Major trends in the Land Surface Phenology (LSP) of Africa, controlling for land cover change

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Abstract

Monitoring land surface phenology (LSP) trends is important in understanding how both climatic and non-climatic factors influence vegetation growth and dynamics. Controlling for land cover changes in these analyses has been undertaken only rarely, especially in poorly studied regions like Africa. Using regression models and controlling for land cover changes, this study estimated LSP trends for Africa from the Enhanced Vegetation Index (EVI) derived from 500 m surface reflectance Moderate Resolution Imaging Spectroradiometer (MODIS) (MOD09A1), for the period of 2001 to 2015. Overall End of Season (EOS) showed slightly more pixels with significant trends (12.9% of pixels) than Start of Season (SOS) (11.56% of pixels) and Length of Season (LOS) (5.72% of pixels), leading generally to more "longer season" LOS trends. Importantly, LSP trends that were not affected by land cover changes were distinguished from those that were influenced by land cover changes such as to map LSP changes that have occurred within stable land cover classes and which might, therefore, be reasonably associated with climate changes through time. As expected, greater slope magnitudes were observed more frequently for pixels with land cover changes compared to those without, indicating the importance of controlling for land cover. Consequently, we suggest that future analyses of LSP trends should control for land cover changes such as to isolate LSP trends that are solely climate driven and/or those influenced by other anthropogenic activities or a combination of both.

Keywords: Phenology, Time-series analysis, MODIS, Africa, Vegetation, climate change.

1. Introduction

Remote sensing techniques for mapping land surface phenology (LSP), defined “as the seasonal pattern of variation in vegetated land surfaces observed from remote sensing” (M. H. Friedl et al. 2006), provide the capability for long-term observation across large areas, especially those where ground data are lacking (X. Zhang, Tan, and Yu 2014; Julien and Sobrino 2009; X. Zhang, Friedl, and Schaaf 2006; Jeong et al. 2011). Remote sensing has been used to study the response of LSP to climatic and non-climatic factors and has, thus, contributed to increased understanding of climate change impacts on the terrestrial ecosystem. Several authors have used remote sensing to estimate inter-annual trends in LSP (usually related to the timing of specific events). Myneni et al. (1997) was one of the first studies to report a 12 days increase in the length of growing season (LOS) for the Northern Hemisphere during the period 1982–1991 using satellite sensor data. Several other studies have been carried out since then, mostly focusing on LSP trends in the Northern Hemisphere (e. g., Zhou et al., 2001; de Beurs & Henebry, 2005; Delbart et al., 2005; Piao et al., 2007; Julien & Sobrino, 2009; Jeong et al., 2011; Zhu et al., 2012, 2014; Ivits et al., 2012; Zhang et al., 2014; Yang et al., 2015; Liu et al., 2016) with a limited number of studies covering the Southern Hemisphere (Heumann et al. 2007; A Vrieling, De Beurs, and Brown 2008; Anton Vrieling, De Leeuw, and Said 2013; Verbesselt, Hyndman, Newnham, et al. 2010; Verbesselt, Hyndman, Zeileis, et al. 2010; Anton Vrieling, de Beurs, and Brown 2011; Garonna, De Jong, and Schaepman 2016).

The above studies estimate LSP trends over a particular inter-annual period and evaluate the possible drivers for such trends, but do not consider land cover changes as a confounding driver that can significantly influence the observable changes in LSP. This lack of research into the influence of land cover changes on LSP trends has been highlighted previously (Reed 2007; Tang et al. 2015; X. Zhang, Tan, and Yu 2014). Additionally, only a limited number of studies have recognised that other non-climatic factors can significantly influence trends in LSP. For example, Krishnaswamy *et al.* (2014) suggested that other factors besides temperature and precipitation were responsible for browning and greening trends in tropical mountain regions; Olsson *et al.* (2005) suggested that changes in vegetation type were responsible for an increase in greening in the Sahel as rainfall only partially explained increasing vegetation cover; and Verbesselt *et al.* (2010a,b), Ivits *et al.* (2012) and Begue *et al.* (2014) identified land management practices as a major factor influencing phenological changes in South Eastern Australia, Europe and Mali, respectively.

Because of the potentially confounding influence of land cover changes, it would be preferable to control for these changes, for example, by ensuring that only homogeneous pixels (i.e., those that have a constant land cover throughout the entire time-series) are used to characterise inter-annual trends for comparison with changing climate drivers. This would allow separation of those LSP trends that are solely climate-driven from those that are influenced by non-climatic factors. To the best of our knowledge, Jeganathan et al. (2014) may be the only study to have deliberately controlled for land cover changes while analysing inter-annual and seasonal vegetation dynamics.

