**A systematic review of vegetation phenology in Africa**

Tracy Adole, [T.Adole@soton.ac.uk](mailto:T.Adole@soton.ac.uk)

Jadu Dash, [J.DASH@soton.ac.uk](mailto:J.DASH@soton.ac.uk)

Global Environmental Change and Earth Observation Research Group, Geography and Environment, University of Southampton.

Peter M. Atkinson, [pma@lancaster.ac.uk](mailto:pma@lancaster.ac.uk)

Faculty of Science and Technology,

Lancaster University.

**Abstract**

The study of vegetation phenology is important because it is a sensitive indicator of climate changes and it regulates carbon, energy and water fluxes between the land and atmosphere. Africa, which has 17% of the global forest cover, contributes significantly to the global carbon budget and has been identified as potentially highly vulnerable to climate change impacts. In spite of this, very little is known about vegetation phenology across Africa and the factors regulating vegetation growth and dynamics. Hence, this review aimed to provide a synthesis of studies of related Africa’s vegetation phenology and classify them based on the methods and techniques used in order to identify major research gaps. Significant increases in the number of phenological studies in the last decade were observed, with over 70% of studies adopting a satellite-based remote sensing approach to monitor vegetation phenology. Whereas ground based studies that provides detailed characterisation of vegetation phenological development, occurred rarely in the continent. Similarly, less than 14% of satellite-based remote sensing studies evaluated vegetation phenology at the continental scale using coarse spatial resolution datasets. Even more evident was the lack of research focusing on the impacts of climate change on vegetation phenology. Consequently, given the importance and the uniqueness of both methods of phenological assessment, there is need for more ground-based studies to enable greater understanding of phenology at the species level. Likewise, finer spatial resolution satellite sensor data for regional phenological assessment is required, with a greater focus on the relationship between climate change and vegetation phenological changes. This would contribute greatly to debates over climate change impacts and, most importantly, climate change mitigation strategies.

*Keywords: Africa, Climate Change, Phenology, Remote sensing, Vegetation, Vegetation indices, Satellite sensors*

1. **Introduction**

Phenology can be defined as the study of periodic life-cycle events, the impact of changes in climate and environment on the different phases of these events, and the interrelations among these phases either from the same or different species (Lieth, 1974). Vegetation phenology, which deals with the phenology of plants and their seasonal cycles, focuses on the onset of the growing season to the end of senescence in a plant’s annual cycle and its relationship with climatic and non-climatic factors (Zhang *et al.*, 2012; Zhao *et al.*, 2013). The relationship between vegetation phenology and climatic factors has been researched since the 1950s (Schnelle, 1955). However, it was formally established in the early 1990s that vegetation phenology is strongly dependent on climatic variables, making it a sensitive marker of seasonal changes in climate variables and their manifestation on the ground (van Schaik *et al.*, 1993; Wright & van Schaik, 1994).

An important advantage of phenological studies is the ability to carry-out long-term and broad-scale natural experiments, which can be synchronised readily with large scale climatic data (Myneni *et al.*, 1997; Menzel *et al.*, 2006). This has facilitated monitoring the impacts that changes in climate may have on vegetation growth (Chmielewski & Rötzer, 2001; Cleland *et al.*, 2007) and has aided in characterising climate-related events like droughts (White *et al.*, 1997; Brown *et al.*, 2012; Ivits *et al.*, 2014). Vegetation phenology also plays an important role in controlling the global carbon, water, and nitrogen cycles, especially the global carbon cycle, as the timing and duration of growing seasons greatly influences terrestrial energy budgets and atmospheric CO2 exchange (Keeling *et al.*, 1996; Higgins & Scheiter, 2012). This makes vegetation phenology an important factor to consider in planning and developing climate change mitigation strategies (Peñuelas *et al.*, 2009; Richardson *et al.*, 2013).

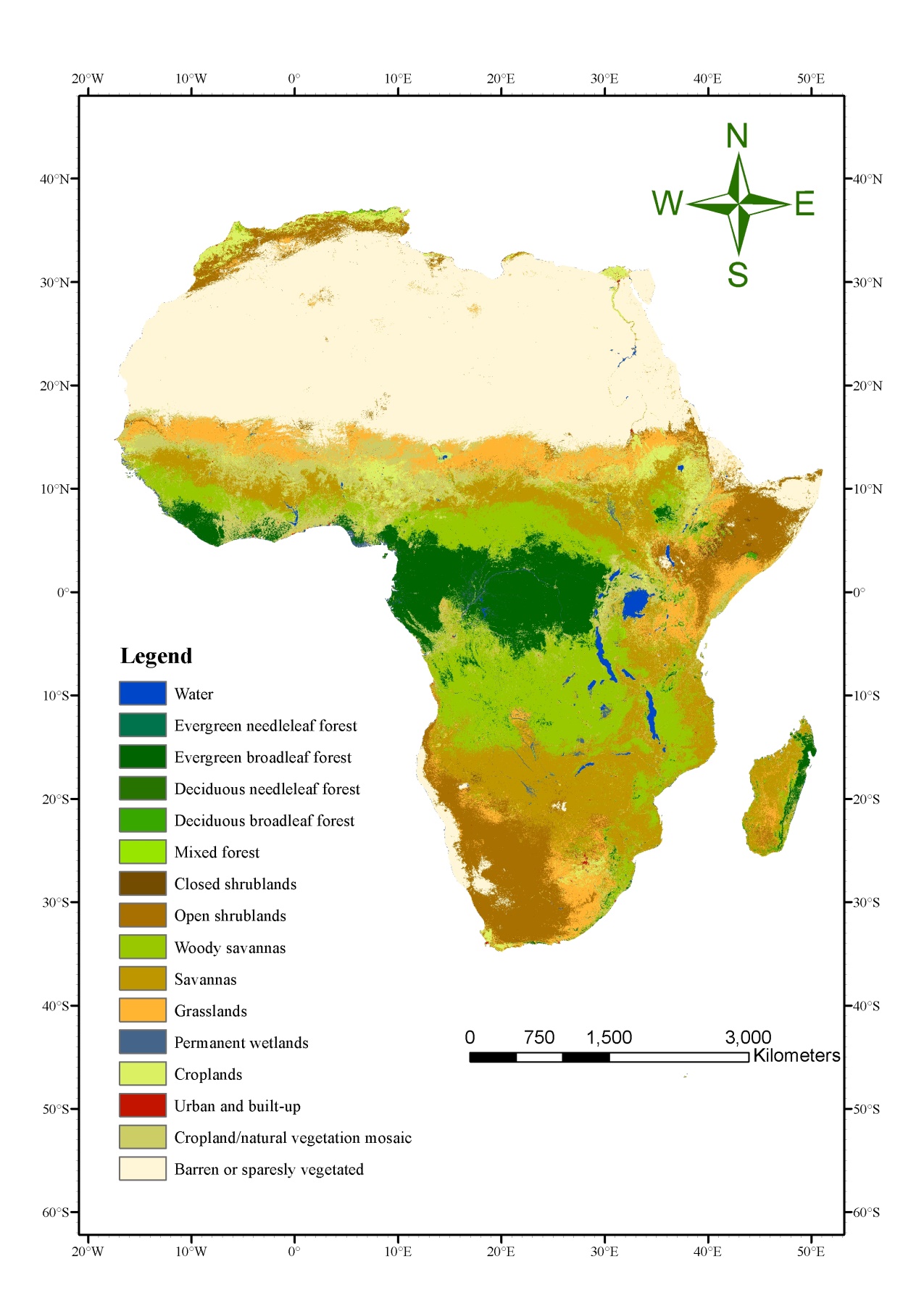
In the last few decades, the study of vegetation phenology has gained attention especially in relation to investigating climate change and its impacts on terrestrial ecosystem. Several studies have shown that increases in global temperature can influence photosynthetic activity, litterfall and the length of the growing-season of plants (Chmielewski & Rötzer, 2001; Chmielewski *et al.*, 2004; Zhang *et al.*, 2004). These studies are either ground-based or remote sensing studies or a combination of both. This increase in temperature, in particular during the spring, has been shown to increase vegetation greenness, advance the arrival of spring, and significantly alter growing season length especially in most parts of the Northern hemisphere (Myneni *et al.*, 1997; Menzel & Fabian, 1999; Zhou *et al.*, 2001). Similarly, other studies involving controlled experiments that simulate increases in temperature have provided further evidence of a lengthened growing season driven by changes in climatic conditions (Matsumoto *et al.*, 2003; Wolkovich *et al.*, 2012). This further emphasises the importance of a greater understanding of vegetation phenology and its drivers, especially in poorly studied regions. Unfortunately, one of those regions is the African continent as identified by the IPCC (2014) report on climate change.

