for Earth System Science, Rodovia Presidente Dutra, Km 40, SP-RJ CEP: 12630-000, Cachoeira Paulista, SP, Brasil. Phone: 55+12 31869522.

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**Abstract**

The climate in the Caatinga, especially precipitation, influences the pattern of spatial and temporal distribution of the vegetation that in turn influences the regional climate from the feedback mechanism of energy flows, water and momentum. This climate-vegetation interaction in the Caatinga is differentiated depending on the type of climatic pattern in the region. The objective of this work is to identify the main phenological features of the annual growth cycles of vegetation and characteristics of the seasonal rainfall in five climatic regions in the Caatinga biome. We use time series (2001-2008) of vegetation indices such as NDVI and LSWI, and precipitation that was derived of TRMM satellite data and surface station data. The results indicate that precipitation variability in the rainy season influences directly the variability of vegetation growing cycles. That influence is not linear but adjusted to a logarithmic function being the best fit with the index LSWI ($r2 = 0.67$) than with NDVI ($r2 = 0.54$). The influence of precipitation on vegetation, using phenological metrics such as start, end, peak and length of the vegetation growing cycles showed greater lag in climatic regions with higher precipitation in the Caatinga region.

**Keywords**: Plant phenology of the Caatinga, climatic seasonality, annual cycle of vegetation, time series.

## Introduction

The lost of natural vegetation is one of the major environmental problem the Caatinga biome faces. Based on MMA-IBAMA (2010) deforestation monitoring, up to 2008 about 45,39% of land under native vegetation was converted in other uses, overall agricultural use. These conversions have direct effect on the biosphere-atmosphere interaction, with impact in the local climate, carbon storage and fluxes, hydrological cycle and biodiversity. Changes in the vegetation cover density, in special the lost of the above ground strata, also strong influence on the vegetation phenology, with effects on regional plant productivity. As well, climate seasonality, in special precipitation, has direct influence on vegetation phenology and growth seasonality (Bustamante et al, 2012). The vegetation response to climate variability, and effect on primary productivity defines cycles with higher and lower carbon flux and storage (Ahl et al., 2006). Changes in net primary productivity, with consequences changes in water use by plants, have potential influence in the regional climate.

In the Caatinga region, study of seasonal variation is possible by the use of time series of vegetation spectral indices, e.g. NDVI (Normalized Difference Vegetation Index), the EVI (Enhanced Vegetation Index) and LSWI (Land Surface Water Index). These indices are able to capture changes in photosynthetic activity, relating leave production (translated in primary production) in time, allowing inferring the vegetation water status, vegetation phenology and the stage (initial, end, length) of the growing cycle, at regional scale (Eklundh, 2011).

The aim of this work is to identify the key phenological characteristics of vegetation growth, related to precipitation seasonality in five climatological regions in the Caatinga biome, by using NDVI and LSWI time series, TRMM satellite data as precipitation indicator and climatic observational surface stations distributed in the region. Therefore relate, remotely, seasonal precipitation patters with vegetation phenology, identifying the response time of vegetation to precipitation occurrence and length, using as bases climatological classes which was elaborated in this work for the period 2001 to 2008, for the Caatinga regions.

## Methods

The Caatinga area (Figure 1) covers an area of 844.453 km², 9,92% of Brazil's territory (IBGE, 2004) from latitude $3^0$ to $17^0$S and Longitude from $35^0$ e $45^0$W. The term Caatinga refers to xerophytic, woody, thorny, and deciduous physiognomies with a seasonal herbaceous layer (Veloso et al., 1991). These vegetation types are spatially arranged in mosaics, which vary from dry thorn forest to open shrubby vegetation (Andrade-Lima, 1981), being these variations attributed to large-scale variations in the climate, orographic patterns, and small-scale variations in topography and soils (Andrade-Lima, 1981; Sampaio, 1995). The region experiences historical anthropic perturbation on its land cover, once there is where the European first arrived in the South America early 1500's. However, higher rates of land cover change was observed in the past 50 years, mainly for cattle ranching, subsistence agriculture and for timber extraction to be used in domestic cooking and industrial charcoal production (Araújo et al., 2007). Some regions are under desertification process, which is natural in its genesis, but has being potentialized by inadequate use of the soil. The climate is characterized as semi-arid, with clear dry, lasting seven to nine months, and wet, three to five months, seasons (Mendes, 1992; Araujo, 2007).

Two major physiognomic vegetation structures are found in the region, forest and non-forest, however trees rarely grow above 20m and vegetation is dominated by shrubs and small trees (Sampaio & Silva (2005). The shrub vegetation is characterized by deciduous thorn species (Steppical Savanna, according to VELOSO et al., 1991). In lower abundance evergreen, semi-deciduous, and deciduous trees are found (Tavares et al., 2000; Ferraz et al., 2003).

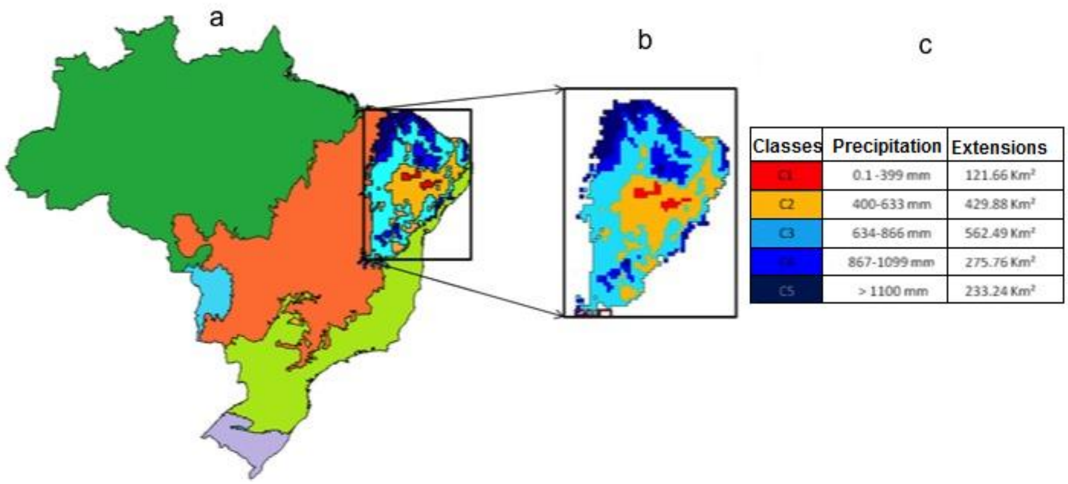


Figure 1. Location of the study area (Caatinga) in the context of Brazilian biomes (a), Caatinga precipitation climate classification (period 1999 - 2008) (b), and precipitation intervals of the used classes (C1 to C5) and their extensions (c).