In addition to the above gaps in research methodology, substantial gaps exist with respect to the study of the vegetation phenology of Africa (Adole, Dash, and Atkinson 2016; IPCC 2014). While it has been shown that other factors besides climate are responsible for some variation in phenology and increases in greenness in different regions of the African continent (Herrmann, Anyamba, and Tucker 2005; Martínez et al. 2011; Polansky and Boesch 2013), studies investigating this phenomenon across the whole of Africa are limited.

This paper represents the first analysis of inter-annual LSP trends in Africa that controls for land cover changes, using MODIS data. The aim was to separate out the LSP trends that are not influenced by (mainly) anthropological disturbances such as deforestation, agricultural land conversion, land management, land degradation, land transformation and urbanization, from trends that may have been influenced by these disturbances.

2. Data and methodology

Moderate spatial and temporal resolution satellite sensor data were used for the analysis, specifically the MODIS/Terra Surface Reflectance 8-Day L3 Global 500 m SIN Grid V005 data (MOD09A1), and MODIS Land Cover Type Yearly L3 Global 500 m SIN Grid V005 data (MCD12Q1). 16 years (18 Feb 2000 – 29 Aug 2015) of MOD09A1 tiles and 13 years (2001 – 2013) of MCD12Q1 tiles covering the entire African continent were downloaded from NASA's LP DAAC (https://lpdaac.usgs.gov/).

2.1. *LSP estimation*

The Enhanced Vegetation Index (EVI), was selected for use in this research (Huete et al. 2002; Reed, Schwartz, and Xiao 2009) and calculated from the MOD09A1 data after residual atmospheric and sensor effects were filtered out in a Quality Assurance (QA) assessment procedure. (see "MODIS Land Products Quality Assurance Tutorial," 2016 for details of the QA procedure).

A time-series cycle of two years EVI stacked data was used to estimate LSP in order to account for non-uniform growing seasons across Africa. The yearly values of Start of Season (SOS), End of Season (EOS) and Length of Season (LOS) in each image pixel for the period of 2001 to 2015 were estimated using the methodology described in (Dash, Jeganathan, and Atkinson 2010). As explained in Dash et al., (2010) the Discrete Fourier Transform (DFT) was applied to smoothen the EVI time-series and to account for the bimodal seasonality and double cropping agricultural systems found in some parts of Africa, the first six harmonics as used. However, only the first season results were considered for this analysis. After smoothing, the LSP parameters used in this study were derived using the inflection point method. This method overcomes the uncertainties of using a pre-defined threshold which may lead to later onset and earlier end of vegetation growing season. An algorithm described in Dash et al., (2010) was used for this study. Beginning from the maximum peak, this algorithm iteratively searches for valley points (change in derivative value). Value points which shows a change in derivative value from positive to negative at the beginning of the growing cycle is the Start of Season (SOS), while a change in derivative value from negative to positive at the decaying end of the phenology cycle is the End of Season (EOS). To ensure the appropriate valley points are identified especially in irregular time-series two major conditions were incorporated into this algorithm: (1) at least four consecutive rising EVI values must be identified before key LSP parameters are defined, and (2) the difference between peak and the valley points must be greater than one fifth of the maximum EVI value. (Schematic diagram of methodology is shown in Figure 1).

2.2. *Land cover change detection and trend analysis*

From the MCD12Q1 global land cover data, the 17-class International Geosphere Biosphere Programme (IGBP) global vegetation classification scheme, was selected for analysis (M. A. Friedl et al. 2010; Scepan and Estes 2001). This product was chosen because of its relatively fine spatial resolution, high temporal frequency and highest overall accuracy when compared to other land cover data (Bai 2010; Bontemps et al. 2012; Giri et al. 2013). Also, it has been shown to be consistent with other land cover classification outputs (He, Lee, and Warner 2017). A reclassification was carried out to group land cover types with similar phenological behaviour into broad categories. Details of this reclassification into broad classes are provided in the

Table **1** and Figure 2. Other classes comprising water, permanent wetlands, barren or sparsely vegetated and urban/built-up areas were excluded from the analysis.