* 1. **Vegetation phenology in Africa**

Despite increased interest in phenological studies, the phenology of the African vegetation has received far less attention than that of the Northern hemisphere, notwithstanding the African forest’s important contributions to the global carbon cycle. Given that Africa is home to the second-largest rainforest in the world (central African rainforests) (Zhou *et al.*, 2014), and the second and third largest wetlands in the world: the *Cuvette Centrale* of the Congo River Basin (Betbeder *et al.*, 2014) and the Niger Delta region of Nigeria (Spiers, 1999), vegetation dynamics in this region greatly influence regional and global land-atmosphere feedbacks. Also, 17% of global forest cover (Food and Agriculture Organization of the United Nations, 2010), and approximately 12% of tropical mangroves, which are the most productive natural ecosystem and the most carbon rich forest in the world, are found in Africa (Giri *et al.*, 2010). In addition to the abundance of forest, as shown in Figure 1, Africa also has a diverse range of vegetation types, ranging from deserts, grasslands, savannas and scrublands to woodlands, including broadleaved evergreen, needleleaved evergreen and deciduous forest with complex vegetation dynamics (Favier *et al.*, 2012).

The African continent has been recognised as one of the most vulnerable to climate change impacts (Niang *et al.*, 2014). In addition, Africa’s vegetation has experienced significant change over recent years. Between 2000-2010 the continent experienced a net loss of forest cover of approximately 3.4 million hectares annually (Food and Agriculture Organization of the United Nations, 2010). East Africa in particular, was shown to have increased tropical woody vegetation over grasslands (Doherty *et al.*, 2010), while Mitchard *et al.*, (2009) demonstrated forest encroachment into grassland areas in central Cameroon. There has also been a reported increase in vegetation greenness in the Sahel region (Olsson *et al.*, 2005; Heumann *et al.*, 2007).

Despite the above studies, the phenology of the African vegetation and its role in the global biogeochemical cycle are not clearly understood. Although research on African vegetation phenology is limited, more can be done by refining and integrating these studies, to identify the particular *foci* of phenological assessments that have been conducted, the specific research gaps and the appropriate approaches needed to fill these gaps. However, to date there has been no comprehensive review that summarizes the phenological studies in Africa, which highlights the specific gaps in knowledge and research, and identifies the suitable research methods required. Through this review, we provide a summary of the current state of research in the continent of Africa and some recommendations for future research. This review, thus, aims to contribute to the ongoing debates over climate change in Africa and, most importantly, its effects on vegetation phenology and attempts to mitigate its effects through climate change adaptation and mitigation strategies.

****

**Figure 1:** Land cover map of Africa derived from the MODIS land cover type product (MCD12Q1) data for 2012, downloaded from NASA’s LP DAAC (<https://lpdaac.usgs.gov/>).

1. **Conceptual framework**

Phenological studies have increased in number over the last decade, with studies focusing more on higher latitude regions, and including both small on-the-ground or *in situ* field studies (Chmielewski & Rötzer, 2001) and large scale remote sensing sometimes referred to as land surface phenology (LSP) (Dash *et al.*, 2010; Brown *et al.*, 2012). On-the-ground measurements are made by visual observation and recording of the different stages of a plant’s life cycle (Chmielewski *et al.*, 2004), *in situ* spectral measurements and near-surface remote sensing from laboratory-made sensors (Hufkens *et al.*, 2012; Soudani *et al.*, 2012), and gas exchange measurements from flux towers (Jin *et al.*, 2013). Remote sensing measurement on the other hand, is based primarily on deriving vegetation indices (VIs) and other vegetation parameters like the leaf area index (LAI) or the fraction of absorbed photosynthetically active radiation (FAPAR) from satellite-based sensors (Huete *et al.*, 2002; Boyd *et al.*, 2011).

Based on the above two different approaches to estimating vegetation phenological parameters, a conceptual framework was developed as a systematic basis for reviewing the scientific literature on vegetation phenological studies in Africa (Figure 2). Selected scientific literature was then classified based on geographical area and method of phenological assessment (Figure 2).

**Figure 2:** Conceptual framework for this systematic review showing the stepwise approach to classifying the selected literature based on geographical area and methodology, including the specific methods undertaken and the research focus.

Ground-based

Research focus/techniques

Geographical classification

Satellite-based remote sensing

Visual observation

Near-surface remote sensing

CO2 measurements

Vegetation parameters

Period/Time series

Spatial resolution

Sensor

Vegetation Phenology

Geographical classification

* 1. **Literature search and study selection**

In May 2015, a search was conducted within the peer-reviewed literature on the Web of Knowledge (<http://www.webofknowledge.com>) and Scopus (<http://www.scopus.com>) databases spanning the years 1960 to 2015. A combination of the search terms and keywords *“Phenology”,* and *“Vegetation phenology”* were used, with the results further refined with keywords such as *“Africa”*, *“Asia”*, *“Australia”*, *“North America”,* *“South America”,* and *“Europe”*, and also keywords representing the major countries in the world such as *“USA”, “UK”, “China”*, to provide a set of studies undertaken across several continents and, thus, provide a comparison in terms of the numbers of studies with Africa.

The following criteria were used to select the articles for this review:

1. English-language publications
2. Published in peer-reviewed scientific journals
3. A major or secondary assessment of vegetation phenology should have been conducted in the article

Based on the conceptual framework, all peer-reviewed literature on Africa’s vegetation phenology was examined to determine the following: the year of publication, the study area, the methods of phenological assessment, the spatial and temporal scale of the study, the sensor types and vegetation indices and parameters used (if derived from satellite sensor data), the techniques employed, and the research focus. Further studies were added to the total set of studies by reviewing the literature found in the reference lists of already included papers which evaluated Africa’s vegetation phenology and which also conformed to the criteria above. Figure 3 is a schematic representation of the methodology used in this systematic review and the final number of articles selected.

**Figure 3:** Schematic diagram of literature search and article selection process.

Web of Knowledge search

Scopus search

*“Phenology”* and *“Vegetation phenology”*

*n* = 9566

Refining by geographical distribution

Africa

*n* = 318

Further screening based on criteria above

Africa

*n* = 130

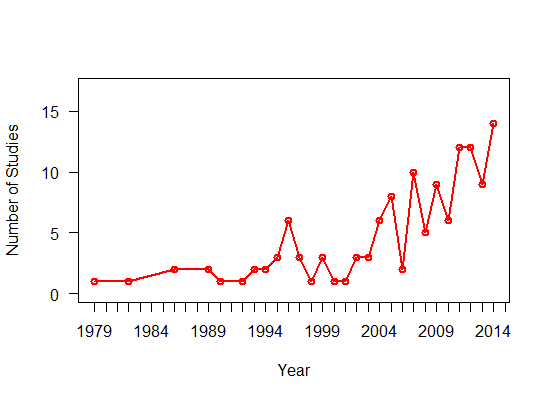
Additional search from related citations in articles

1. **Results**

Approximately 9,566 articles were found based on the first search terms and keywords; “*Phenology”,* and *“Vegetation phenology”*. Refining by geographical distribution based on further keywords, which included the names of continents and major countries in the world, Europe produced the maximum number of articles at 823, while North America and Asia produced 783 and 714 articles, respectively. South America and Africa had 394 and 318 articles, respectively, while for Africa only 130 articles were selected for this review having satisfied the necessary criteria described in section 3.1 (Figure 3).

* 1. **Publication year and geographical distribution of studies**

The results appear to support the claim that there has been a surge in phenological studies over the past decade, as over 75% of the articles were published between 2000 and 2015 (Figures 4). This surge can be attributed to an increased focus on climate change issues globally, with vegetation phenology having been shown to have a significant relationship with changes in climate (Chmielewski *et al.*, 2004).

