Title

Large scale pre-rain vegetation green up across Africa

Running head

Pre-rain vegetation green up

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Abstract

Information on the response of vegetation to different environmental drivers, including rainfall, forms a critical input to ecosystem models. Currently, such models are run based on parameters that, in some cases, are either assumed or lack supporting evidence (e.g., that vegetation growth across Africa is rainfall-driven). A limited number of studies have reported that the onset of rain across Africa does not fully explain the onset of vegetation growth, for example, drawing on the observation of pre-rain flush effects in some parts of Africa. The spatial extent of this pre-rain green-up effect, however, remains unknown, leaving a large gap in our understanding that may bias ecosystem modelling. This paper provides the most comprehensive spatial assessment to-date of the magnitude and frequency of the different patterns of phenology response to rainfall across Africa, and for different vegetation types. To define the relations between phenology and rainfall, we investigated the spatial variation in the difference, in number of days, between the start of rainy season (SRS) and start of vegetation growing season (SOS); and between the end of rainy season (ERS) and end of vegetation growing season (EOS). We reveal a much more extensive spread of pre-rain green-up over Africa than previously reported, with pre-rain green-up being the norm rather than the exception. We also show the relative sparsity of post-rain green-up, confined largely to the Sudano-Sahel region. While the pre-rain green-up phenomenon is well documented, its large spatial extent was not anticipated. Our results, thus, contrast with the widely held view that rainfall drives the onset and end of the vegetation growing season across Africa. Our findings point to a much more nuanced role of rainfall in Africa's vegetation growth cycle than previously thought, specifically as one of a set of several drivers, with important implications for ecosystem modelling.

Introduction

The African continent contains the world's largest area of savanna and around 17% of the world's tropical forests. Savannas alone account for 30% of the primary production from global terrestrial vegetation, underlining the importance of the African vegetation (Grace *et al.*, 2006). Indeed, African vegetation contributes 38% of the global climate-carbon cycle feedback (Friedlingstein *et al.*, 2010). In spite of this, African vegetation is relatively under-studied (Adole *et al.*, 2016), and the few existing vegetation models are associated with significant uncertainties (Scheiter & Higgins, 2009; Hemming *et al.*, 2013). Another fundamental concern is the vulnerability of African vegetation to climate change, further worsened by interactions between changes in climatic drivers and anthropogenic land use, which puts at risk both the condition and the amount of overall vegetation cover (IPCC, 2014). Apart from their role in global carbon sequestration, the savannas and forests of Africa support a large number of ecosystem services, which are also vulnerable to climatic and anthropogenic changes; for example, the perceived threat to livestock farming and production due to expanding woodlands (Skowno *et al.*, 2016), and reduced crop productivity caused by increasing temperatures and changes in precipitation (Brown & Funk, 2008). These ecosystem services, in addition to their functions, are influenced heavily by the condition of vegetation and its seasonality (Brottem *et al.*, 2014), which could lead to multiple feedbacks into the climate system (Keenan *et al.*, 2014; Buitenwerf *et al.*, 2015; Wu *et al.*, 2016). In the context of anthropogenic, agro-climatic and climate changes, which may affect future ecosystem services, greater understanding of vegetation dynamics across Africa and its drivers is crucial.

In recent years, the importance of phenology has increased as a result of a wide range of empirical-, modelling- and meta-analysis-based evidence, suggesting that long-term changes in key phenological parameters such as the start of season and end of season are key indicators of biological impact resulting from climate change (Cleland *et al.*, 2007; Richardson *et al.*, 2013). Moreover, the role of several climatic factors has been identified in the seasonal timing and seasonal productivity of vegetation cycles (Ma *et al.*, 2015; Shen *et al.*, 2016). Specifically, in arid and semi-arid environments water availability is deemed to be the primary factor controlling vegetation seasonality and growth (Zhang *et al.*, 2005; Chidumayo, 2015). Of particular interest is the close linkage between precipitation and vegetation growth. Studies have suggested that rainfall control of vegetation greening trends (Hickler *et al.*, 2005; Martínez *et al.*, 2011) was associated with the 1980s recovery of vegetation growth from the Sahelian droughts (Olsson *et al.*, 2005). Likewise, parameters estimated from seasonal growth patterns of vegetated land surfaces have been shown to be correlated with derivatives of rainfall data (Zhang *et al.*, 2005; Guan *et al.*, 2014; Verger *et al.*, 2016). The start of vegetation growing season (SOS) and start of raining season (SRS) have been shown to be highly correlated by several researchers (Zhang *et al.*, 2005; Guan *et al.*, 2014). Despite these general findings, the dynamics of vegetation growth are not identical in areas with similar rainfall regimes, suggesting that rainfall alone does not satisfactorily explain vegetation growth patterns. For example, non-climatic greening was observed in some parts of sub-Saharan Africa (Hoscilo *et al.*, 2014), and no significant relationship was found between SOS and SRS in the northern Sahara desert (Yan *et al.*, 2016).