Time series data of MODIS vegetation indices were used for the period 2000 to 2008, as well as the combined data from TRMM and surface meteorological stations. Vegetation maps produced by PROBIO and MMA-IBAMA (2010) were used as complementary information. These satellites images correspond to four tiles (h13v09_v10 e h14v09_v10) with spatial resolution of 1km and temporal resolution of 16 days, performing 23 times per year and 184 in the studied period.

Figure 1C shows the methodological classes used to identify the precipitation and vegetation seasonality in the region, being C1 the lower precipitation class and C5 the highest. For each class (C1 to C5) NDVI values were extracted from the images and the LSWI index calculated according to Jurgens (1997) and Xiao et al. (2002, 2004). The land surface water index (LSWI) is linear combination of NIR and SWIR bands and calculated as:

$$LSWI= (\rho_{NIR}- \rho_{MIR})/( \rho_{NIR}+ \rho_{MIR}) \qquad (1)$$

Where, $\rho_{NIR}$ and $\rho_{MIR}$ are reflectance in near infra red-NIR (841-875 nm) and short wave infra red-SWIR (1628-1652 nm) regions, respectively.

We also extract precipitation data "*merge*" for every climatological class. These data are from now on referred as "PREC". Means from the vegetation indices (NDVI and LSWI) and PREC were calculated for correlation analysis. The calculation was performed for each date analyzed, within the 2001–2008 period. This analysis was based for identifying the vegetation phenology and precipitation seasonality.

The time series, for each analyzed variable analyzed, is defined as $(t_i, I_i)$, $i = 1,2, \ldots, N$, and the model function as:

$$f(t) = c_1w_1(t) + c_2w_2(t) + \ldots + c_Mw_M(t) \qquad (2)$$

Where, $c_1w_1(t)$, $c_2w_2\ (t)$, …,$c_Mw_M(t)$ are arbitrary base functions.

The number of annual vegetation growth cycles is calculated using the model function $f(t)$, where the time serie $(t_i, I_i)$, $i = 1,2, \ldots, N$ , for three years, which is the minimum time required by the algorithm, is adjusted as the following model:

$$f(t) = c_1 + c_2t + c_3t + c_4 \operatorname{sen}(\omega t) + c_5 \cos(\omega t) + c_6 \operatorname{sen}(2\omega t) + c_7 \cos(2\omega t) + c_8 \operatorname{sen}(3\omega t) + c_9 \cos(3\omega t), \qquad (2)$$

Where, $\omega = 6\ \pi/N$. The three first functions determine the growth cycle and the interannual trend. As so that, the three sine and cosine pair equations correspond, respectively, to one, two and three cycles of annual vegetation growth.

The Savitzki-Golay (Press et al., 1994) filter is applied to correct, reduce and smooth the noise presented in the series. With this filter, every data with value $I_i$, ($i$ = 1, 2,...,$N$) is adjusted to the following square polynomial relation:

$$f(t) = c_1 + c_2t + c_3t^2 \qquad (3)$$

to all $2n + 1$ points in the moving window and replacing the value $I_i$ with the value of polynomial at position $t_1$. . The result is a smoothen curve, adjusted to the time series values of the climatic variable.

After defining the annual growth cycles (phenology) and the rain regime (seasonality), the calculation is performed for phenology and seasonality considering 'beginning', end, length, spike (maximum value in the cycle), and integrals of the growing season according to Eklundh and Jonsson (2011). These analyses are summarized in boxplots, correlations and regressions.

## Results and Discussion

The results are presented in two parts: Seasonal profiles of vegetation and precipitation in the Caatinga biome (3.1), and metrics of vegetation phenology and precipitation seasonality (3.2).

Seasonal profiles of vegetation and precipitation in the Caatinga biome

Five climatological classes that cover the Caatinga biome in Brazil was analyzed over eight years (2001 - 2008) and a fixed time step of16 days. The results indicate that rainfall were not uniform and showed inter-annual and seasonal variability, as seen in Figure 2. In general, the highest precipitation in the rainy season does not exceed 260 mm per month, except in 2004, and reach the lowest value of zero for all climatological classes. Monthly precipitation in 2004 showed higher values than the other studied years (2001-2008), therefore 2004 was above the climatological average for the study area (Silva et al, 2011).

According to Infoclima report (2004), heavy rains in 2004 over the Northeast Brazil were due in part to the displacement of cold fronts to the north, the influence of the intertropical convergence zone (ITCZ), band of dense clouds which lies along the equator and performed south of its normal portion, and the presence of upper tropospheric cyclonic vortex (UTCV) in the South Atlantic Ocean (Infloclima, 2004).

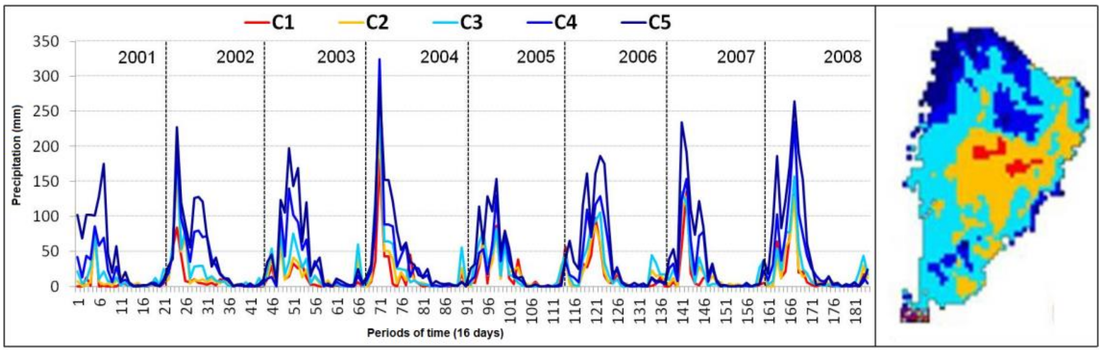


Figure 2. Interannual variability of rainfall in the Caatinga biome over the period of eight years (2001-2008), time step of 16 days. This biome was classified into 5 classes from highest to lowest rainfall.