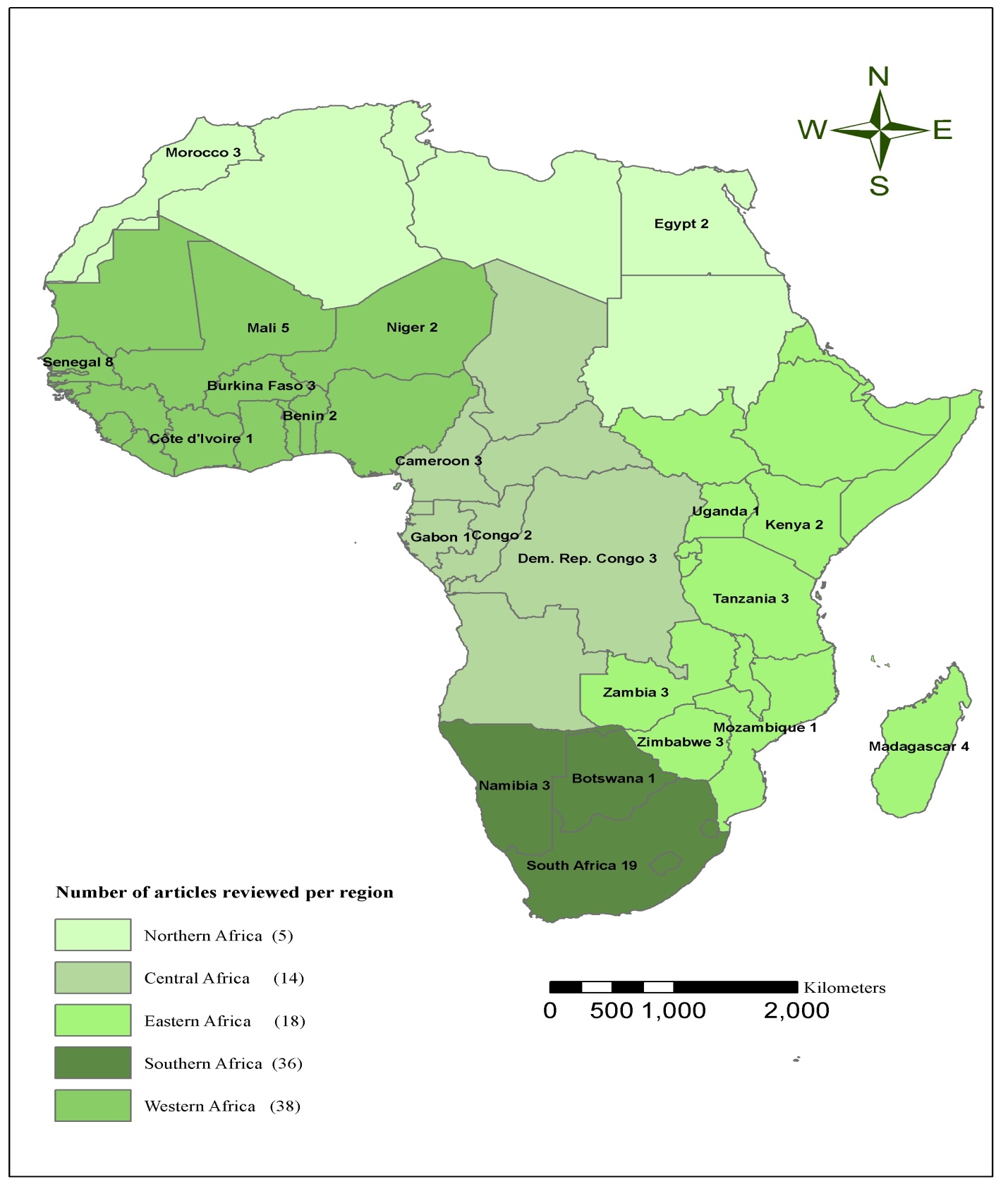


**Figure 4:** Number of publications on Africa’s vegetation phenology plotted against time in years. This figure shows the increase in vegetation phenology studies since 1979.

Further regional analysis within Africa revealed that more phenological studies have been carried out in Western and Southern Africa (Figure 5 and 6). Western Africa also recorded the most satellite-based remote sensing phenological studies, while Northern Africa had the least satellite-based remote sensing phenological studies and the least studies in general.

It is important to note that, while some countries recorded no phenological studies, at a regional scale, some studies may have covered part of their vegetation within a continental (semi-continental) study. Examples are in studies which covered parts of all countries in Western Africa (e.g. Philippon *et al.*, 2007; Vrieling *et al.*, 2011).

**Figure 5:** Regional distribution of studies based on method of measurement showing the larger number of remote sensing studies compared to ground studies in most regions except Northern and Eastern Africa.

**Figure 6:** Geographical distribution of studies showing the number of studies per country (numbers) and per region (coloured shading). The number of studies in a region includes studies carried out at the regional level and at the country level.

* 1. **Measuring phenology in Africa**
     1. **Ground-based approaches**

Using *in situ* field techniques, ground-based measurements can provide detailed and fine temporal resolution data on plant phenology, although these data may suffer from very limited spatial coverage (Studer *et al.*, 2007). From the literature search, 33% of the phenological studies carried out in Africa were ground-based, and the absolute number of ground studies has increased in recent years (Figure 7). However, over 37% of these studies were done in Southern Africa, mostly in South Africa (Figures 5, 6). The spatial coverage of ground-based studies in Africa is limited, ranging from study areas of 4.35 km2 (Janecke & Smit, 2011) to 7500 km2  (O’Farrell *et al.*, 2007), and these were carried out at specific sites only. Also, the temporal duration of these studies is limited and most measure the phenology of individual plant species only. The longest recorded phenological record for a ground-based study was 37 years and this was carried out for three apple species and one pear species in the southwestern Cape of South Africa (Grab & Craparo, 2011). Only about seven studies (de Bie *et al.*, 1998; Esler & Rundel, 1999; Chapman *et al.*, 2005; Do *et al.*, 2005; Pons & Wendenburg, 2005; O’Farrell *et al.*, 2007; Yamagiwa *et al.*, 2008) measured phenology at the community level.

**Figure 7:** Number of studies by decade by method of measurement showing the dramatic increase in remote sensing studies in the 2000s.

A general concern for all ground-based measurements globally, is the evident lack of a standard approach to measuring vegetation phenological stages in Africa. While some studies measured the emergence of reproductive structures (Seghieri *et al.*, 2012; Polansky & Boesch, 2013) in determining Start of Season (SOS), others measured leaf opening (Do *et al.*, 2005) and above ground biomass (Wakeling *et al.*, 2012).

The types of technique applied in ground-based measurements of vegetation phenology in Africa are still, in some ways, limited. Over 80% of ground-based studies estimated phenology by visual observation of the timing of the developmental cycles or different stages of a plant’s life cycle, from germination/flowering to litter-fall. Only one study (Jin *et al.*, 2013), as part of its assessment used CO2 fluxes observed with the eddy covariance technique to estimate gross primary production (GPP), from which phenological parameters were estimated. Similarly, near-surface remote sensing involving the use of hand-held or aircraft carrying sensors has been utilized for phenological studies. However, only five of the 43 ground-based phenological studies employed this technique: Duchemin *et al.* (2006), Higgins *et al.* (2011), Soudani *et al.* (2012) and Mbow *et al.* (2013) employed the use of laboratory made sensors (e.g., the cosine corrected SKYE Instruments sensors, CMOS sensor, hand-held MSR87 multispectral radiometer) while Fuller (1999) used a light aircraft to capture aerial photography at a scale of 1:30,000 for measuring canopy phenology. The reflectance values in the red and near-infrared spectra of the images acquired in these studies were used to determine the normalized difference vegetation index (NDVI). Unlike the traditional visual observation technique used in most ground-based studies, mathematical methods were used to estimate phenological parameters from NDVI, just like satellite-based remote sensing studies (see section 3.2.3 and Table 2). Examples used for estimating phenological stages are the Bayesian model fitting method used in Higgins *et al.* (2011), and a histogram thresholding algorithm in Fuller (1999).

* + 1. **Remote sensing**

As observed with ground-based studies, the number of satellite-based remote sensing phenological studies in Africa has increased with a surge in the 2000s (Figure 7). They account for over 70% of all phenological studies in Africa (Figure 7). However, unlike ground-based studies, many of the satellite-based remote sensing phenological assessments in Africa have been able to provide full spatial coverage of the entire continent (Figure 8).

* + - 1. ***Sensor types, spatial resolution and geographical coverage***

The merit and strength of satellite-based remote sensing phenological assessments are highly dependent on the temporal and spatial resolution of the sensor type used for analysis, and the length of the temporal record (Boyd *et al.*, 2011). Table 1 shows the characteristics of the different types of sensors used for phenological studies in Africa.

As shown in Figure 9 and Table 1, six different satellite sensors were identified as having been used for phenological studies in Africa. With a daily orbiting frequency and spatial resolutions of 1 km and 8 km, the Advanced Very High Resolution Radiometer (AVHRR) on-board the National Oceanic and Atmospheric Administration (NOAA) satellites was the most widely used sensor (Figure 9). Additionally, because of its available data records from 1981-to-date, the AVHRR sensor is well suited for long-term studies and was used for all studies in this review that had time-series of data longer than 20 years, with the longest time-series of 30 years in Vrieling *et al.* (2013). Moreover, over 65% of studies covering the entire continent employed the 8 km spatial resolution NDVI datasets, while the 1 km datasets were used mainly for regional and individual country assessments (see Figure 8).

**Figure 8:** Therange of spatial resolutions and the geographical extent employed by the reviewed studies. This shows that a coarse spatial resolution (1000 – 5000 m) was used generally at the regional scale (extent) and a very coarse spatial resolution (7000 – 8000 m) at the continental scale (extent).

**Table 1: Characteristics of sensor types used in satellite-based remote sensing phenological studies in Africa**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sensor** | **Satellite** | **Orbiting frequency** | **Spatial resolution in studies** | **Temporal resolution in studies** | **Time-series range in studies** | **Vegetation indices and parameters in phenological studies** |
| AVHRR | NOAA | Daily | 1 km 7 km and 8 km | 15-day, 10-day | 1981 - 2011 | NDVI |
| MODIS | Terra and Aqua | 1-2 days | 250 m, 500 m, 1 km and 5 km | 8-day, 16-day | 2000 - 2013 | NDVI, EVI, LAI and LSWI |
| SPOT- Vegetation | SPOT | 1-2 days | 1 km | 10-day | 1998 - 2013 | NDVI, EVI and FAPAR |
| SEVIRI | Meteosat Second Generation (MSG) geostationary satellite series (EUMET- SAT) | Daily | 3 km | 15 mins | 2007 - 2011 | LAI |
| METEOSAT B2 | Meteosat | Daily | 5 km | 30 mins | 1983 – 1984 | NDVI |
| Sea Winds Scatterometer | QuikSCAT | Daily | 25 km | 4-day | 2000 - 2003 | Backscatter |

**Figure 9:** The sensor types used for phenological studies in Africa plotted against the number of studies using them, and showing the VIs and/or vegetation parameters estimated from them.