"Pre-rain green-up" is an interesting phenomenon whereby vegetation growth starts at the end of the dry season, just before the start of the rainy season (Ryan *et al.*, 2017). This phenomenon has been observed as far back as the 1940s in some woody species at the field scale (Miller, 1949). With the emergence of remote sensing of land surface phenology (LSP) (defined as *"the seasonal pattern of variation in vegetated land surfaces observed from*

remote sensing" (Friedl *et al.*, 2006)), pre-rain green-up has now been observed across larger areas, but mostly in African woodlands (Guan *et al.*, 2014; Ryan *et al.*, 2017; Yan *et al.*, 2017). However, the number of studies is limited and does not describe the nature and extent of this relationship at the continental scale. Similarly, only a few studies undertaken at the regional scale have attempted to investigate the lag between the end of rainy season (ERS) and the end of vegetation growing season (EOS) in Africa (Zhang *et al.*, 2005; Yan *et al.*, 2017). Therefore, detailed quantification of the magnitude and frequency of this pattern across different vegetation types at the continental scale is currently needed. Consequently, this research seeks to answer the following questions:

(1) what is the magnitude and spatial distribution of the time lags between vegetation phenophases and rainfall parameters across the different vegetation types in Africa?

(2) what is the magnitude of the association between vegetation phenological and rainfall parameters across the different vegetation types in Africa?

Understanding the relationships between LSP and rainfall parameters is critical in developing a robust phenological model and LSP representation in terrestrial ecosystem models. Currently, most global land-atmosphere models have shown varying projections of vegetation response to climate change, associated with large uncertainties in the terrestrial carbon cycle (Shao *et al.*, 2013). These uncertainties are known to arise from inaccurate estimation of seasonal productivity patterns (Restrepo-Coupe *et al.*, 2017), incorrect assumptions in biosphere–atmosphere process models driven by vegetation growth (Whitley *et al.*, 2016), and poor understanding of functional responses of vegetation phenology to climate change (Richardson *et al.*, 2012). Moreover, current climate change models predict uneven rainfall distribution both in terms of timing and amount across the continent; some areas are expected to receive excess rainfall, whereas other regions are expected to receive less (Res *et al.*, 2001;

Niang *et al.*, 2014). This in turn, will affect the vegetation phenology and the resulting vegetation-atmosphere feedbacks such as albedo, water, energy and gas fluxes across the region (Wu *et al.*, 2016).

We used satellite remote sensing and meteorological data to quantify the lag in number of days between SRS and SOS, and ERS and EOS. We further examined the relationships between a range of LSP and rainfall parameters, including the length of growing season (LOS) with length of raining season (LRS), and time of maximum vegetation growth (VItmax) with time of maximum rain (Rtmax), across all of Africa. The productivity-based relationship between Integrated EVI (IntEVI) and cumulative annual rainfall (Rcum) was also explored.

By investigating the above relationships, we provide the most comprehensive and detailed view of the response of vegetation phenological variables to rainfall across Africa, by vegetation type. This greater insight into the mechanisms underlying African vegetation dynamics provides useful information necessary to support and increase the accuracy of future terrestrial biosphere models (TBMs) and global ecosystem models.

Materials and methods

MODIS data and pre-processing

This study used the Moderate Resolution Imaging Spectroradiometer (MODIS) products (Justice *et al.*, 1998) for LSP estimation and land cover classification. These products were downloaded from NASA's LP DAAC (https://lpdaac.usgs.gov/).

The MODIS/Terra Surface Reflectance 8-Day L3 Global 500 m data (MOD09A1) from February 2000 to June 2016 were selected for LSP estimation. Apart from the delivery of relatively fine spatial detail, the 500 m spatial resolution was selected because it has the spectral bands required to derive the Enhanced Vegetation Index (EVI). These bands are currently absent in finer spatial resolution MODIS data such as the MOD09Q1 and MOD13Q1. The EVI was developed with the inclusion of the blue reflectance band (B) to correct for atmospheric scattering effects and soil background influences (Huete *et al.*, 2011). It is derived according to the following equation:

$$EVI = G * \frac{(NIR - Red)}{(L + NIR + C1 * Red - C2 * Blue)}$$

where the coefficients are L=1 (canopy background adjustment factor); C1= 6 and C2 = 7.5 (aerosol correction factors); and G = 2.5 (gain factor) (Huete *et al.*, 2011).