In the northern Caatinga biome rainfall is higher than the other regions, being represented by C4 and C5 climatological classes. In this region, the maximum rainfall during the rainy season, between February and May, ranged from 130 mm to 300 mm, while in the dry season, rainfall did not exceed 20 mm.

Eastern and southern regions of the Caatinga were classified as intermediate rainfall, represented by C3 class, reaching the maximum rainfall of 200 mm in the rainy season. As expected, in Central biome, represented by C1 and C2, we found the lowest values of precipitation, where the maximum values did not exceed 90 mm.

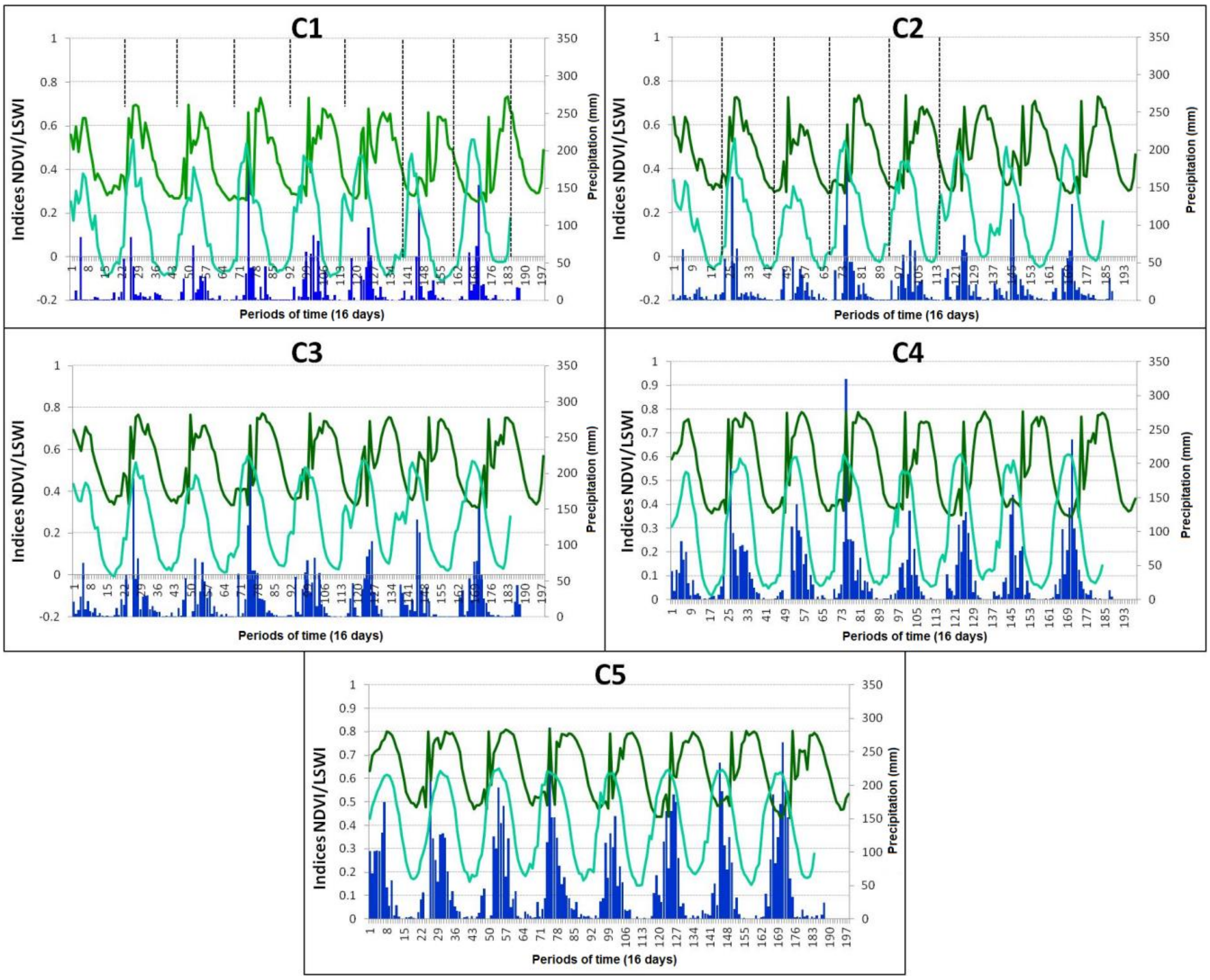


Figure 3. Interannual variability of Caatinga vegetation obtained from NDVI and LSWI indices in different climatic regions over the period of 2001-2008.

Figure 3 shows the interannual variability of vegetation (NDVI and LSWI) and precipitation over the period of 2001-2008, indicating that there is a clear relationship between vegetation and rainfall in the Caatinga biome. That means, less precipitation (C1) associated with low values of NDVI and LSWI, lower vegetation cover, and more precipitation (C5) associated with high values of NDVI and LSWI, higher vegetation cover. The analysis of vegetation indices (NDVI and LSWI) for each climatological class shows in Figure 3, that although the behavior of the indices are similar, LSWI has a greater length than NDVI values, using the same scale ( -1 to 1 ), especially in the minimum values with values close to zero and sometimes lower than this value, on the other hand, the maximum peaking at around 0.5 or 0.6.

This index (LSWI) has high correlation with plant canopy water content capturing a better response of the plant in relation to moisture stress than NDVI. As expected, the correlation between NDVI and LSWI for all analyzed years and all vegetation classes were very high ($r > 0.95$).

NDVI uses the red and infrared channels of electromagnetic radiation spectrum, being a good indicator of photosynthetic activity, this index presents some limiting factors such as existence of saturation points and atmospheric interference

(Ponzoni and Shimabukuro, 2007). While LSWI by exploiting the near and middle-infrared spectral regions estimates the variation of plant canopy water content (Gao, 1996) and therefore is expected to have some difference from NDVI performance.