The second most used sensor compared to the AVHRR is the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor with a total number of 37 studies (Figure 9). This sensor is on-board the Terra Earth Observing System (EOS) AM and the Aqua EOS PM satellites with spatial resolutions of 250 m, 500 m, and 1 km (Table 1). Apart from the finer spatial resolution of the MODIS data products, they also provide data with lower noise from clouds or atmospheric haze, aerosols and negligible water vapour impacts (Huete *et al.*, 2002). Only four studies assessed the LSP of the entire African continent using MODIS data at spatial resolutions of 1 km (Linderman *et al.*, 2005; Zhang *et al.*, 2005) and 5 km (Guan *et al.*, 2013, 2014b), with time-series of 3 years and 12 years, respectively (Figure 8). Other MODIS-based phenological studies with finer spatial resolution were carried out either regionally or in individual countries (Figure 8).

Another fairly well used sensor is the Satellite Pour l'Observation de la Terre (SPOT) Vegetation with a total of nine studies. These sensors (VEGETATION 1 and VEGETATION 2) were launched on-board the SPOT satellites in 1998 and 2002, respectively (Aitkenhead, 2014). The main advantage of the SPOT-Vegetation sensor is its consistent temporal reconstructed reflectance time-series data of three times per month (a rationale for selection by some of the studies in this review, e.g., Verhegghen *et al.*, 2012).

Other sensors used for LSP estimation in Africa include, Meteosat Second Generation (MSG), Spinning Enhanced Visible and Infrared Imager (SEVIRI) (Guan *et al.*, 2014a), METEOSAT B2 (Amram *et al.*, 1994) and the Sea Winds Scatterometer (Ringelmann *et al.*, 2004; Ryan *et al.*, 2014) (Table 2).

From Figure 8 it can be observed that most studies that utilized sensors with fine spatial resolution data were carried out either within individual countries or at the regional scale and none were yet undertaken for the entire continent. The most applicable spatial resolution with the longest time series for applications at the continent scale is the 8 km resolution.

* + - 1. ***Biophysical variables and phenological parameters***

Phenological parameters in remote sensing are usually estimated from vegetation indices (VIs). They are usually estimated from an arithmetic combination of different spectral reflectance values mainly in the red (R) and near infrared (NIR) region of the electromagnetic spectrum. Figure 8 shows the VIs and vegetation parameters in each study and the sensor type that these parameters were estimated from. The NDVI was the most commonly estimated VI (see Figure 9) which, as mentioned above, is the most widely used for vegetation studies globally (Reed *et al.*, 2009).

The NDVI was used in over 90% of the longer-term studies of 20 to 30 years (Heumann *et al.*, 2007; Philippon *et al.*, 2007; Vrieling *et al.*, 2008, 2011, 2013; Brown *et al.*, 2010, 2012) and was commonly derived from spectral data of the AVHRR sensor (see Figure 9). An exception to this is the 30 years global inter-annual LSP study of Zhang *et al.* (2014) using the Enhanced Vegetation Index (EVI) specifically the EVI2 (Jiang *et al.*, 2008) derived from AVHRR data. Despite the advantages of the EVI over the NDVI, only 21% of studies (see Figure 9) used the EVI, mostly derived from MODIS data.

Other biophysical variables that can be used to estimate vegetation phenology include the fraction of absorbed photosynthetically active radiation (FAPAR) and the leaf area index (LAI), which are both closely related to vegetation canopy structure (Huete *et al.*, 2011), and these have been used sparsely over Africa (see Figure 9). The FAPAR was used by four studies only (Meroni *et al.*, 2013, 2014a,b,c), and was derived from 1 km SPOT-Vegetation data. Likewise, the LAI was used in only 3% of studies, and was derived from MODIS data in Huemmrich *et al.* (2005) and Bobée *et al.* (2012) and SEVIRI data in Guan *et al.* (2014a) (Figure 9).

The backscatter derived from the Sea Winds Scatterometer in Ringelmann *et al.* (2004) and Ryan *et al.* (2014) and the Land Surface Water Index (LSWI) derived from MODIS data in Jin *et al.* (2013) were other vegetation parameters also used in phenology studies in Africa.

* + 1. **Phenology estimation**

Estimation of phenological parameters from satellite sensor data commonly requires a stepwise methodology, which involves the initial calculation of VIs from satellite sensor data, removal of “bad” pixels in the time-series, interpolation of the missing values, smoothing of the complete time-series, and estimation of phenological parameters from the smoothed data. There are several smoothing techniques used for smoothing VI data and for estimating phenological parameters from the smoothed data. The smoothing techniques can be classified into three broad categories: statistical, curve fitting and data transformation (Atkinson *et al.*, 2012). Likewise, phenological parameter estimation techniques can also be classified into three broad categories: threshold, curve-derived and function model fitting methods (de Beurs & Henebry, 2010).

Table 2 gives an overview of the different types of techniques and the number of studies that employed the use of these techniques in Africa. Although, threshold methods have been identified as the most commonly used technique globally (de Beurs & Henebry, 2010), only 40 studies estimated phenological parameters using this technique, while 37 studies used the model fitting method, of which one was a ground-based study (section 3.2.1 and Table 2).

Visual observation, the traditional approach of estimating phenological parameters, was employed in 39 studies in this review. However, one of these studies (Tappan *et al.*, 1992), a satellite-based remote sensing study, used this technique in estimating phenological parameters from already smooth VI images with the help of soil polygon maps and by visual interpretation of the plots.

Other non-conventional approaches have been used in phenological assessment in Africa. Viennois *et al.* (2013) characterised canopy phenology in central African tropical forests by averaging MODIS EVI data over the wet and dry seasons. Cook & Vizy (2012) and Roehrig & Laudien (2009) without the use of VIs, were able to estimate the length of growing seasons from climatic data, using approaches previously undertaken by other researchers (White *et al.*, 1997). Only Jin *et al.* (2013), as a part of their assessment, defined phenology from GPP estimated from eddy covariance CO2 fluxes.

**Table 2: Summary of studies, their research areas, methods and techniques**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Technique**  **Research aim** | **Visual observation** | **Threshold** | **Curve-derived** | **Model fitting** | **Other** | **Grand Total** |
| **Ground-based** | **38** | **4** |  | **1** |  | **43** |
| Characterisation | 3 | 1 |  |  |  | 4 |
| Explanation | 31 | 3 |  | 1 |  | 35 |
| Ecosystem management | 4 |  |  |  |  | 4 |
| **Remote sensing** | **1** | **36** | **11** | **36** | **3** | **87** |
| Characterisation | 1 | 12 | 1 | 15 | 1 | 30 |
| Explanation |  | 23 | 10 | 19 | 2 | 54 |
| Ecosystem management |  | 1 |  | 2 |  | 3 |
| **Grand Total** | **39** | **40** | **11** | **37** | **3** | **130** |

* + 1. **Ground validation of LSP**

The validation of remotely sensed phenological parameters is important to establish the reliability of estimates of vegetation growth stages from satellite sensor data, and yet this is rarely undertaken due to a lack of sufficient coverage of ground data (Reed, 2007). One of the major challenges with LSP estimation in Africa is ground validation. Validating satellite-derived phenology estimates in Africa is currently near-impossible, especially on a large scale, either due to the complete absence of, or very few, available ground-based phenological studies. Only 15 studies carried out some form of validation and these were done over very small study areas, and with a temporal scale range of one to three years. Some of these studies adopted non-conventional approaches in validating phenological data. Examples are Vintrou *et al.*, (2014) who in the absence of ground-based phenology, used a crop model SARRA-H (System for Regional Analysis of Agro-Climatic Risks) to validate phenological variables from MODIS EVI data, and Ringelmann *et al.* (2004) who used *in situ* soil moisture time-series, weather station data, satellite-derived rainfall estimates (RFE) and NDVI to validate planting dates estimated from Backscatter Sea Winds Scatterometer data. These studies also presented results which demonstrated a significant correlation between satellite-based phenological data and field observations (Jin *et al.*, 2013; Meroni *et al.*, 2014b).

* 1. **Focus of vegetation phenological research**

The focus or aim of all 130 studies in this review was categorised into three major groups: characterisation, explanation and ecosystem management. The characterisation group comprises studies that focus on: methodological approaches in estimating and mapping vegetation phenology, variation in vegetation phenology overtime, and the use of vegetation phenology in land cover classification/mapping and characterisation of land cover changes. Explanation on the other hand includes studies involved in determining the drivers of phenology or the relationship between vegetation phenology and other parameters, including phenological responses to climate change. Lastly, ecosystem management comprises studies that evaluated vegetation phenological dynamics to understand and make decisions on the environment. It is important to note that these groups potentially are non-exclusive, that is, some studies may overlap between categories and so a judgement was made in each case to determine the main focus.

