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Phenology-adaptive pixel-based compositing using optical earth observation imagery

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ABSTRACT

The need for operational monitoring of landscape processes on the national to global scale led to an increased demand for pixel-based composites using complete earth observation (EO) archives. Commonly, composites are generated without explicit consideration of temporal criteria but are rather based on optimizing band indices within a pre-defined temporal window. However, for certain applications phenology-adapted composites that represent the land surface as being in the same phenological stage are required, e.g. tree type discrimination where greening up or senescence dates are modified by terrain elevation. We developed a novel pixel-based compositing technique that dynamically adjusts the selection process to the underlying land surface phenology (LSP) of each pixel. By doing so, phenologically sound composites across large areas can be derived for regular intervals and different phenological points in time, e.g. peak, end or minimum of season. Various day-of-year (DOY) scoring functions were implemented to flexibly define the phenological target. The technique is general enough for global application and can be applied to any kind of gridded EO archive, herein demonstrated for MODIS and Landsat data. Multi-annual composites were successfully generated for Zambia for most seasons. As an exception, we found even very frequent MODIS observations to be insufficient for peak vegetation composites due to interference with the rainy season. The phenology-adaptive composites were compared to static ones, i.e. using a single target DOY. Results clearly indicated that biomass levels differ significantly between the techniques, and a phenological normalization across elevation gradients and land cover classes could be achieved. However, the implications are non-trivial and the characteristics of both methods need to be considered cautiously before deciding which approach is superior with regards to a specific thematic application. The quality of the MODIS and Landsat composites, as well as the performance of the phenology-adaptive and static compositing techniques were assured using a quantitative cross-comparison. A 12-year annual time series demonstrated the feasibility for land cover change and modification mapping. Several change processes were clearly discriminable. The resulting phenologically coherent composites are important to establish national, regional or even global landscape monitoring, reporting and verification systems.

1. Introduction

The need for establishing operational landscape monitoring systems on the national to global scale is more pressing than ever (Hansen and Loveland, 2012), e.g. to support the Reducing Emissions from Deforestation and Forest Degradation (REDD) mechanism. In this context, it is inevitable to establish national measurement, reporting and verification systems (Herold and Skutsch, 2011), which can only be instated on the basis of non-leaking, wall-to-wall remote sensing products (DeFries et al., 2007; Gibbs et al., 2007).

The availability of moderate (100–500 m) to medium (10–100 m) resolution optical imagery steadily increased throughout the past decade, starting with Moderate Resolution Imaging Spectroradiometer data (MODIS. 250–500 m; Justice et al., 2002). Unlimited access to 30 m Landsat data (Woodcock et al., 2008) – recently complemented by 10–20 m Sentinel-2 data (Drusch et al., 2012) – fostered a new era in the field of earth observation (EO) and changed the usage of satellite imagery fundamentally (Wulder et al., 2012). However, with the ever increasing data volume also comes unprecedented data pressure: although data has become available to everyone, the high technical demand in terms of data handling currently bar part of the science community from utilizing complete EO archives adequately. As such, it is of major importance to provide ready-to-use, pre-processed baseline data for regular intervals. Pixel-based composites (PBC) are suitable products as they substantially reduce the data volume to enable 'traditional' analyses (e.g. land cover/change classification as in Griffiths et al., 2013a), provide cloud-free and seamless images over large areas

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(Holben, 1986), but nonetheless make use of the full archive depth implicitly.

The generation of top-of-atmosphere (TOA) reflectance PBCs (e.g. Roy et al., 2010) is a straightforward and often sufficiently precise procedure. However, atmospheric correction is strictly necessary for multi-temporal analyses (Röder et al., 2005). For this purpose, a number of large-area production systems exist (e.g. Masek et al., 2006), which enabled the generation of seamless composites across the Carpathians (Griffiths et al., 2013b) and Canada (White et al., 2014). A full integration with further corrections for topographic and bi-directional effects, as well as homogenizing algorithmic for multiple sensors (e.g. Frantz et al., 2016a) might additionally enable within-state gradual change detection to the full extent – such as forest degradation (Vogelmann et al., in press).

Numerous compositing techniques were developed so far, and a detailed overviews of existing methods and their specific (dis-) advantages can be found in Dennison et al. (2007) or Lück and van Niekerk (2016). Most commonly, compositing criteria are based on optimizing band or index statistics (e.g. Flood, 2013; Holben, 1986), sometimes amended by view angle constraints (e.g. Huete et al., 2002), in order to provide regularly spaced time series with fairly high frequency (e.g. Justice et al., 2002; Roy et al., 2010). Nevertheless, this approach is not feasible where adverse climatic settings and non-systematic acquisition plans prevent gap-free annual coverage (e.g. Griffiths et al., 2013b). As such, another class of compositing algorithms not only uses observations from a narrow temporal window, but instead considers all data within a couple of years. Instead of optimizing a single spectral criterion, a parametric weighting scheme is used to combine a multitude of criteria, especially introducing temporal characteristics to anchor the PBC to a pre-defined Day-of-the-Year (DOY, Griffiths et al., 2013b).