The analysis of the Land Surface Water Index (LSWI) for each climatological classes at the study area showed that in classes with lower precipitation (C1), LSWI was negative, thus indicating low amount of foliar biomass during low or non rainfall periods, especially in dry season. In classes with high precipitation, like C4 and C5, the minimum values of LSWI does not reach zero in dry season, indicating the presence of soil moisture available for plant maintenance.

In the Caatinga biome, areas with higher NDVI and LSWI correspond to regions of tropical forest, mainly deciduous forests and some few evergreen forests. Overall, these regions have longer rainy season than regions with lower values of NDVI and LSWI, which ensures greater availability of moisture most of the year, including the dry season, reinforced the idea that precipitation is a limiting factor for the development of vegetation in tropical regions such as the Caatinga.

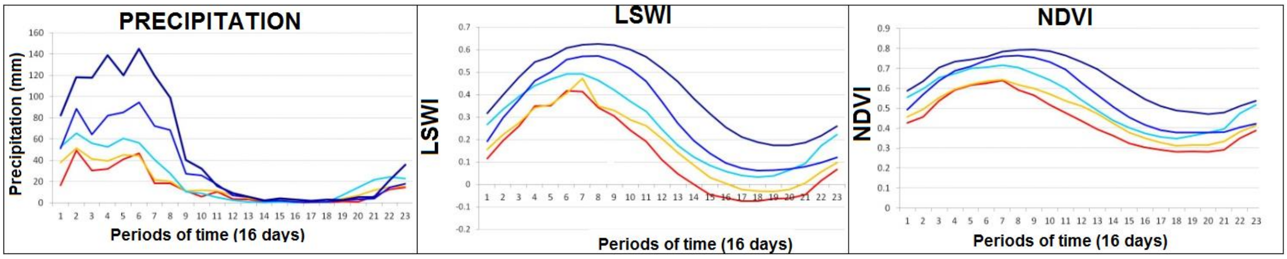


Figure 4. NDVI, LSWI and precipitation average values for the period 2001-2008 for each climatological class at the Caatinga biome.

Figure 4 shows that there is a correspondence between precipitation and the vegetation indices (NDVI and LSW). That is, the vegetation response to precipitation decrease takes some weeks to be observed. The end of the rainy season for all climatological classes occurred in May, however the NDVI and LSWI values began to decrease gradually some weeks after. The NDVI and LSWI peaks associated to great photosynthetic activity can be observed in the beginning of April for C1 and C2, in second half of April for C4, and in May for C5, reflecting the rainfall effect occurred in previous months.

The maximum rainfall in the rainy season increased gradually over the classes, with 49 mm (C1), 51 mm (C2), 65 mm (C3), 94 mm (C4) and 145 mm (C5). The NDVI maximum values for C1 and C2 were very similar, being the maximum value 0.65, considering a scale of -1 to 1. The following maximum were 0.71, 0.76, and 0.79 for C3, C4 and C5 classes respectively. We also found that in classes with lower annual precipitation, the decrease of LSWI values tends to occur prior to classes with higher precipitation, indicating the ability of soil and vegetation to store water and then loses it during the dry season. The lowest (negative) LSWI values of C1 and C2 show the intense water stress suffered by vegetation during dry season, long periods with little or no rain in the Caatinga region.

3.2 Metrics of vegetation phenology and precipitation seasonality

The analyses of interannual variability of both precipitation and vegetation indices, as well as, the metrics of seasonality of the analyzed variables are presented in the boxplots of Figures 5 to 8. These figures show that in the Caatinga biome precipitation and vegetation development occur in seasonal cycles, thus, we have 7 annual cycles for the period 2001-2008, when each cycle begin in the second half of the year. The results show that precipitation and vegetation interannual variability change according to the seasonal metrics (like: beginning, end, length and peak of annual cycle), presenting in some cases extreme values defined as outliers in the graphs. Figure 9 also shows boxplots with the lag between precipitation and vegetation, using the same set of variables: precipitation, NDVI and LSWI.

Overall, in precipitation over the all analyzed classes, the start of the rainy season has a gradient that follow a positive parabola (concavity upwards), the end and length of the rainy season slightly resemble a negative parabola (Figure 6), while the peak metric shows an increasing gradient from C1 to C5 (Figure 7). In the analysis of vegetation growing cycles using vegetation indices, the metric that assess the start of the growth cycle shows that the beginning of the cycle seems to have no set pattern, other metrics, like end peak and length, show upward trend gradient.

Figure 7b shows that the length of the rainy season is always lesser than the length of the vegetation-growing season. On the other hand, the length of NDVI is a little greater than LSWI, it means that there is not statistical difference between both.