From Table 2 it can be observed that approximately 26% of studies were categorised under characterisation, with most focusing on mapping vegetation phenology and temporal trend analysis (Jönsson & Eklundh, 2004; Heumann *et al.*, 2007; Wessels *et al.*, 2011; Vrieling *et al.*, 2013). For the Sahel, Soudan, and Guinean regions in Africa, Heumann *et al.* (2007) investigated phenological trends and reported significant changes between 1982–2005 in the Length of Growing Season (LGS) mostly in the Soudan and Guinean regions. On a continental scale, phenological trend analysis was undertaken by Vrieling *et al.* (2013), and observed that inter-annual variability in LGS was high in arid and semi-arid regions.

For land cover classification and mapping, variation in phenological parameters was used to classify and map different vegetation types especially in cases where there was insufficient ground data (Betbeder *et al.*, 2014). An example is given by Betbeder *et al.* (2014) who mapped the *Cuvette Centrale* of the Congo River Basin using phenological differences of EVI from MODIS time-series to characterise different forested wetlands.

The group explanation included over 68% of studies of which the majority focused on phenological patterns and their relationship with climatic variability (Zhang *et al.*, 2005; Philippon *et al.*, 2007; Brown *et al.*, 2010; Guan *et al.*, 2013, 2014b; Dubovyk *et al.*, 2015). Across the entire African continent, studies like Zhang *et al.* (2005) and Guan *et al.* (2013, 2014b) identified precipitation as the major environmental factor controlling variability in the seasonality of vegetation growth, canopy structure and function. In contrast, variability in temperature was attributed to be the major determinant of phenological patterns in South Africa’s savanna vegetation (Chidumayo, 2001) and some apple varieties in South Africa (Grab & Craparo, 2011). Also, the inter-annual growth trends of some tropical rainforest trees in West Africa were not related with rainfall patterns; rather solar radiation was suggested to be responsible for growth trends (Polansky & Boesch, 2013).

Notwithstanding the growing interest in climate change studies, only four studies (Chapman *et al.*, 2005; Grab & Craparo, 2011; Brown *et al.*, 2012; Cook & Vizy, 2012) focused on climate change, specifically how a changing climate is impacting on the growing seasons of plants in Africa. These studies demonstrated significant correlations between climatic variables and the phenophases of plants, like the associated temperature increases and advance in flowering dates of apple and pear trees in South Africa (Grab & Craparo, 2011), and the global shift in SOS and LGS of crops in response to increases in temperature and moisture availability (Brown *et al.*, 2012).

The ecosystem management group constituted less than 10% of the 130 studies. These studies used vegetation phenology to understand animal behavioural pattern, livestock production practices, and ecosystem diversity (Pons & Wendenburg, 2005; O’Farrell *et al.*, 2007; Yamagiwa *et al.*, 2008; Butt *et al.*, 2011). They showed that vegetation phenological parameters, and their variability across time and latitudinal gradients, influence the timing and direction of transhumance movements and livestock management practices. This is because foliage (and, thus, forage) quality largely depends on the phenophases of vegetation (O’Farrell *et al.*, 2007; Butt *et al.*, 2011). Additionally, the relationship between the timings of the abundance of vegetation resources, derived from vegetation phenophases and animal behavioural pattern was established in these studies (Pons & Wendenburg, 2005; Yamagiwa *et al.*, 2008).

1. **Discussion: Challenges and opportunities for research and development** 
   1. **Number and spatial coverage/resolution of studies**

Ground-based phenological observations are seriously lacking in Africa both in terms of the spatial coverage and in terms of temporal records. While most regions in the temperate latitudes have observation networks with long time-series of data acquired through extensive ground-based measurement of vegetation phenology (e.g., the US National Phenology Network and the Woodland Trust, UK) (Boyd *et al.*, 2011; Zhang *et al.*, 2012) there are no known phenological observation networks in the African continent. Also absent are any digital camera networks for phenological observation in Africa, networks which have already been established in other continents (Richardson *et al.*, 2009; Nasahara & Nagai, 2015). Only one study (Higgins *et al.*, 2011) used digital cameras for phenological observation. However, this was achieved by capturing images in scheduled flights by a helicopter on which the camera was mounted rather than fixed cameras taking continuous photograph of the landscape. Additionally, the use of different measurement protocols in ground-based studies makes it challenging to compare between the few existing measurements. Hence, there is an urgent need for a systematically organized long-term monitoring network for ground-based phenological assessment for the entire African continent. This is required to support systematic and well-documented ground-based observations with unifying standards of measurements to provide detailed characterisation of species and community level responses to climatic changes. This is more important considering that most satellite-based remote sensing phenological assessments lack ground validation due to the complete absence or very limited records of ground observed phenology (Reed, 2007).

Although, phenological studies have been increasing in number over recent years, the spatial coverage of studies has been limited to regions and individual countries, with some regions having a relatively higher proportion of studies than others, and with very few covering the entire continent. For example, Southern Africa had 47 studies while Central Africa had 17, and only 10% of the total number of studies reviewed covered the entire continent. These studies were mostly satellite-based phenological studies. Furthermore, those studies which covered the entire continent, were at relatively coarse spatial scale (i.e. 8 km), thus, masking out the complexity and the inter-annual variability of Africa’s vegetation phenology. Hence, a relatively fine spatial resolution LSP mapping is essential for Africa to ensure: (1) a more accurate characterisation of the phenology of the African vegetation, (2) a detailed description of the phenological trends especially at local scales which may have been previously undetected when using coarse spatial resolutions, and (3) an increased knowledge of the inter-annual variability of the LSP and other environmental factors.

Before improved measurement protocols can be implemented it is important to note some of the major challenges responsible for the concerns raised above. These are the inadequate research capacity of institutions, financial constraints and lack of funding for physical science based research across the continent (Irikefe *et al.*, 2011; World Bank, 2014). The financial constraint is a major concern that has prohibited ground-based survey or observations in Africa (Wagenseil & Samimi, 2006) as field studies would require intensive resource from the already financially constrained national governments of African countries. Furthermore, physical accessibility issues and political instability in some regions of Africa (Laurance *et al.*, 2006) are other challenges that have been associated with deterring field acquisition of both scientific and social data.

* 1. **LSP estimation method**

The type of sensor and spatial resolution used for remote sensing studies are very important and can greatly influence assessment results (Pelkey *et al.*, 2003). The MODIS sensor has several advantages over the AVHRR sensor (Huete *et al.*, 2002). One major advantage is reduced cloud and atmospheric contamination, noting that cloud is prevalent in tropical regions of the world (Huete *et al.*, 2002). Despite these advantages, at the African continent scale the advantages of this sensor have not been fully utilized as only three studies measured the LSP of the entire African continent using the MODIS sensor. In addition, the potential of the next generation of satellite instruments, such as the Sentinel series from the European Space Agency, for addressing some of these constraints in vegetation monitoring needs to be explored. This sensor series, especially the recently launched Sentinel-2 which is designed for terrestrial observation with a possible resolution of 10 m and potential temporal coverage of 5 days, is likely to provide unparalleled opportunities for local scale monitoring (Zhu *et al.*, 2015).

Notwithstanding the reduction of cloud and atmospheric contamination in the MODIS data, these phenomena still have significant effects on MODIS VI values, hence the use of smoothing techniques or time-series filters like Fourier analysis (Wagenseil & Samimi, 2006), the double logistic model (Zhang *et al.*, 2004), asymmetric Gaussian model (Jönsson & Eklundh, 2004), Savitzky- Golay filter (Chen *et al.*, 2004) and the Whittaker filter (Atkinson *et al.*, 2012) in smoothing out noise from VI time-series data. These techniques all have their advantages and disadvantages which are also dependent on the frequency of cloud contamination and the seasonality strength of VIs in the time-series (Atkinson *et al.*, 2012). However, these techniques can result in variation in estimated phenological parameters. Therefore, it is important to consider the purpose of each study and the specific study area when selecting smoothing and estimation techniques (de Beurs & Henebry, 2010; Atkinson *et al.*, 2012). The results, shown clearly in Table 2, revealed that reviewed studies employed a wide range of techniques in estimating phenological parameters, from visual observations to mathematical and climate models. Knowing that these studies were applied both at regional and individual country levels, a means by which these metrics can be evaluated and combined together to give broader phenological records of the entire continent is an open area for further research. This possibility has also been highlighted by Atkinson *et al.* (2012) who suggested the use of a statistical ensemble-based approach.

* 1. **Forecasting and climate change**

The review confirms the dearth of studies on vegetation phenology and its relationship with climate change in Africa, as reported by the IPCC (2014). Only four studies (see section 3.3) evaluated the relationship between vegetation phenology and climate change. Amongst these studies, only one (Cook & Vizy, 2012) assessed climate change impacts on the growing season at the continental scale, but based on a different approach of determining LGS by using climate models rather than the conventional satellite-derived VIs. However, it is also important to acknowledge that the coverage of fine spatial resolution climate data records over Africa is sparse.