Shortcomings of this method mainly occur where phenological differences within target areas result in spectrally ambiguous composites. For instance, barren fields might be falsely classified as fallows if the composited information was acquired in an unfortunate phenological state (Griffiths et al., 2013a), or seasonal variations in broadleaved canopies might erroneously be classified as deforestation (DeFries et al., 2007). This makes a strong case for the generation of phenologically coherent PBCs, wherein spatial and temporal variations in LSP are considered explicitly. These can result from large-scale factors like climate (White et al., 1997), or can be effective at smaller spatial scales (e.g. due to local variations in water availability). Inter-annual variations in LSP can also be substantial (White et al., 1997).

Consequently, a pixel-based LSP dataset as temporal target layer would allow for a more data-driven parameterization and could eliminate the need to manually parameterize the target DOY. Accordingly, we propose a compositing technique, that

1) employs a parametric weighting scheme with full consideration of annual LSP at the pixel-scale, to generate phenologically coherent composites across large areas,
2) allows for a data-driven parameterization of temporal compositing characteristics,
3) is flexible with regards of using different compositing criteria,
4) is general enough for global application, and
5) may be applied to any gridded EO archive.

We introduce our study area with an emphasis on LSP determinants in Section 2. Section 3 provides a brief input data description regarding reflectance and LSP products, including an assessment of data availability. The phenology-adaptive compositing technique is described in Section 4, and will be applied to MODIS and Landsat data. It is assessed whether the selected observations are close to the target DOY and year. As a direct result of the outstanding temporal characteristics of MODIS, we demonstrate the effectiveness of our approach by comparing phenology-adaptive MODIS PBCs to their "fixed-DOY" equivalents using differences in the Enhanced Vegetation Index (EVI), followed by a quantitative analysis and a demonstration of the phenological normalization across an elevation gradient and between land covers. Global applicability is demonstrated by generating MODIS PBCs across a large latitudinal gradient. The Landsat PBC quality is ensured by a quantitative comparison to MODIS, and eventually, a 12-year annual Landsat time series is employed to characterize drastic and decadal-scale scale landscape dynamics. Results are presented in Section 5, and are discussed in Section 6, including a discussion of the utility of the phenology-adaptive and static techniques with regard to different applications. The paper ends with conclusions in Section 7.

2. Study area

Zambia was chosen as primary study area (approx. 750×10^3 km^2) due to its relevance as being qualified for REDD support. Furthermore, the interaction of regional wind currents and terrain supported the development of distinct vegetation patterns with both large-scale gradients and local variations in LSP.

Zambian climate is strongly dependent on elevation, and features tropical-warm climate on the predominant high plateaus (1000 m a.s.l.). Tropical-hot climate characterizes the lower valley plains (325–920 m a.s.l.) in the South, while tropical-cool climate is found on the highest plateaus, e.g. the Nyika Plateau in the North-East (2100–2200 m a.s.l.). The terrain of Zambia is shown in Fig. 1*a*). The seasonality is closely tied to seasonal changes in large scale air movement and solar configuration, which results in three hygrothermal seasons; i.e. (i) the hot wet season (November–April), (ii) cool dry season (May–August) and (iii) hot dry season (September–October). The season start, end and lengths, and the precipitation sums are altered both by the local relief and by the geographic location. In general, the season lengths and the precipitation sums decrease from North-West (180–190 days, 1000–1400 mm) to South-East (120–130 days, <800 mm) due to the temporally shorter influence of the Intertropical Convergence Zone (ITCZ) in the South. The on- and offsets of the rains are also tied to the migration of the ITCZ over Zambia, which is located north of Zambia during the dry season. On average, the rains start in mid-October in the North-West and arrive in the South-East at the end of November. The rains stop in the South at mid-March and last until the end of April in the North-West. The monthly rainfall sums for 2005 are shown in Fig. 1*b*). The timing of the minimum and maximum temperatures also follow this pattern, where the coolest temperatures are found in June/July and the hottest temperatures in October/November immediately before the onset of the rains (Schultz, 1983).

The main part of the country is covered by semi-evergreen Miombo woodlands. Evergreen dry forests are found in western Zambia on infertile Kalahari sands and are replaced by grasslands where seasonal waterlogging suppresses tree growth. The drier and hotter southern part of the country is dominated by deciduous woodlands, where Mopane woodlands are found in the lowest and driest regions. Permanent shallow flooding along the rivers and swamps, in combination with the relatively flat terrain support large areas of seasonally flooded grasslands (Olson et al., 2001).

3. Data

3.1. Surface reflectance

3.1.1. MODIS

We acquired daily MODIS surface reflectance images (MOD09GA) with 500 m spatial and 1–2 day nominal temporal resolution (Vermote and Vermeulen, 1999) from the Land Processes Distributed Active Archive Center's (LP DAAC) Data Pool. All images between 2003 and 2007 for the four tiles covering Zambia (as well as for 11 tiles covering a large latitudinal gradient) were downloaded, resulting in 1814 images per tile. The number of clear-sky observations is shown in Fig. 2(*a*); on average 625 observations were available ($\sigma = 147$, min =