The EVI was also designed to increase sensitivity in large vegetative biomass regions, consequently overcoming the problems associated with vegetation indices like the normalized difference vegetation index (NDVI) (Huete *et al.*, 2002). Prior to deriving the EVI, residual atmospheric and sensor effects were filtered out and only pixels of the highest quality, which had all possible corrections of MODIS Land Quality Assessment (MODLAND QA), were retained. This was done using the quality assessment procedure as detailed in https://lpdaac.usgs.gov/sites/default/files/public/modis/docs/MODIS_LP_QA_Tutorial-3.pdf ensuring that only high quality pixels were used for this analysis. This involved computing 36 different combinations of MODIS land surface reflectance quality parameters from the 32-bit Science Data Set (SDS) Quality Assurance (QA) layer (the 500 m Reflectance Band Quality). All measurements not within these 36 parameters were filtered out, ensuring that only pixels that were atmospherically and adjacently corrected, and of the highest quality on all bands were retained. To produce a time-series of EVI appropriate to analysing the complex growing seasons in Africa, a “cycle” of approximately two years (i.e., 86 “stacked” layers) of EVI data (i.e., the end of July of year 1 to June of year 3) was used. This long cycle was produced to capture yearly estimates of seasonal phenological parameters across Africa, because start of growing season in the northern latitudes commences much earlier in the year than in the southern latitudes.

To define the vegetation types in Africa, we used the 17-class International Geosphere Biosphere Programme (IGBP) global vegetation classification scheme (Friedl *et al.*, 2002, 2010) from the MODIS/Terra Land Cover Type Yearly L3 Global 500 m data (MCD12Q1). We carried out a reclassification, merging similar classes of plant functional types in the IGBP scheme that differ based on extent of canopy cover only, but have similar phenological behaviour. Table 1 shows the 17 classes and the reclassification applied. Croplands and cropland/natural vegetation mosaic were not merged together because cropland/natural vegetation mosaic is a mixture of croplands, forests, shrublands, and grasslands, which may not be sufficiently well defined for use in modelling the pattern of cropland responses to seasonal rainfall. Homogeneous pixels over the 13 years record of the MCD12Q1 were extracted and used to stratify the land cover into their different vegetation types. Five major classes were derived: (1) Croplands, (2) Forest (Deciduous and evergreen forest), (3) Grasslands, (4) Shrublands (Closed and open shrublands), and (5) Woodlands (Woody savannas and savannas) (see Table 1 and Figure 1). However, due to the limited spatial extent of deciduous forest, and persistent clouds in forested areas, further investigation of the forest category was not considered as estimates of LSP may not be reliable.

CHIRPS data

This study used the 0.05º gridded rainfall dataset from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). This dataset was generated by combining satellite sensor and station data using smart interpolation techniques, and has been shown to have less bias in examining wet seasons than most other products, especially in data-sparse regions in Africa (Funk *et al.*, 2015). It has also been shown to be more precise in estimating the entire seasonal cycle of rainfall because it is spatially more detailed and corresponds more closely to ground data (Toté *et al.*, 2015). As with the MODIS data, 16 years of daily rainfall data from 2000 to 2016 were downloaded from CHIRPS (http://chg.geog.ucsb.edu/data/chirps/).

LSP estimation

Several methods have been used to estimate LSP from time-series of vegetation indices (VI)(Atkinson *et al.*, 2012). These methods usually involve a stepwise approach beginning with the removal of "bad" pixels in the time-series, interpolation of the missing values, smoothing of the complete time-series, and estimation of the LSP parameters. In this research, we used the algorithm from Dash *et al.* (2010) and Pastor-Guzman *et al.* (2018) to remove "bad" pixels and interpolate missing values in the EVI time-series. Then the Discrete Fourier Transform (DFT) (Atkinson *et al.*, 2012) was employed to smooth the data temporally.

The inflection point-based method, which considers points where maximum rate of change occurs in the time-series, was used to estimate the LSP parameters. This method, which has been used extensively, captures explicitly the start and end of growing seasons as there are no pre-defined thresholds (Dash *et al.*, 2010; Qader *et al.*, 2015). A schematic diagram of the methodology is shown in Figure 2. Five LSP parameters (Start of growing season (SOS), End of growing season (EOS), Length of growing season (LOS), time of maximum EVI (VItmax), and Integrated EVI (IntEVI)) were estimated for each cycle (Figure 3). This led to yearly estimates of each LSP parameter for a total of 15 years (2001 – 2015). The derived MODIS Land cover classes were used as a mask to select class-specific LSP parameters.