Another aspect is understanding the influence of natural climatic drivers on vegetation phenology. Although, several studies have shown the relationship between the phenological patterns of the African vegetation and climatic drivers, precipitation-driven studies are more numerous than temperature and solar radiation studies (see section 3.3),. Furthermore, owing to the complexity and the highly irregular phenological patterns of Africa’s vegetation, which has multi-annual life cycles and is driven by a combination of three climatic drivers (i.e. Precipitation, temperature and solar radiation), an enhanced understanding of the interplay of all these factors is needed. Consequently, there exist opportunities to investigate and forecast the possible responses of vegetation phenology to changes in climatic conditions. While it is imperative that this opportunity is realized, it is also important that the associated challenges are considered when carrying out such research. Some of these challenges are, the numerous uncertainties with regards to the regulatory mechanisms of vegetation phenology, model parameterization and forecasting future climate systems (Zhao *et al.*, 2013), the evolutionary trends of individual plants (Visser *et al.*, 2010), and integrating individual plants to ecosystem level phenology (Cleland *et al.*, 2007).

1. **Conclusion**

The phenology of vegetation is an important measure of terrestrial ecosystem processes. In addition to being an indicator of climate change, it is also useful in studying ecological processes like energy exchanges (e.g., water and carbon exchange), habitat provision, food insecurity and other ecosystem services. Given the increasing occurrences of climate change impacts in the 21st century, it is important to understand vegetation phenological responses to natural climatic variability and to anthropogenic activities, especially its role in local climate feedback mechanisms. Consequently, based on several studies across the globe and as reported by the IPCC, there is high confidence that changes in climatic factors have impacted on vegetation phenology in Europe, Asia, Australasia and North America (IPCC, 2014). However, that same confidence has not been attributed to reported climate change impacts on vegetation phenology in Africa. Rather, research gaps were identified which include assessing the effect of natural climate variability on ecosystems and the development of monitoring networks for long-term change assessment (IPCC, 2014).

This review corroborates the findings of the IPCC Fifth Assessment Report (AR5) and other peer reviewed literature. It identified several research gaps and opportunities associated with vegetation phenological studies in Africa. Based on this review, the following recommendations are made for future studies and for decision-makers and policy-makers:

* Development of a widespread monitoring network for vegetation phenology across the entire continent with presence in all countries, with a view to facilitating extensive country-based vegetation phenology studies.
* Characterisation of the vegetation phenological parameters at a relatively fine spatial resolution to capture the complexity due to multi-annual seasons and landscape heterogeneity.
* Investigation of vegetation phenological feedbacks (or the role of vegetation phenology in vegetation-climate feedback mechanisms), and the relationship between climate change and vegetation phenological changes.

Addressing these issues will provide greater understanding of the role of the African vegetation in the global carbon cycle and climate system, ultimately contributing to current climate change adaptation and mitigation strategies.

**Acknowledgments**

The authors would like to thank the Commonwealth Scholarship Commission in the UK for funding and support provided to Tracy Adole. Authors are also grateful for the insightful and constructive comments of the anonymous reviewers.

**References**

Aitkenhead, M. (2014) SPOT-VEGETATION – 15 years of success: what’s next? *International Journal of Remote Sensing*, **35**, 2397–2401.

Amram, O., Flouzat, G. & Cherchali, S. (1994) An efficient water concept for monitoring vegetation in West Africa. *Proceedings of IGARSS ’94 - 1994 IEEE International Geoscience and Remote Sensing Symposium*, **1**, 9–11.

Atkinson, P.M., Jeganathan, C., Dash, J. & Atzberger, C. (2012) Inter-comparison of four models for smoothing satellite sensor time-series data to estimate vegetation phenology. *Remote Sensing of Environment*, **123**, 400–417.

Betbeder, J., Gond, V., Frappart, F., Baghdadi, N.N., Briant, G. & Bartholome, E. (2014) Mapping of central africa forested wetlands using remote sensing. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **7**, 531–542.

de Beurs, K.M. & Henebry, G.M. (2010) *Spatio-Temporal Statistical Methods for Modelling Land Surface Phenology*. *Phenological Research: Methods for Environmental and Climate Change Analysis* (ed. by I.L. Hudson) and M.R. Keatley), pp. 177–208. Springer Netherlands.

de Bie, S.E., Ketner, P., Paasse, M. & Geerlingt, C. (1998) Woody Plant Phenology in the West Africa Savanna. *Journal of Biogeography*, **25**, 883–900.

Bobée, C., Ottlé, C., Maignan, F., De Noblet-Ducoudré, N., Maugis, P., Lézine, a. M. & Ndiaye, M. (2012) Analysis of vegetation seasonality in Sahelian environments using MODIS LAI, in association with land cover and rainfall. *Journal of Arid Environments*, **84**, 38–50.

Boyd, D.S., Almond, S., Dash, J., Curran, P.J. & Hill, R. a. (2011) Phenology of vegetation in Southern England from Envisat MERIS terrestrial chlorophyll index (MTCI) data. *International Journal of Remote Sensing*, **32**, 8421–8447.

Brown, M.E., de Beurs, K. & Vrieling, A. (2010) The response of African land surface phenology to large scale climate oscillations. *Remote Sensing of Environment*, **114**, 2286–2296.

Brown, M.E., de Beurs, K.M. & Marshall, M. (2012) Global phenological response to climate change in crop areas using satellite remote sensing of vegetation, humidity and temperature over 26years. *Remote Sensing of Environment*, **126**, 174–183.

Butt, B., Turner, M.D., Singh, A. & Brottem, L. (2011) Use of MODIS NDVI to evaluate changing latitudinal gradients of rangeland phenology in Sudano-Sahelian West Africa. *Remote Sensing of Environment*, **115**, 3367–3376.

Chapman, C. a., Chapman, L.J., Struhsaker, T.T., Zanne, A.E., Clark, C.J. & Poulsen, J.R. (2005) A long-term evaluation of fruiting phenology: importance of climate change. *Journal of Tropical Ecology*, **21**, 31–45.

Chen, J., Jönsson, P., Tamura, M., Gu, Z., Matsushita, B. & Eklundh, L. (2004) A simple method for reconstructing a high-quality NDVI time-series data set based on the Savitzky-Golay filter. *Remote Sensing of Environment*, **91**, 332–344.

Chidumayo, E.N. (2001) Climate and phenology of savanna vegetation in southern Africa. *Journal of Vegetation Science*, 347–354.

Chmielewski, F.M., Müller, A. & Bruns, E. (2004) Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. *Agricultural and Forest Meteorology*, **121**, 69–78.

Chmielewski, F.-M. & Rötzer, T. (2001) Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, **108**, 101–112.

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H. a & Schwartz, M.D. (2007) Shifting plant phenology in response to global change. *Trends in ecology & evolution*, **22**, 357–65.

Cook, K.H. & Vizy, E.K. (2012) Impact of climate change on mid-twenty-first century growing seasons in Africa. *Climate Dynamics*, **39**, 2937–2955.

Dash, J., Jeganathan, C. & Atkinson, P.M. (2010) The use of MERIS Terrestrial Chlorophyll Index to study spatio-temporal variation in vegetation phenology over India. *Remote Sensing of Environment*, **114**, 1388–1402.

Do, F.C., Goudiaby, V. a., Gimenez, O., Diagne, A.L., Diouf, M., Rocheteau, A. & Akpo, L.E. (2005) Environmental influence on canopy phenology in the dry tropics. *Forest Ecology and Management*, **215**, 319–328.

Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L. & Thornton, P.K. (2010) Implications of future climate and atmospheric CO 2 content for regional biogeochemistry, biogeography and ecosystem services across East Africa. *Global Change Biology*, **16**, 617–640.

Dubovyk, O., Landmann, T., Erasmus, B.F.N., Tewes, A. & Schellberg, J. (2015) Monitoring vegetation dynamics with medium resolution MODIS-EVI time series at sub-regional scale in southern Africa. *International Journal of Applied Earth Observations and Geoinformation*, **38**, 175–183.

Duchemin, B., Hadria, R., Erraki, S., Boulet, G., Maisongrande, P., Chehbouni, a., Escadafal, R., Ezzahar, J., Hoedjes, J.C.B., Kharrou, M.H., Khabba, S., Mougenot, B., Olioso, a., Rodriguez, J.C. & Simonneaux, V. (2006) Monitoring wheat phenology and irrigation in Central Morocco: On the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. *Agricultural Water Management*, **79**, 1–27.

Esler, K.J. & Rundel, P.W. (1999) Comparative patterns of phenology and growth form diversity in two winter rainfall deserts: the Succulent Karoo and Mojave Desert ecosystems. *Plant Ecology*, **142**, 97–104.

Favier, C., Aleman, J., Bremond, L., Dubois, M. a., Freycon, V. & Yangakola, J.M. (2012) Abrupt shifts in African savanna tree cover along a climatic gradient. *Global Ecology and Biogeography*, **21**, 787–797.

Food and Agriculture Organization of the United Nations (2010) *Global forest resources assessment 2010: Main report*, Rome, Italy.

Fuller, D.O. (1999) Canopy phenology of some mopane and miombo woodlands in eastern Zambia. *Global Ecology and Biogeography*, **8**, 199–209.

Gaughan, A.E., Stevens, F.R., Gibbes, C., Southworth, J. & Binford, M.W. (2012) Linking vegetation response to seasonal precipitation in the Okavango–Kwando–Zambezi catchment of southern Africa. *International Journal of Remote Sensing*, **33**, 6783–6804.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. & Duke, N. (2010) Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, **20**, 154–159.