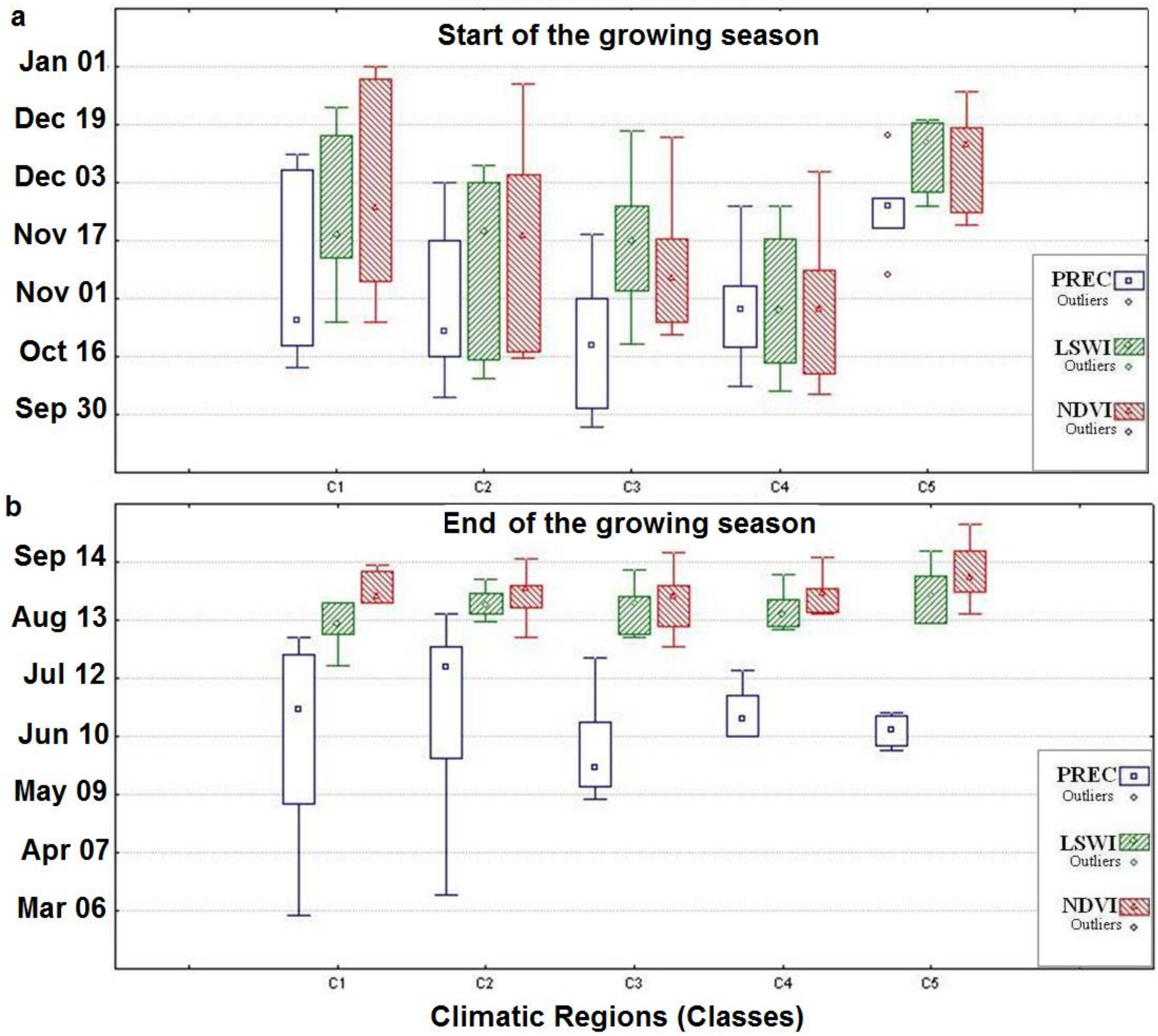


Figure 5. Boxplots of the following phenological metrics: start (a) and end (b) of the vegetation growing cycle, using NDVI and LSWI; and metrics of precipitation seasonality in the Caatinga biome classified into 5 climatic regions, sorted in order of rainfall, from lowest to highest (C1, C2, C3, C4 and C5, respectively). The data correspond to seven precipitation and vegetation seasonal cycles (2001-2008).

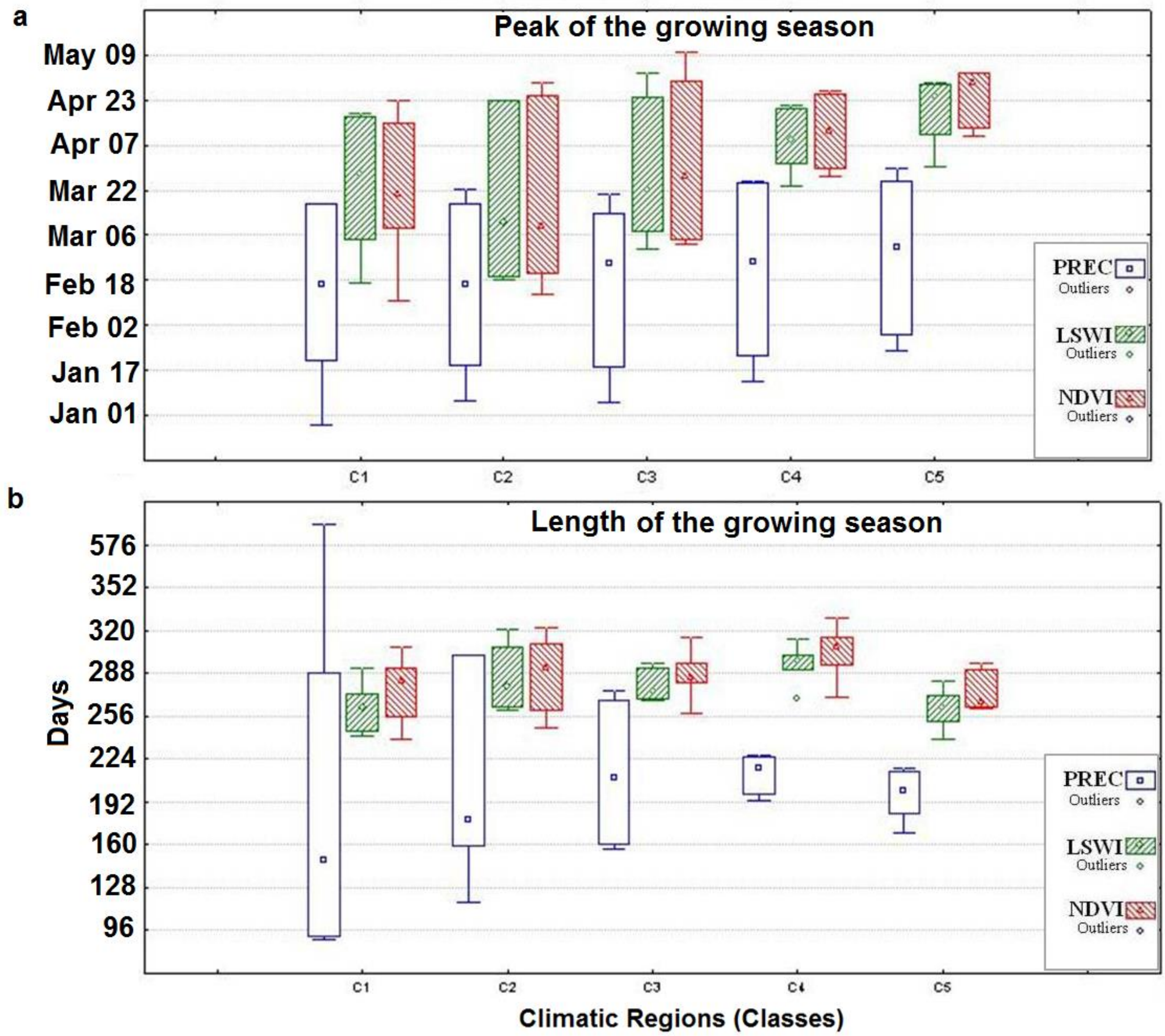


Figure 6. Boxplots of the following phenological metrics: peak (a) and length (b) of the vegetation growing cycle, using NDVI and LSWI; and metrics of precipitation seasonality in the Caatinga biome classified into 5 climatic regions, sorted in order of rainfall, from lowest to highest (C1, C2, C3, C4 and C5, respectively). The data correspond to seven precipitation and vegetation seasonal cycles (2001-2008).