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

Merged land cover type	**Initial land cover types**
Evergreen forest	Evergreen needleleaf forest
	Evergreen broadleaf forest
Deciduous forest	Deciduous needleleaf forest
	Deciduous broadleaf forest
Shrublands	Closed shrublands
	Open shrublands
Woody savanna/savanna	Woody savannas
	Savannas
Grasslands	Grasslands
Croplands	Croplands
Croplands/natural vegetation mosaic	Croplands/natural vegetation mosaic

To estimate the inter-annual LSP trends, two main categories of pixel were analysed based on the nature of their time-series: (1) only pixels with the same land cover in all years of the time-series of 13 years were used to estimate the temporal trends, and these were separable based on the type of land cover and (2) pixels which changed from one land cover class to another were also analysed, but this time to determine if land cover changes significantly influenced the estimated LSP parameters. The latter category was further characterised into sub-groups based on the number of times the land cover had changed in the entire time-series. Only changes in vegetative land cover were considered. These were classified in the following way: 1) changes between two classes only were labelled as "*one change*", for example, a change from grasslands to croplands; 2) changes between three classes were labelled as "*two changes*", for example a change from woody savanna to croplands and then to grasslands or back to savanna; 3) and those pixels that changed land cover types more than three times were labelled as *"> two changes"*, (Woody savanna/savanna - cropland/natural vegetation - grasslands - croplands) (See Figure 2 for spatial patterns of land cover types and the different classes of pixels used in this study).

The Spearman's non-parametric rank correlation coefficient was used to characterise the magnitude and direction of temporal trends in day of year with significance testing (*F*-test at the 95% confidence level). This test was used because of its robustness in relation to identifying trends in non-Gaussian distributed data (A Vrieling, De Beurs, and Brown 2008; Yue, Pilon, and Cavadias 2002). Simple linear regression was then fitted to estimate the magnitude of the trends in number of days per year.

Table 2: Number and proportion of pixels showing significant positive (Sig. pos.) and significant negative (Sig. neg.) trends (p-value < 0.05) in each land cover change class. The *"no change"* class is of greatest interest when analysing trends in LSP because it controls for land cover change (i.e., there was no land cover change in this group).

Land cover change category	**Proportion of pixels in each category**	**SOS**				**EOS**				**LOS**			
		Number of pixels		**Proportion of pixels**		**Number of pixels**		**Proportion of pixels**		**Number of pixels**		**Proportion of pixels**	
		Sig. pos.	**Sig. neg.**	**Sig. pos.**	**Sig. neg.**	**Sig. pos.**	**Sig. neg.**	**Sig. pos.**	**Sig. neg.**	**Sig. pos.**	**Sig. neg.**	**Sig. pos.**	**Sig. neg.**
No change	75%	676823	286722	2.78%	1.18%	687864	387520	2.83%	1.59%	264082	155223	1.09%	0.64%
One change	18%	854507	217825	3.52%	0.90%	838527	352015	3.45%	1.45%	307371	160246	1.26%	0.66%
Two changes	3%	467500	110228	1.92%	0.45%	474940	162754	1.95%	0.67%	241246	89551	0.99%	0.37%
> Two changes	3%	144460	52850	0.59%	0.22%	195508	54218	0.80%	0.22%	144022	28400	0.59%	0.12%
Total	100%	2143290	667625	8.82%	2.75%	2196839	956507	9.04%	3.93%	956721	433420	3.94%	1.78%
Overall sig. (+ & -)		**2810915**		**11.56%**		**3153346**		**12.97%**		**1390141**		**5.72%**	

3. Results

3.1. *LSP trend analysis*

The spatial patterns of SOS for 2001 and 2015 are shown in Figure 3. No clear seasonality was observed in most forested areas in Africa. The LSP trends found to be significant (95% confidence level) were mapped for all LSP parameters, and these mapped trends for SOS are shown in Figure 4. A summary of the significant statistical trends (p-value < 0.05) for all LSP parameters by land cover change group are displayed in Table 2. Overall, less than 13% of pixels in each LSP parameter showed significant trends (see Table 2) and an estimated 70% of these pixels had trends that were significantly positive (i.e., the LSP event date becoming later). For example, of the 12.97% (3,153,346) significant pixels in EOS, 9.04% (i.e., 70% of the total number of significant pixels) were significantly positive.

Table 3 also shows the different combinations of LSP trends in this study. An estimated 9% of the entire continent had delayed SOS dates, with 0.75% resulting in "*delayed longer season*" (i.e. delayed SOS and increased LOS), 1.36% resulting in *"delayed shorter season"* (i.e. delayed SOS and reduced LOS), and 6.62% with no significant LOS trend. Similarly, of the estimated 3% advancing SOS dates, 1.54% led to *"earlier longer season"* (i.e. advanced SOS and increased LOS), 0.05% resulted in *"earlier shorter season"* (i.e. advanced SOS and reduced LOS), and 1.19% resulted in no significant LOS trend (see Table 3). These observations suggest that despite significant shifts in SOS and/or EOS dates, there was less change in LOS, indicating that both SOS and EOS are becoming later or earlier in synchrony, as shown in Table 3.