Grab, S. & Craparo, A. (2011) Advance of apple and pear tree full bloom dates in response to climate change in the southwestern Cape, South Africa: 1973–2009. *Agricultural and Forest Meteorology*, **151**, 406–413.

Guan, K., Medvigy, D., Wood, E.F., Caylor, K.K., Li, S. & Jeong, S. (2014a) Deriving Vegetation Phenological Time and Trajectory Information Over Africa Using SEVIRI Daily LAI. *Geoscience and Remote Sensing*, **52**, 1113–1130.

Guan, K., Wolf, A., Medvigy, D. & Caylor, K. (2013) Seasonal coupling of canopy structure and function in African tropical forests and its environmental controls. *Ecosphere*, **4**, 1–21.

Guan, K., Wood, E.F., Medvigy, D., Kimball, J., Ming Pan, K.K.C., Sheffield, J., Xu, X. & Jones, M.O. (2014b) Terrestrial hydrological controls on land surface phenology of African savannas and woodlands. *Journal of Geophysical Research Biogeosciences*, **119**, 1652–1669.

Heumann, B.W., Seaquist, J.W., Eklundh, L. & Jönsson, P. (2007) AVHRR derived phenological change in the Sahel and Soudan, Africa, 1982-2005. *Remote Sensing of Environment*, **108**, 385–392.

Higgins, S.I., Delgado-Cartay, M.D., February, E.C. & Combrink, H.J. (2011) Is there a temporal niche separation in the leaf phenology of savanna trees and grasses? *Journal of Biogeography*, **38**, 2165–2175.

Higgins, S.I. & Scheiter, S. (2012) Atmospheric CO2 forces abrupt vegetation shifts locally, but not globally. *Nature*, **488**, 209–212.

Huemmrich, K.F., Privette, J.L., Mukelabai, M., Myneni, R.B. & Knyazikhin, Y. (2005) Time-series validation of MODIS land biophysical products in a Kalahari woodland, Africa. *International Journal of Remote Sensing*, **26**, 4381–4398.

Huete, A., Didan, K., Leeuwen, W. Van, Miura, T. & Glenn, E. (2011) *MODIS vegetation indices*. *Land remote sensing and global environmental change* (ed. by B. Ramachandran), C.O. Justice), and M.J. Abrams), pp. 579–602. Springer New York, Springer New York.

Huete, A., Didan, K., Miura, T., Rodriguez, E.., Gao, X. & Ferreira, L.. (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, **83**, 195–213.

Hufkens, K., Friedl, M., Sonnentag, O., Braswell, B.H., Milliman, T. & Richardson, A.D. (2012) Linking near-surface and satellite remote sensing measurements of deciduous broadleaf forest phenology. *Remote Sensing of Environment*, **117**, 307–321.

IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, (ed. by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,1132pp.

Irikefe, V., Vaidyanathan, G., Nordling, L., Twahirwa, A., Nakkazi, E. & Monastersky, R. (2011) Science in Africa: The view from the front line. *Nature*, **474**, 556–559.

Ivits, E., Horion, S., Fensholt, R. & Cherlet, M. (2014) Drought footprint on European ecosystems between 1999 and 2010 assessed by remotely sensed vegetation phenology and productivity. *Global Change Biology*, **20**, 581–593.

Janecke, B.B. & Smit, G.N. (2011) Phenology of woody plants in riverine thicket and its impact on browse availability to game species. *African Journal of Range & Forage Science*, **28**, 139–148.

Jiang, Z., Huete, A.R., Didan, K. & Miura, T. (2008) Development of a two-band enhanced vegetation index without a blue band. *Remote Sensing of Environment*, **112**, 3833–3845.

Jin, C., Xiao, X., Merbold, L., Arneth, A., Veenendaal, E. & Kutsch, W.L. (2013) Phenology and gross primary production of two dominant savanna woodland ecosystems in Southern Africa. *Remote Sensing of Environment*, **135**, 189–201.

Jönsson, P. & Eklundh, L. (2004) TIMESAT - A program for analyzing time-series of satellite sensor data. *Computers and Geosciences*, **30**, 833–845.

Keeling, C.D., Chin, J.F.S. & Whorf, T.P. (1996) Increased activity of northern vegetation inferred from atmospheric CO2 measurements. *Nature*, **382**, 146–149.

Laurance, W.F., Alonso, A., Lee, M. & Campbell, P. (2006) Challenges for forest conservation in Gabon, Central Africa. *Futures*, **38**, 454–470.

Lieth, H. (1974) *Purposes of a phenology book*. *Phenology and seasonality modeling*, pp. 3–19. Springer Berlin Heidelberg.

Linderman, M., Rowhani, P., Benz, D., Serneels, S. & Lambin, E.F. (2005) Land-cover change and vegetation dynamics across Africa. *Journal of Geophysical Research D: Atmospheres*, **110**, 1–15.

Matsumoto, K., Ohta, T., Irasawa, M. & Nakamura, T. (2003) Climate change and extension of the Ginkgo biloba L. Growing season in Japan. *Global Change Biology*, **9**, 1634–1642.

Mbow, C., Fensholt, R., Rasmussen, K. & Diop, D. (2013) Can vegetation productivity be derived from greenness in a semi-arid environment? Evidence from ground-based measurements. *Journal of Arid Environments*, **97**, 56–65.

Menzel, a & Fabian, P. (1999) Growing season extended in Europe. *Nature*, **397**, 659.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aaasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.E., Zach, S. & Zust, A. (2006) European phenological response to climate change matches the warming pattern. *Global Change Biology*, **12**, 1969–1976.

Meroni, M., Fasbender, D., Kayitakire, F., Pini, G., Rembold, F., Urbano, F. & Verstraete, M. (2013) *Regional drought monitoring using phenologicallytuned biomass production estimates from SPOTVEGETATION FAPAR*. *2013 Second International Conference on Agro-Geoinformatics (Agro-Geoinformatics)*, pp. 495–499. IEEE, Piscataway, NJ, USA.

Meroni, M., Fasbender, D., Kayitakire, F., Pini, G., Rembold, F., Urbano, F. & Verstraete, M.M. (2014a) Early detection of biomass production deficit hot-spots in semi-arid environment using FAPAR time series and a probabilistic approach. *Remote Sensing of Environment*, **142**, 57–68.

Meroni, M., Rembold, F., Verstraete, M., Gommes, R., Schucknecht, A. & Beye, G. (2014b) Investigating the Relationship between the Inter-Annual Variability of Satellite-Derived Vegetation Phenology and a Proxy of Biomass Production in the Sahel. *Remote Sensing*, **6**, 5868–5884.

Meroni, M., Verstraete, M.M., Rembold, F., Urbano, F. & Kayitakire, F. (2014c) A phenology-based method to derive biomass production anomalies for food security monitoring in the Horn of Africa. *International Journal of Remote Sensing*, **35**, 2472–2492.

Mitchard, E.T. a., Saatchi, S.S., Gerard, F.F., Lewis, S.L. & Meir, P. (2009) Measuring Woody Encroachment along a Forest–Savanna Boundary in Central Africa. *Earth Interactions*, **13**, 1–29.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G. & Nemani, R.R. (1997) Increased plant growth in the northern latitudes from 1981–1991. *Nature*, **386**, 698–702.

Nasahara, K.N. & Nagai, S. (2015) Review: Development of an in situ observation network for terrestrial ecological remote sensing: the Phenological Eyes Network (PEN). *Ecological Research*, **30**, 211–223.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) *Africa*. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by V.R. Barros), C.B. Field), D.J. Dokken), M.D. Mastrandrea), K.J. Mach), T.E. Bilir), M. Chatterjee), K.L. Ebi), Y.O. Estrada), R.C. Genova), B. Girma), E.S. Kissel), A.N. Levy), S. MacCracken), P.R. Mastrandrea), and L.L.White), pp. 1199–1265. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

O’Farrell, P.J., Donaldson, J.S. & Hoffman, M.T. (2007) The influence of ecosystem goods and services on livestock management practices on the Bokkeveld plateau, South Africa. *Agriculture, Ecosystems and Environment*, **122**, 312–324.

Olsson, L., Eklundh, L. & Ardö, J. (2005) A recent greening of the Sahel—trends, patterns and potential causes. *Journal of Arid Environments*, **63**, 556–566.

Pelkey, N.W., Stoner, C.J. & Caro, T.M. (2003) Assessing habitat protection regimes in Tanzania using AVHRR NDVI composites: Comparisons at different spatial and temporal scales. *International Journal of Remote Sensing*, **24**, 2533–2558.

Peñuelas, J., Rutishauser, T. & Filella, I. (2009) Ecology. Phenology feedbacks on climate change. *Science (New York, N.Y.)*, **324**, 887–888.

Philippon, N., Jarlan, L., Martiny, N., Camberlin, P. & Mougin, E. (2007) Characterization of the interannual and intraseasonal variability of West African vegetation between 1982 and 2002 by means of NOAA AVHRR NDVI data. *Journal of Climate*, **20**, 1202–1218.

Polansky, L. & Boesch, C. (2013) Long-term Changes in Fruit Phenology in a West African Lowland Tropical Rain Forest are Not Explained by Rainfall. *Biotropica*, **45**, 434–440.