Estimation of rainfall parameters

The start of rainy season (SRS) and end of rainy season (ERS) have been determined in a variety of ways, and there is still no consensus on the most appropriate definition. Examples can been seen in Liebmann *et al.* (2012) and Yan *et al.* (2016) who employed the climatological anomalous accumulation method in determining the start and end of rainy season, and Zhang *et al.* (2005) and Guan *et al.* (2014) who employed the percentage method. In this research, we adopted the definition first proposed by Stern *et al.* (1981), and used by several researchers and meteorological agencies (Sarria-dodd & Jolliffe, 2001; Segele & Lamb, 2005; Mupangwa *et al.*, 2011). This method defines SRS as the first period of two to 10 days where specified amounts of rainfall (10, 20, 30 mm) are reached or exceeded followed by no continuous dry period of specified length (7, 8, 10 days). This approach was selected as it is designed to also account for sowing dates in croplands to remove false start dates. To determine the wet and dry periods, a threshold was set to differentiate between wet and dry days. All wet days had at least 0.1 mm rainfall and others below this threshold were classed as dry days (Sarria-dodd & Jolliffe, 2001). Two sets of criteria were adopted to determine the SRS: (1) the first wet day in a 40-day duration after a dry spell where the total rainfall in the first consecutive 10 days is 25 mm or more, which is followed by no consecutive dry period of seven days or more, (2) the first wet day in a 30-day duration after a dry spell where the total rainfall in the first consecutive three days in a row is 15 mm or more, which is followed by no consecutive dry period for 10 days or more. If one of the criteria is not met, then testing resumes considering the other. End of season dates were defined as dates after the start of season where no rain occurs over a period of 20 days or, in a 30-day duration, the total number of wet days is less than four (Zhang *et al.*, 2005).

Due to the complexity of rainy seasons in Africa, especially for regions with a bimodal annual rainfall cycle, results were rigorously cross-checked again for false starts. This involved an iterative procedure to check if start dates occurred around 10% accumulation of the total annual precipitation and end dates occurred after 95% accumulation of total annual precipitation. In addition, spatial agreement was seen in the results when compared with previous studies on seasonal rainfall onset and end date retrievals (Zhang *et al.*, 2005; Brown & de Beurs, 2008; Liebmann *et al.*, 2012; Guan *et al.*, 2014). Other rainfall parameters derived were: the length of rainy season (LRS) which is the number of days between SRS and ERS, time of maximum rainfall (Rtmax) and cumulative annual rainfall (Rcum).

Statistical approach

All LSP parameters were aggregated to match the spatial resolution of the rainfall data by assigning the modal value in 10 by 10 0.005^0 grid cells to a 0.05^0 grid cell. The mode was used because the mean can be skewed due to the occurrence of outliers, and the median is less representative of the average of a dataset. Pixels showing no clear vegetation seasonality were excluded from the analysis. Pixels with no distinct rainfall seasonality for the entire time-series were also excluded.

The lag, which is the time difference in number of days between SOS and SRS, and EOS and ERS, was calculated for each land cover type. A -10 and 10 days “no change” category was applied to the start of growing and rainy season lags to account for uncertainties in the SOS and SRS estimates and the MODIS 8-day composites. This range was selected because lags of less than 10 days may sometimes arise due to the difference in the Julian date of the MODIS 8-days composite and the daily rainfall data. Further analysis involved fitting linear regression models to determine the association of spatial shifts with the means of different combinations of LSP and rainfall parameters (Table 2).

Results

Frequency of lags between LSP and rainfall parameters across Africa

The difference between the SRS and SOS can be classified into three categories: SOS arriving (a) before, (b) after, and (c) at the same time as the SRS. Figure 4 presents these differences for cropland, grassland and woodland. Croplands fell mostly in the second category showing SOS arrival after SRS, while grasslands fell into two categories: SOS arriving at the same time as SRS and SOS arriving before SRS. For woodlands, however, SOS arrived much before the SRS.

Across Africa, SOS generally occurred prior to the SRS except in the Sudano-Sahelian region were SOS occurred after the SRS (Figure 5). The distribution of the pixels seen in Figure 5c is skewed towards positive lag values with more occurring between 15 and 45 days (i.e., SOS before SRS). More than 88% of the studied vegetative area had SOS arriving more than 10 days before the SRS, of which 90% was found in woodlands. This phenomenon was distributed across all of Africa, but was ubiquitous in southern Africa, with longer lags concentrated in Angola and Zambia. An estimated 9% of pixels had lags of between -10 and 10 days (i.e. SOS and SRS arriving almost at the same time), with over 90% of these occurring in woodlands. As seen in Figure 5, approximately 3% of the studied vegetation, mainly along the Sudano-Sahelian region, had SOS arriving 10 days or more after the SRS (i.e. < -10 days lag), with over 35% of this area belonging to croplands and about 46% to woodlands. Greater areas of cropland with longer lag times were observed in eastern Africa, particularly in Ethiopia, while woodlands were mostly located in western Africa.