There were significant EOS trends which led to apparent changes in LOS. For example 0.38% of earlier EOS led to *"shorter season"* and 1.65% of delayed EOS resulted in *"longer season".* In general, significant increases in LOS were associated mostly with delayed EOS (2.4%). That is, over 60% of the significant LOS positive trends was influenced by delayed EOS dates. These were mostly observed in western and eastern Africa. On the other hand, a shorter LOS was mostly due to a delayed SOS and earlier EOS (see Table 3). This shorter LOS was seen in similar geographical sub-regions as observed longer LOS. However, observations were confined to certain regions like northern Nigeria, western Angola and the savannas of central Africa.

Table 3: Observed combinations of changes in SOS and EOS (leading to changes in LOS), showing the percentage of pixels in each combination.

Change in SOS	Change in EOS	Change in LOS	Proportion of area (%)
Earlier	Earlier	Longer season	1.45
Earlier	Earlier	Shorter season	0.05
Earlier	Earlier	-	1.19
Earlier	Delayed	Longer season	0.01
Earlier	-	Longer season	0.08
Earlier	-	Longer season	0.38
Delayed	Delayed	Longer season	0.75
Delayed	Delayed	Shorter season	0.01
Delayed	Delayed	-	6.62
Delayed	Earlier	Shorter season	0.85
Delayed	-	Shorter season	0.50
Delayed	-	Shorter season	1.65

3.2. *LSP trends based on land cover type*

The trends in *"no change"* pixels were identified mainly in woody savanna/savanna and croplands/natural vegetation mosaic. More specifically, 72% of these significant pixels were found in woody savanna/savanna, 16% in croplands/natural vegetation mosaic, 7% in croplands, 4% in grasslands and 1% in shrublands.

Corresponding to the general pattern of SOS becoming later (i.e., more significant positive trends compared to negative trends), woody savanna/savanna had more pixels with trend towards a delayed SOS with a slope of between 2 to 2.4 days year^{-1} across all Africa (spatial pattern of slope magnitudes and frequency distributions are detailed in Figure 5 and Figure 6). A very small proportion of woody savanna/savanna pixels of about 0.4%, distributed in central and eastern Africa, had a trend towards an earlier SOS with a slope of -3 to -4 days year^{-1}. The EOS and LOS trends for woody savanna/savanna were similar to the SOS trends, having more significant positive pixels. However, for woody savanna/savanna the positive LOS trends observed were mostly a result of earlier SOS dates leading to an *"earlier and longer season".* Croplands/natural vegetation mosaic on the other hand had more *"longer season"* LOS trends. This was due to a delayed EOS only, particularly in West African countries like Mali and Senegal. Although there were delayed SOS trends of approximately 2.3 days year^{-1}, similar rates of change in EOS were observed.

3.3. *LSP trends based on land cover change*

Table 2 shows the number and proportion of land cover change events and their corresponding significant trends. The significant SOS trends in the *"one change"* category with 18% of the total number of pixels had 4.41% of the total significant trend, while the *"no change"* category with 75% of the total number of pixels had 3.96% of the total significant trend. In addition, linear regression of a 13 years profile of significant pixels in both the "*one change"* and *"two changes"* categories showed significant shifts in LSP parameters. This can be seen in Figure 7, which shows the time-series for three pixels, one in the (a) *"one change"* category, (b) *"two changes"* category, and (c) *">two changes"* category. In the three cases, the SOS dates shifted from February to June as the land cover changed from woody savanna/savanna to croplands and/or grasslands. The results show that SOS dates were delayed with an average of 9.5 days year^{-1} in both categories of change. In the same way, EOS dates shifted from December to February with an average increase of 5 days year^{-1}. Inevitably, LOS shortened by an average rate of 4 days year^{-1} for both categories of change. However, there was no significant difference between the rate of change in the different land cover change categories.