Pons, P. & Wendenburg, C. (2005) The impact of fire and forest conversion into savanna on the bird communities of West Madagascan dry forests. *Animal Conservation*, **8**, 183–193.

Reed, B.C. (2007) Trend Analysis of Time-Series Phenology of North America Derived from Satellite Data. *GIScience & Remote Sensing*, **43**, 24–38.

Reed, B.C., Schwartz, M.D. & Xiao, X. (2009) *Remote Sensing Phenology: Status and the way forward*. *Phenology of Ecosystem Processes* (ed. by A. Noormets), pp. 231–246. Springer New York, New York, NY.

Richardson, A.D., Braswell, B.H., Hollinger, D.Y., Jenkins, J.P. & Ollinger, S. V. (2009) Near-surface remote sensing of spatial and temporal variation in canopy phenology. *Ecological Applications*, **19**, 1417–1428.

Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O. & Toomey, M. (2013) Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology*, **169**, 156–173.

Ringelmann, N., Scipal, K., Bartalis, Z. & Wagner, W. (2004) Planting date estimation in semi-arid environments based on Ku-band radar scatterometer data. *IGARSS 2004. 2004 IEEE International Geoscience and Remote Sensing Symposium*, **2**.

Roehrig, J. & Laudien, R. (2009) Evaluation of agricultural land resources by implementing a computer-based spatial decision support system for national deciders in Benin, West Africa. *Journal of Applied Remote Sensing*, **3**, 033502.

Ryan, C.M., Williams, M., Hill, T.C., Grace, J. & Woodhouse, I.H. (2014) Assessing the phenology of southern tropical Africa: A comparison of hemispherical photography, scatterometry, and optical/NIR remote sensing. *IEEE Transactions on Geoscience and Remote Sensing*, **52**, 519–528.

van Schaik, C.P., Terborgh, J.W. & Wright, S.J. (1993) The Phenology of Tropical Forests: Adaptive Significance and Consequences for Primary Consumers. *Annual Review of Ecology and Systematics*, **24**, 353–377.

Schnelle, F. (1955) *Pflanzen-Phänologie*, Leipzig, Germany: Akademische VerlagsgeselIschaft.

Seghieri, J., Carreau, J., Boulain, N., De Rosnay, P., Arjounin, M. & Timouk, F. (2012) Is water availability really the main environmental factor controlling the phenology of woody vegetation in the central Sahel? *Plant Ecology*, **213**, 861–870.

Soudani, K., Hmimina, G., Delpierre, N., Pontailler, J.Y., Aubinet, M., Bonal, D., Caquet, B., de Grandcourt, a., Burban, B., Flechard, C., Guyon, D., Granier, a., Gross, P., Heinesh, B., Longdoz, B., Loustau, D., Moureaux, C., Ourcival, J.M., Rambal, S., Saint André, L. & Dufrêne, E. (2012) Ground-based Network of NDVI measurements for tracking temporal dynamics of canopy structure and vegetation phenology in different biomes. *Remote Sensing of Environment*, **123**, 234–245.

Spiers, A.G. (1999) *Review of international/ continental wetland resources*. *Global review of wetland resources and priorities for wetland inventory* (ed. by C.M. Finlayson) and A.G. Spiers), pp. 63–104. Supervising Scientist Report 144/ Wetlands International Publication 53, Supervising Scientist, Canberra.

Studer, S., Stöckli, R., Appenzeller, C. & Vidale, P.L. (2007) A comparative study of satellite and ground-based phenology. *International Journal of Biometeorology*, **51**, 405–414.

Tappan, G.G., Tyler, D.J., Wehde, M.E. & Moore, D.G. (1992) Monitoring rangeland dynamics in Senegal with advanced very high resolution radiometer data. *Geocarto International*, **7**, 87–98.

Verhegghen, A., Mayaux, P., De Wasseige, C. & Defourny, P. (2012) Mapping Congo Basin vegetation types from 300 m and 1 km multi-sensor time series for carbon stocks and forest areas estimation. *Biogeosciences*, **9**, 5061–5079.

Viennois, G., Barbier, N., Fabre, I. & Couteron, P. (2013) Multiresolution quantification of deciduousness in West-Central African forests. *Biogeosciences*, **10**, 6957–6967.

Vintrou, E., Bégué, A., Baron, C., Saad, A., Seen, D. Lo & Traoré, S.B. (2014) A comparative study on satellite- and model-based crop phenology in West Africa. *Remote Sensing*, **6**, 1367–1389.

Visser, M.E., Caro, S.P., van Oers, K., Schaper, S. V & Helm, B. (2010) Phenology, seasonal timing and circannual rhythms: towards a unified framework. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **365**, 3113–3127.

Vrieling, a, De Beurs, K.M. & Brown, M.E. (2008) Recent trends in agricultural production of Africa based on AVHRR NDVI time series. *Proceedings of SPIE - The International Society for Optical Engineering*, **7104**, 1–10.

Vrieling, A., de Beurs, K.M. & Brown, M.E. (2011) Variability of African farming systems from phenological analysis of NDVI time series. *Climatic Change*, **109**, 455–477.

Vrieling, A., De Leeuw, J. & Said, M.Y. (2013) Length of growing period over africa: Variability and trends from 30 years of NDVI time series. *Remote Sensing*, **5**, 982–1000.

Wagenseil, H. & Samimi, C. (2006) Assessing spatio‐temporal variations in plant phenology using Fourier analysis on NDVI time series: results from a dry savannah environment in Namibia. *International Journal of Remote Sensing*, **27**, 3455–3471.

Wakeling, J.L., Cramer, M.D. & Bond, W.J. (2012) The savanna-grassland “treeline”: Why don’t savanna trees occur in upland grasslands? *Journal of Ecology*, **100**, 381–391.

Wessels, K., Steenkamp, K., Von Maltitz, G. & Archibald, S. (2011) Remotely sensed vegetation phenology for describing and predicting the biomes of South Africa. *Applied Vegetation Science*, **14**, 49–66.

White, M. a., Thornton, P.E. & Running, S.W. (1997) A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biogeochemical Cycles*, **11**, 217–234.

Wolkovich, E.M., Cook, B.I., Allen, J.M., Crimmins, T.M., Betancourt, J.L., Travers, S.E., Pau, S., Regetz, J., Davies, T.J., Kraft, N.J.B., Ault, T.R., Bolmgren, K., Mazer, S.J., McCabe, G.J., McGill, B.J., Parmesan, C., Salamin, N., Schwartz, M.D. & Cleland, E.E. (2012) Warming experiments underpredict plant phenological responses to climate change. *Nature*, **485**, 494–497.

World Bank (2014) *A decade of development in sub-Saharan African science, technology, engineering and mathematics research*, Washington, DC : World Bank Group.

Wright, S.J. & van Schaik, C.P. (1994) Light and the Phenology of Tropical Trees. *The American Naturalist*, **143**, 192–199.

Yamagiwa, J., Basabose, A.K. & Kaleme, K.P. (2008) Phenology of Fruits Consumed By a Sympatric Population of Gorillas and Chimpanzees in Kahuzi- Biega National Park , Democratic Republic of Congo. *Human Evolution*, **Suppl.39**, 3–22.

Zhang, X., Friedl, M. a., Schaaf, C.B., Strahler, A.H. & Liu, Z. (2005) Monitoring the response of vegetation phenology to precipitation in Africa by coupling MODIS and TRMM instruments. *Journal of Geophysical Research D: Atmospheres*, **110**, 1–14.

Zhang, X., Friedl, M., Schaaf, C.B. & Strahler, A.H. (2004) Climate controls on vegetation phenological patterns in northern mid‐and high latitudes inferred from MODIS data. *Global Change Biology*, **10**, 1133–1145.

Zhang, X., Friedl, M., Tan, B., Goldberg, M. & Yu, Y. (2012) Long-Term Detection of Global Vegetation Phenology from Satellite Instruments. *Phenology and Climate Change*, 297–320.

Zhang, X., Tan, B. & Yu, Y. (2014) Interannual variations and trends in global land surface phenology derived from enhanced vegetation index during 1982-2010. *International Journal of Biometeorology*, **58**, 547–564.

Zhao, M., Peng, C., Xiang, W., Deng, X., Tian, D., Zhou, X., Yu, G., He, H. & Zhao, Z. (2013) Plant phenological modeling and its application in global climate change research: overview and future challenges. *Environmental Reviews*, **21**, 1–14.

Zhou, L., Tian, Y., Myneni, R.B., Ciais, P., Saatchi, S., Liu, Y.Y., Piao, S., Chen, H., Vermote, E.F., Song, C. & Hwang, T. (2014) Widespread decline of Congo rainforest greenness in the past decade. *Nature*, **509**, 86–90.

Zhou, L., Tucker, C.J., Kaufmann, R.K., Slayback, D., Shabanov, N. V. & Myneni, R.B. (2001) Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *Journal of Geophysical Research*, **106**, 20069.

Zhu, Z., Wang, S. & Woodcock, C.E. (2015) Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. *Remote Sensing of Environment*, **159**, 269–277.