Figure 7 shows the time lag of the beginning (a) and end (b) of the season between precipitation and vegetation response, while Figure 8 shows the time lag of the peak (a) and length (b) of the season between precipitation and vegetation response. The lag between the start of rainy season with the beginning of the vegetation growing cycle does not have a set pattern along the precipitation gradient, represented by C1 to C5 classes. The time lag of the end, peak and length metrics show trend of upward gradient. These results indicate that, except for the lag between the start of rainy season with the beginning of the vegetation growing cycle, the lag between vegetation responses to precipitation increases according to the positive precipitation gradient, thus, in lower precipitation regions with dominant vegetation of grassy-herbaceous and shrub the lag is smaller than regions with higher rainfall and deciduous, semi-deciduous and evergreen forests.

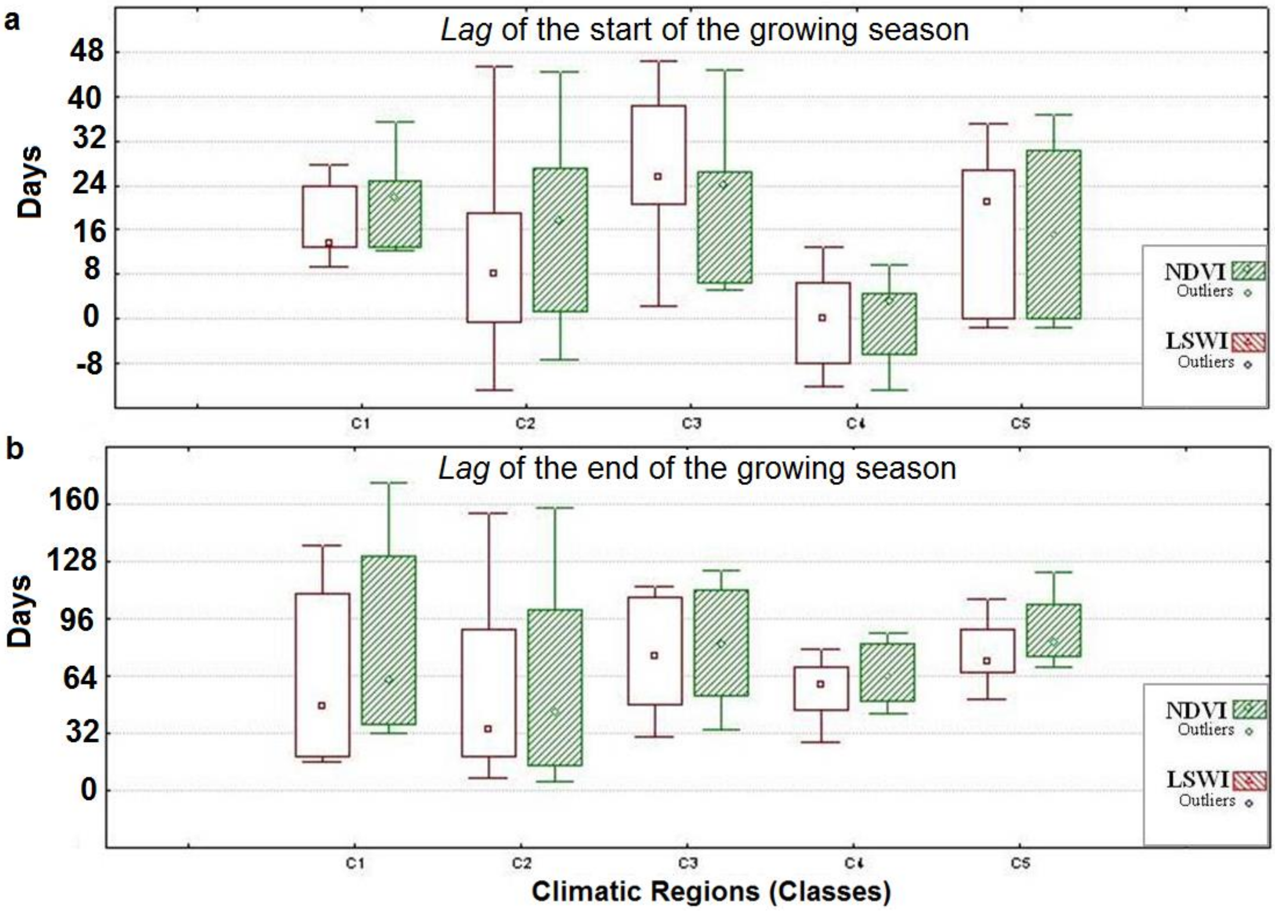


Figure 7. Boxplot of time lag between precipitation and vegetation response, comparing the start (a) and end (b) metrics of the vegetation growing cycles with precipitation seasonality in the Caatinga biome classified into 5 climatic regions, sorted in order of rainfall, from lowest to highest (C1, C2, C3, C4 and C5, respectively). The data correspond to seven precipitation and vegetation seasonal cycles (2001-2008).