Figure 6 shows the distribution of the lag occurrences within each land cover type. Within cropland, an estimated 10% of pixels had SOS arriving at the same time as the SRS, and over

80% had SOS arriving after the SRS. The average lag times for croplands were -18 days in the north and 54 days in the south. In contrast, over 89% of woodlands had SOS arriving before the SRS, with averages of 29 days in the north and 36 days in the south, with longer lag times in the southern woodlands (Figure 5). Grasslands and shrublands had very similar onset lag patterns, with an early SOS before the SRS in over 80% of pixels with average lags of 38 and 34 days, respectively.

In contrast to the SOS, the EOS generally lagged behind the ERS across all Africa (Figures 4 and 7) with a longer lag duration in southern Africa. Interestingly, the Sudano-Sahelian region also exhibited a distinct lag range of between 90 to 120 days with peaks in western and eastern Africa of 120 to 150 days. In addition, the distribution of pixels (Figure 8c), unlike that for SOS, had several peaks within a wide range of values (50 to 120 days). Over 90% of pixels had a lag of between 30 to 150 days, with the longest durations occurring in woodlands. While most land cover types had varied lags, the lag for over 70% of grasslands varied between 30 to 60 days.

In relation to the season lengths (LOS and LRS), areas with SOS arriving after SRS had shorter LOS (Figure 8), when compared to those with SOS arriving before SRS. The average LOS within these pixels varied between 220±30 days to 250±40 days while those with SOS arriving before SRS varied between 270±45 days to 300±30 days. The LRS within both categories of pixels varied greatly, and no observable pattern was detected.

Spatial relations between LSP and rainfall parameters

Table 2 shows the complex set of spatial associations between LSP and rainfall parameters (all statistically significant at $p < 0.0000$). While a large association was seen between SOS and SRS (R^2= 0.92), IntEVI and Rcum (R^2= 0.58), and VItmax and Rtmax (R^2= 0.52), other combinations of LSP and rainfall parameters showed very little correlation, especially between EOS and ERS, and LOS and LRS. Interestingly, for grasslands, EOS and ERS, and LOS and LRS produced large R^2 values of 0.76 and 0.87, respectively. The same large association was seen across all LSP and rainfall parameters for grasslands. In contrast, only the timings of onset (i.e., SOS and SRS), maxima (i.e., VItmax and Rtmax) and production (IntEVI and Rcum) produced large R^2 values for woodlands. Although, statistically significant, the correlations between EOS and ERS, LOS and LRS, and LOS and Rcum were very small for woodlands. The same association was observed in shrublands between LOS and Rcum. In contrast, a small association was found between SOS and SRS, and between IntEVI and Rcum, in shrublands when compared to all other land cover types.

For croplands, similar to most land cover types (excluding grasslands) the correlation between LOS and LRS was small. In addition, only a small association was observed between VItmax and Rtmax for croplands. However, large correlations were observed for SOS and SRS, and LOS and Rcum.

Discussion

Early and late greening response of vegetation to rainfall

Our results suggest that pre-rain vegetation green-up occurs across most of Africa. The results are corroborated by the pre-rain green-up reported previously by a limited set of studies, both ground-based (Childes, 1989; De Bie *et al.*, 1998; Higgins *et al.*, 2011; Seghieri & Do, 2012; February & Higgins, 2016) and satellite-based (Guan *et al.*, 2014; Ryan *et al.*, 2017; Yan *et al.*, 2017). However, we show that the pre-rain green-up is far more widespread across the entire African continent than previously reported. In addition, we were able to determine quantitatively its occurrence across all the major vegetation types studied, confirming its prevalence mostly in woodlands and grasslands in northern and southern Africa. Our findings show that more pre-rain green-up occurred in woodlands, sometimes as much as 3 months before the onset of rain. This pattern of pre-rain green-up in woodlands was more widespread in the southern part of Africa, consistent with previous work (Ryan *et al.*, 2017).