4. Discussion

Several studies have suggested that significant changes have occurred in Africa's vegetation in recent decades (Zhou et al. 2014; Eklundh 2003; Herrmann, Anyamba, and Tucker 2005; Martínez et al. 2011). It has also been implied that changes in land cover can equally drive changes in the rate of green-up observed from remote sensing methods (Hoscilo et al. 2015), and the findings of this research support this view. It is, therefore, accepted that changes in land cover can significantly influence observed LSP trends and, consequently, any inferences made about the impact of climate changes on vegetation phenology. Analysis of the set of LSP trends across all of Africa revealed that of the 11.56% (SOS), 12.97% (EOS) and 5.72% (LOS) of pixels that were significantly trending, an estimated 65 – 70% belong to "*changed*" land cover change categories (i.e., pixels that have changed land cover type in the time period 2001 to 2013). Although, climatic factors may have contributed to these LSP trends, results show that changes in land cover can also influence LSP trends. This is because phenological response to environmental cues varies based on the type of land cover (Ryan et al. 2017; Guan et al. 2014). Additionally, pixels with a greater slope magnitude were observed more frequently in the "*changed*" pixels category compared to the *"no change"* category (see Figure 7).

Previous studies are generally in agreement with our findings (Heumann et al. 2007; Anton Vrieling, De Leeuw, and Said 2013) with respect to the overall pattern of LSP trends and the observation of significant positive LOS being associated mostly with delayed EOS.

This was seen irrespective of the datasets and study periods of the different studies, therefore, indicating the influence of other common drivers of LSP. Some interesting differences with previous studies were observed. While Heumann *et al.* (2007) found significant positive trends for LOS across the whole of western Africa, the present results revealed *"delayed shorter seasons"* in LOS in northern Nigeria (i.e. significant negative trends in LOS were associated mainly with significant positive trends in SOS). Similarly, the magnitude of the rate of change in days year^{-1} in this analysis was greater than those from Julien and Sobrino (2009); Vrieling *et al.* (2013) and Zhang *et al.* (2014). These differences could be attributed to the types of dataset and the duration of the study periods used in these studies (X. Zhang, Tan, and Yu 2014; de Beurs and Henebry 2005). While these previous studies used the 8 km AVHRR NDVI datasets with longer duration ranging from 1981 to 2011, none exceeding 2011, the present study used the EVI derived from the MODIS/Terra Surface Reflectance 8-Day L3 Global 500 m product. This much finer spatial resolution is expected to reveal greater variation in trends due to the well-known spatial convolution associated with the measurement process. Also, the present study period (2001 to 2015), while not as long as for some previous studies, accounted for more recent seasonal vegetation events across the continent. However, there are some issues associated with these data. The degradation of the blue band (Band 3, 470 nm) in these data has been recorded as having a negative influence on temporal trend analysis previously (Wang et al. 2012). In addition, sensor degradation have been shown to influence magnitude of vegetation indices derived from this data, but not seasonality (Y. Zhang et al. 2017). Furthermore, the accuracy of the land cover data which is not very high may have influenced the areas of changes observed in the different change categories. Additionally, as a result of the availability of land cover data not exceeding 2013, an assumption that no significant changes in land cover occurred between 2013 and 2015 was made (while noting that Terra MODIS 500 m data are the earliest with the longest time-series; 2000-present). Another assumption in this research was the consistency of the unchanged land cover pixels of cropland/natural vegetation mosaic. Changes in the percentage composition of this land cover type and inter-annual crop rotation to a different crop type can significantly influence LSP timings. Also, the analysis of LSP trends to determine the magnitude of change based on land cover changes was restricted to the time period 2001 to 2013.

5. Conclusion

Trends in phenology are increasingly being used to infer the effects of climate changes on vegetation development and growth patterns. Understanding the drivers of vegetation phenological trends is, therefore, paramount in vegetation-climate studies. However, most studies analyse the relation of phenology with these drivers without due consideration for confounding land cover changes which may also significantly impact LSP. Considering the magnitude of the land cover changes taking place across the African continent, this research controlled for land cover change such as to analyse inter-annual time-series of LSP parameters independent of these effects. For the purposes of comparison, we also analysed LSP trends for pixels for which the land cover changed.

When controlling for land cover change, significant trends were observed in all groups of pixels, and an estimated 70% of these trends in both SOS and EOS were significantly positive, that is, mostly delayed SOS and EOS dates. These occurred more in the Sudano-Sahelian and Sudanian regions of Africa. Importantly, the land cover changes significantly affected the LSP trends; larger trends were observed in the “changed” land cover groups. If these land cover changes were not controlled for in the LSP trend analysis, some of the reported trends would have been erroneously significantly larger. Based on these results, we suggest that future analyses of LSP trends should control for land cover changes such as to isolate those LSP trends that are solely climate-driven and/or those influenced by other anthropogenic activities or a combination of both.

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