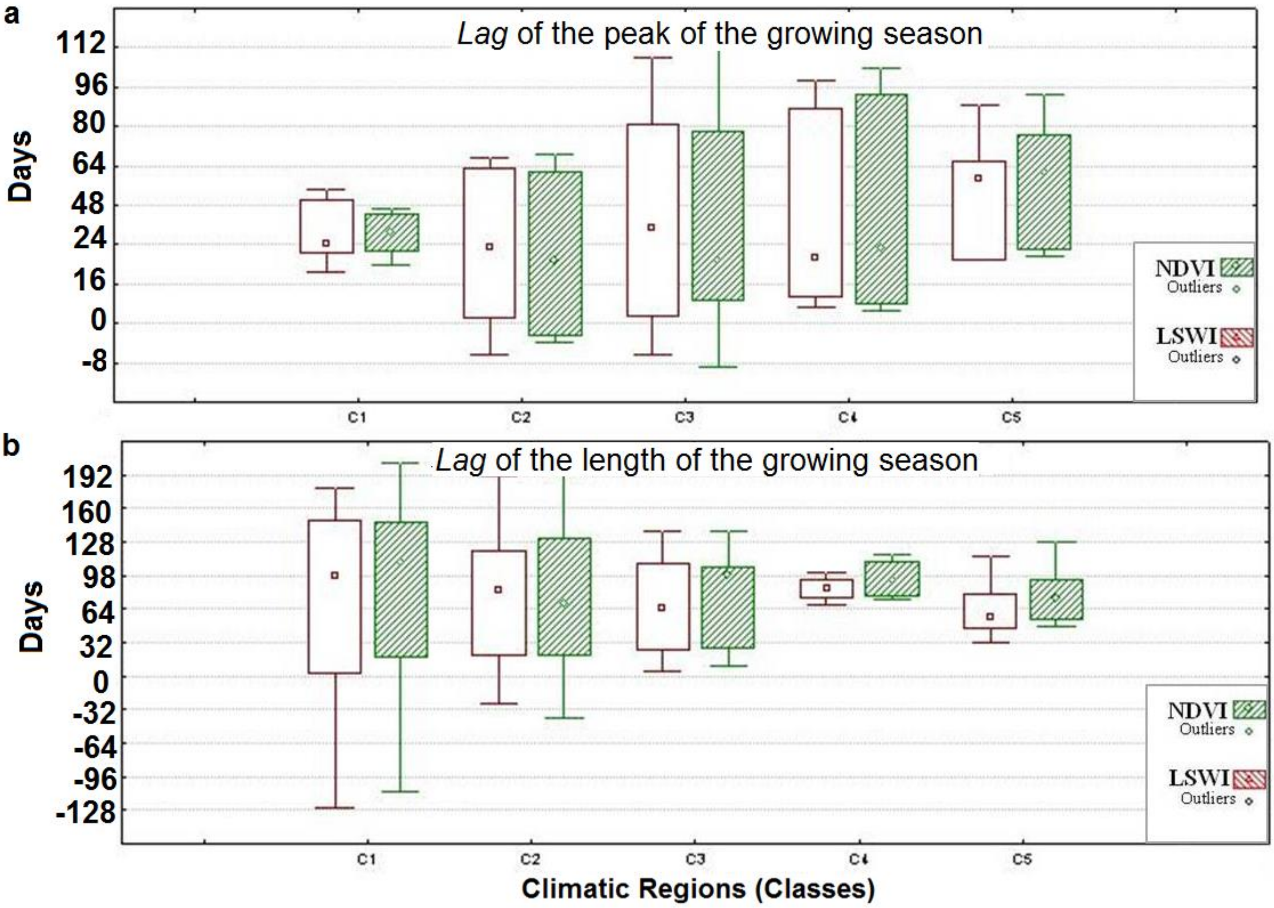


Figure 8. Boxplot of time lag between precipitation and vegetation response, comparing the peak (a) and length (b) metrics of the vegetation growing cycles with precipitation seasonality in the Caatinga biome classified into 5 climatic regions, sorted in order of rainfall, from lowest to highest (C1, C2, C3, C4 and C5, respectively). The data correspond to seven precipitation and vegetation seasonal cycles (2001-2008).

Figure 9 shows the results of the large seasonal integral metrics that means integral of the function describing the precipitation (or vegetation) season from the season start to the season end (EKLUNDH; JNSSON, 2011), thus this integral shows the cumulative effect of precipitation (or vegetation) during the season. These results indicate that both precipitation seasonal cycles and vegetation growing cycles increase in size (area) due to precipitation gradient in the study area, represented by climatological classes ranging from C1 (lower precipitation) to C5 (higher precipitation).

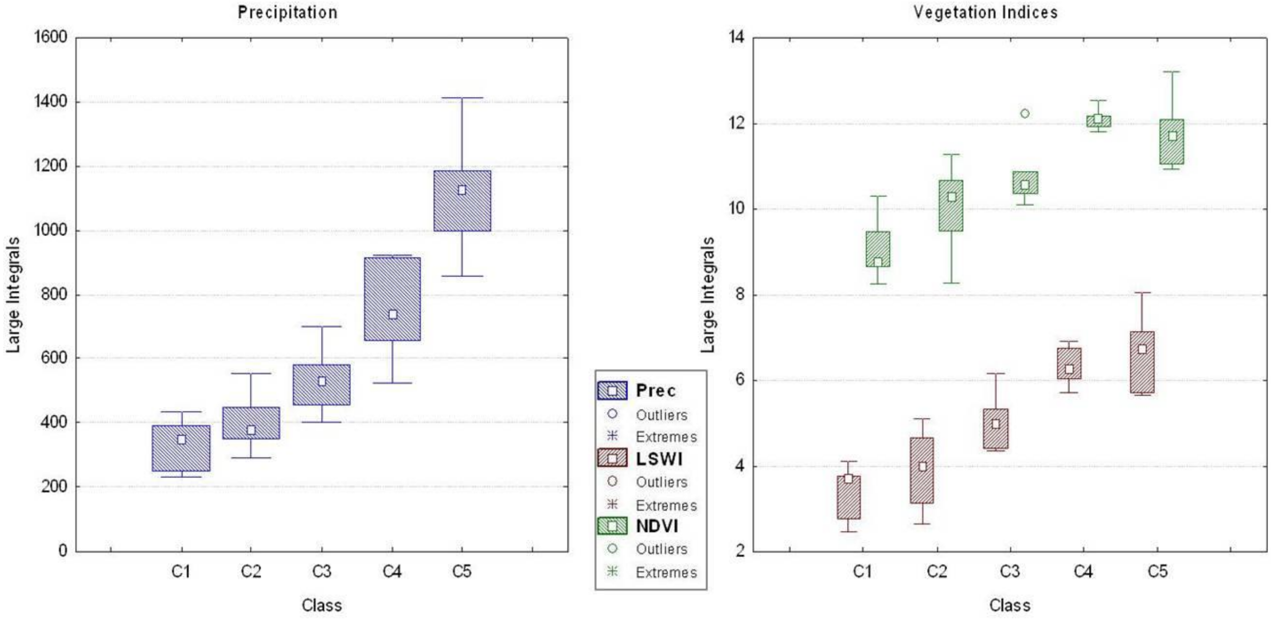


Figure 9. Boxplot of the large seasonal integral for the precipitation and vegetation indices (NDVI and LSWI) identified in seven annual cycles (seasons), 2001-2008.