Several explanations have been proposed for the observed pre-rain green-up. It was suggested that a form of memory mechanism developed from adaptation to previous climatic cues could be responsible for early greening (by about two months) in Miombo woodland in central and southern Africa (Goward & Prince, 1995). Also implicated were daylength and temperature thresholds being responsible for early greening of certain woody plant species in southern Africa (Van Rooyen *et al.*, 1986). Responses of plants to other anticipatory climatic factors besides rainfall have also been reported in the Australian savanna (Prior *et al.*, 2004; Bowman & Prior, 2005). In Senegal, where we also observed pre-rain green-up, it was suggested that air relative humidity occasioned by the Inter-Tropical Convergence Zone (ITCZ) is a major determinant of early leaf flush in this region (Do *et al.*, 2005). Other mechanisms primarily located within plants have been proposed by several researchers. One of these is the rehydration of stem tissues in the dry season caused by reduction in water stress levels following leaf shedding (Reich & Borchert, 1982; Borchert, 1994; Williams *et al.*, 1997). During this rehydration process, when the required water potential for plant cellular development is attained, early leafing begins (Reich & Borchert, 1982). The phreatophytic nature of some woody plants (their ability to tap underground water reserves with deep root systems, and utilize the previous season's water and nutrients) and low water consumption have also been suggested to cause early green up (Roupsard *et al.*, 1999; Guan *et al.*, 2014). Similarly, the ability of some woody plants to withdraw and conserve nitrogen and carbon for later use to construct new leaves from these stored reserves has been implicated in early green up (February & Higgins, 2016). These features give savanna trees competitive advantage over their herbaceous neighbours, which can drive temporal niche separation; a possible explanation for pre-rain green-up (Higgins *et al.*, 2011; February & Higgins, 2016; Ryan *et al.*, 2017). Another interesting phenomenon, which may have influenced the pre-rain green-up observed in western Africa, is the reverse phenology of the widely distributed *Faidherbia albida* (Acacia) tree (Roupsard *et al.*, 1999; Seghieri & Do, 2012). This species enters leaf out during the dry season and sheds leaves during the rainy season. As described above, its unique facultative phreatophytism and low water consumption are responsible for the reversed phenological pattern. Besides climatic or endogenously plant-controlled causes of early greening, biotic factors such as pressures from herbivory have been hypothesised as reasons for early initiation of leafing in some woody plants (Aide, 1988, 1992). It was suggested that this is an antiherbivore defence mechanism by plants, essentially to escape seasonally from herbivores in order to avoid nutrient losses caused by herbivory (Aide, 1992; Rossatto *et al.*, 2009). However, evidence supporting this strategy in Africa savannas is unavailable (Higgins *et al.*, 2011).

Contrary to previous work (Guan *et al.*, 2014), our findings showed pre-rain green-up occurring in the vast majority of grasslands across Africa, albeit with a short duration, mostly within 10 to 30 days. This can be attributed to SOS being triggered by the small bouts of rains that occur just before the actual start of the rainy season. This is possible because grasslands have very high sensitivity to water fluctuations (Scholes & Archer, 1997; Whitecross *et al.*, 2017). In addition, the large R^2 values in Table 2 also suggest this tight coupling of grasslands and water availability across the continent. Our results also showed that pre-rain green-up occurred in some of the shrublands which can be explained by their deep root systems (Childes, 1989).

In contrast to other land cover types, post-rain green-up was largely observed in croplands, all located in the Sudano-Sahelian region (Figures 5 and 6). This region consists mainly of croplands (Figure 1), and is known to have a short rainy season and prolonged dry season (Liebmann *et al.*, 2012; Dunning *et al.*, 2016) (Figure 8). This lengthened dry season usually influences farmers' decision to begin sowing, because despite relying to some extent on climatological history, they generally wait for a major burst of rain and ascertain the status of the soil moisture before commencing sowing (Marteau *et al.*, 2011). The variety of crops being cultivated can also explain the post-rain green-up observed. For example, the different species of millet and sorghum sown are largely dependent on water availability for growth, and these are the main staple crops in the Sudano-Sahelian region, cultivated mostly under rainfed conditions (Guan *et al.*, 2015).

Woodlands and shrublands found in the Sudano-Sahelian region revealed post-rain green-up. Leafing of dominant woody plants in this region is controlled by rainfall and, as mentioned above, this is caused by the occurrence of marked shorter rainy seasons (Seghieri *et al.*, 2009). The woody plants in this region endure long dry seasons of over 8 months. Hence, they depend on the occurrence of the first rains to begin leafing (Seghieri *et al.*, 2009; Seghieri & Do, 2012).

The early and late greening responses of vegetation also influence the lag between ERS and EOS. For example, longer EOS lags were evident in vegetation with pre-rain green-up phenological patterns. According to several researchers, this early greening before the onset of rains enables plants to obtain early access to, and optimally utilize, nutrients released during the first rains; hence, the longer growing season for such plants (Do *et al.*, 2005). Nevertheless, long EOS lag durations were observed in the Sudano-Sahelian region, especially in croplands with post-rain green-up. As mentioned above, the variety of crops affects the phenological pattern. Crops such as cassava, grown mostly in western Africa, are usually harvested 9 to 18 months after sowing (Ezui *et al.*, 2016), thus, leading to long lags between the ERS and EOS.

Relationships between LSP and rainfall parameters

Consistent with previous studies (Zhang *et al.*, 2005; Guan *et al.*, 2014), our analysis revealed large correlations between SOS and SRS across Africa. Notwithstanding this large correlation, vegetation green-up is not driven by rainy season onset as plants green-up early, prior to the rainy season onset. This phenomenon suggests that other factors may have a much greater influence over the onset of the vegetation growing season. However, large correlations were observed for all the major vegetation types in this study, except for shrublands (

Table), and this is influenced by the spatial variability in SOS dates across Africa (Adole *et al.*, 2018).

The EOS and ERS had a small association for woodlands and croplands, but large association for shrublands and grasslands. This was expected as the EOS for woodlands extends much later than for ERS. Similarly, because the end of the crop growing season depends largely on sowing date and the variety of crops grown (Brown & de Beurs, 2008), only a small correlation between ERS and crop EOS was expected. The tight coupling of grasslands to water explains the large correlation observed for grasslands, and the large associations between all other grassland LSPs and rain parameters analysed in this study (Table 2).

The LOS and the total amount of annual rainfall across Africa produced a large association. However, only a small association was observed for woodlands between LOS and the total amount of annual rainfall, and between LOS and LRS. This suggests that the length and total amount of annual rainfall does not significantly influence the length of growing season for woody vegetation. One reason for this could be the ability of woody plants to minimise transpiration over a long period, especially during dry seasons and at the same time maximise photosynthesis (De Bie *et al.*, 1998), thus, leading to a longer LOS than LRS. Nevertheless, the time of maximum greenness produced a large association with time of maximum rainfall, and seasonal integrated EVI produced a large association with total amount of annual rainfall (Table 2). This suggests that rainfall amount affects the seasonal productivity of woodlands. This is in broad agreement with reported increases in productivity in areas with larger amounts of rainfall in some woody species in South Africa (Shackleton, 1999).

From this research, it is evident that while pre-rain green-up is ubiquitous in Africa, post-rain green-up was limited to the Sudano-Sahelian region. From previous studies (Berg *et al.*, 2011; Marteau *et al.*, 2011) and the results of this research, it can be inferred that the post-rain green-up pattern observed in the Sudano-Sahelian region can be explained by the very short, marked rainy season in the region.

The above observations pose serious challenges for existing terrestrial biosphere models (TBMs) and climate change predictions (Ryan *et al.*, 2017). Currently, TBMs like the dynamic global vegetation models (DVGM) use only precipitation or soil moisture thresholds in modelling the response of dry deciduous plants to climatic factors (Sitch *et al.*, 2008; Zhao *et al.*, 2013). Some examples of phenological models are the meteorological data-based phenology model (Jolly *et al.*, 2005) and the carbon–nitrogen dynamics (CN) model (Wang *et al.*, 2016). They both depend on seasonal water availability as a cue for vegetation phenology in the tropics. This potentially creates a large bias in estimating phenological events because the parametrisation process in these models does not account for the ubiquitous pre-rain greening phenomenon, which may be triggered by other environmental factors.

Another aspect worthy of consideration in these global change models is the feedback role of phenology on climate, mostly through CO_2 uptake (Peñuelas *et al.*, 2009; Wu *et al.*, 2016). As previously mentioned, the African vegetation contributes 38% of the global climate-carbon cycle feedback, mostly coming from its savanna comprised mainly of woodlands (Friedlingstein *et al.*, 2010). In a changing climate of projected increases in temperatures, droughts, soil moisture drying, and decreases in precipitation in Africa, especially southern Africa (Niang *et al.*, 2014), there could be an accompanying shift in precipitation seasonality and intensity. This could result in the delay or absence of the anticipated moisture support for plant growth at the time needed in pre-rain green up woodlands, with likely consequences on net primary productivity. Consequently, this may influence the vegetation-mediated feedbacks on climate systems (a positive feedback on climate change), because of the possible reduction in CO_2 uptake from the African savannas. Similarly, increasing temperatures may influence vegetation-mediated feedbacks on climate change estimates in pre-rain green up plants. Studies have suggested that temperature increases might have caused increased productivity and growth in some southern African woodlands (Bunting *et al.*, 2016; Davis *et al.*, 2017), therefore, potentially leading to greater CO_2 uptake.