Figure 10 shows the results of the regression analysis between the integrals of precipitation seasonal cycles (rainy seasons) and vegetation (NDVI and LSWI) growing cycles, where integrals of precipitation are equivalent to the total precipitation in the rainy season, and integrals of vegetation to plant primary productivity of each cycle. These results show that the relationship between precipitation and vegetation is not linear but adjusted to a logarithmic function. This means that in regions with strongly pronounced seasonality (semi-arid and arid regions), precipitation increasing accompanying rapid vegetation increasing, as seen in the increase of both NDVI and LSWI values, on the other hand, in regions with higher rainy season, the same precipitation increasing are accompanied by smaller vegetation increasing, when compared to drier regions.

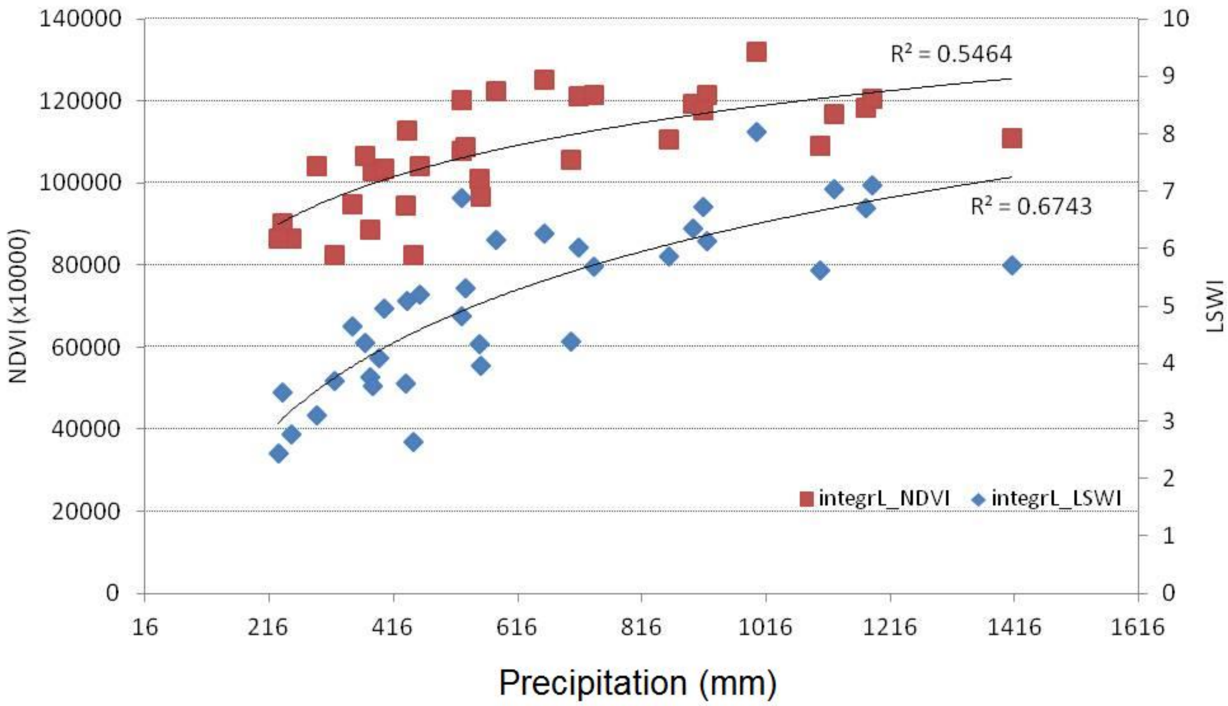


Figure 10. Influence of the rainy season in the vegetation growing cycle obtained from NDVI and LSWI values. integrL is the large seasonal integral metric and represents the integration of the seasonal cycle profile of the precipitation, NDVI and LSWI variables, in the Caatinga region.

Regarding the relationship between both indices, NDVI and LSWI, we found high correlation between them. The analysis of the relationship between precipitation and both vegetation indices indicates that LSWI (r2 = 0.67) showed a better fit with precipitation than NDVI (r2 = 0.55), this due to the LSWI capacity to monitor the vegetation moisture content in the Caatinga region, where much of the vegetation is subject to strong water stress. On the other hand, in areas of high vegetation density, NDVI tends to sature easier than LSWI.

**Conclusion**

Our results support the use of the LSWI indices, as indicator of the vegetation water status. We observed that, in climatological classes with higher precipitation the vegetation was more resistant to the drought, when compared to the vegetation presented in the climatological classes with lower precipitation, which show higher sensibility to water stress. Although NDVI is a good indicator of vegetation biomass, LSWI was the index that allowed to relate better the peaks of vegetation growing season to high humidity levels. The use of climatological classes was efficient to characterize the vegetation behaviors, allowing to split the NDVI intervals in regions with high and low native vegetation soil cover.

Therefore, our results support the hypothesis that the seasonality of Caatinga vegetation is highly correlated to the local precipitation.

The use of filtering technique by Savitzki-Golay improved the identification of the seasonal cycles in the time series evaluated allowing us to identify and characterized the phenology cycles and the inter-annual climate fluctuation. The large seasonal integral, looking at the entire rainy period and vegetation growth, allowed the evaluation of climatic and phonological parameters throughout the climatological classes. The relations between the integral equations, adjusted to a logarithmic curve, indicate a direct influence of the wet season precipitation on plant growth and biomass content. The best adjust for the equations with LSWI ($r^2$ = 0,67) instead NDVI ($r^2$ = 0,55), highlighting the LSWI potential to monitor the humidity content in Caatinga vegetation. Next steps should include greater time series analysis and land use classes.

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