In summary, this research presents a comprehensive classification of the different patterns of LSP responses to rainfall in Africa. It confirms the prevalence of pre-rain green-up in Africa, and further demonstrates that this pattern is more widespread across the continent than previously reported. Additionally, we found that both pre-rain and post-rain green-up had a significant influence on EOS lags across different vegetation types. We were also able to quantify the frequencies of these LSP responses (pre-rain and post-rain) across different vegetation types in Africa and provided supporting evidence from previous studies, mostly ground-based. These findings and other advances in phenological studies were possible because of remote sensing methods (Archibald & Scholes, 2007; Studer *et al.*, 2007). As such, the findings are subject to the common limitations associated with these techniques. Examples of limitations are the potential influences from smoothing and LSP estimation techniques, and influences from the type of sensor (Atzberger *et al.*, 2013). Notwithstanding these limitations, the findings and the supporting literature suggest that rainfall is not the only major environmental factor controlling initiation and cessation of vegetation seasonality in Africa. It proposes that although rainfall is important in vegetation growth (as seen in the large correlations between the rainfall and phenological parameters), other environmental factors, and the interplay between these factors, are likely to exert a greater influence on the onset and end of seasonal vegetation growth patterns. Temperature and photoperiodicity have been suggested to be among the most important factors triggering onset of growing season across Africa. The effect of these other factors and the related role of rainfall in seasonal vegetation growth needs to be investigated at the continental scale to advance our understanding of natural ecosystem processes in Africa and their representation in terrestrial biosphere models. This is especially important, considering the need to understand the likely responses of pre-rain green-up under a changing climate, and how these responses might influence global climate change on vegetation-atmosphere feedbacks.

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Tables

Table 1: Reclassification of land cover types into broad categories based on the International Geosphere Biosphere Programme (IGBP) global vegetation classification scheme.

IGBP number	Initial land cover types	Merged land cover type
1	Evergreen needleleaf forest	Forest
2	Evergreen broadleaf forest	
3	Deciduous needleleaf forest	
4	Deciduous broadleaf forest	
5	Mixed forest	
6	Closed shrublands	Shrublands
7	Open shrublands	
8	Woody savannas	Woodlands
9	Savannas	
10	Grasslands	Grasslands
12	Croplands	Croplands
14	Croplands/natural vegetation mosaic	Croplands/natural vegetation mosaic
11	Permanent wetlands	Non-vegetative cover
13	Urban and built-up land	
15	Permanent snow and ice	
16	Barren or sparsely vegetated	
17	Water	

Table 2: Correlation between LSP and rainfall across space. The associations are reported in R^2 values all at p-value <0.000.

Pheno-rain combinations	**Correlation (R^2) (p-value<0.000) by land cover class**				
	All	**Croplands**	**Grasslands**	**Shrublands**	**Woodlands**
SOS and SRS	0.92	0.70	0.95	0.31	0.97
EOS and ERS	0.10	0.23	0.76	0.50	0.07
LOS and LRS	0.27	0.18	0.87	0.28	0.09
LOS and Rcum	0.34	0.79	0.82	0.04	0.09
IntEVI and Rcum	0.58	0.37	0.55	0.12	0.57
VItmax and Rtmax	0.52	0.28	0.75	0.72	0.69

Figure captions

Figure 1: Reclassified 2013 MODIS land cover product (MCD12Q1).

Figure 2: Flowchart describing the study methodology in three major steps: (1) data processing, (2) data analysis and (3) statistical analysis.

Figure 3: An illustration of LSP parameters used in this research. Black line illustrates smoothed time-series, (a) Start of season (SOS), (b) End of season (EOS), (c) Length of season (LOS), (d) Time of maximum EVI (VItmax), and (e) Integrated EVI (IntEVI).

Figure 4: Examples of pixel profiles for a complete cycle of EVI and daily rainfall time-series. EVI time-series is represented by green curved lines while rainfall is represented by black bars. Vertical dashed lines show LSP and rainfall parameters (SOS and EOS in green and SRS and ERS in blue). (a) Croplands in the Sudano-Sahelian region showing SOS arriving after SRS, (b) Grasslands in the Sudano-Sahelian region showing SOS and SRS arriving approximately at the same time, (c) Grasslands in southern Africa showing SOS arriving before SRS, and (d) Woodlands in southern Africa showing SOS arriving well before SRS.

Figure 5: Difference in days between SRS and SOS (i.e., SRS - SOS in days). Positive values indicate SOS arriving before SRS while negative values indicate SOS arriving after SRS. (a) Spatial distribution of SOS and SRS difference in number of days. (b) Proportion of pixels by land cover type in different categories of SOS and SRS lag. (c) Frequency distribution of SRS and SOS difference.

Figure 6: Proportion of pixels in each land cover type in the different categories of SOS and SRS lag.

Figure 7: Differences in days between EOS and ERS (i.e., EOS - ERS in days). Positive values indicate EOS arriving after ERS while negative values indicate EOS arriving before ERS. (a) Spatial distribution of EOS and ERS difference in number of days, (b) Proportion of pixels by land cover type in different categories of EOS and ERS lag, (c) Frequency distribution of EOS and ERS difference.

Figure 8: Spatial pattern of the average of LSP and rainfall parameters between 2001 and 2015. (a) SOS and SRS and (b) EOS and ERS (shown in months of the year). (c) LOS and LRS (shown in number of days).