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Using spatial context to improve early detection of deforestation from Landsat time series

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ABSTRACT

Mapping deforestation using medium spatial resolution satellite data (e.g. Landsat) is increasingly shifting from decadal and annual scales to sub-annual scales in recent years, but this shift has brought new challenges on how to account for seasonality in the satellite data when detecting deforestation. A seasonal model is typically used to account for seasonality, but fitting a seasonal model is difficult when there are not enough data in the time series. Here, we propose a new approach that reduces seasonality in satellite image time series using spatial context. With this spatial context approach, each pixel value in the image is spatially normalised using the median value calculated from neighbouring pixels whose pixel values are above the 90th percentile. Using Landsat data, we compared our spatial context approach to a seasonal model approach at a humid tropical forest in Brazil and a dry tropical forest with strong seasonality in Bolivia. After reducing seasonal variations in Landsat data, we detected deforestation from the same data using the Breaks For Additive Season and Trend (BFAST) method. We show that, in dry tropical forest, deforestation events are detected much earlier when the spatial context approach is used to reduce seasonal variations in Landsat data than when a seasonal model is used. In the dry tropical forest, the median temporal detection delay for deforestation from the spatial context approach was two observations, seven times shorter than the median temporal detection delay from the seasonal model approach (15 observations). In the humid tropical forest, the difference in the temporal detection delay between the spatial context and seasonal model approach was not significant. The differences in overall spatial accuracy between the spatial context and seasonal model were also not significant in both dry and humid tropical forests. The main benefit for using spatial context is early detection of deforestation events in forests with strong seasonality. Therefore, the spatial context approach we propose here provides opportunity to monitor deforestation events in dry tropical forests at sub-annual scales using Landsat data.

1. Introduction

Mapping deforestation using medium spatial resolution satellite data (e.g. Landsat) is increasingly shifting from decadal (Achard et al., 2014) and annual scales (DeVries, Verbesselt, Kooistra, & Herold, 2015; Griffiths et al., 2012; Kennedy, Yang, & Cohen, 2010; Souza et al., 2013) to sub-annual scales (Dutrieux, Verbesselt, Kooistra, & Herold, 2015; Reiche, Verbesselt, Hoekman, & Herold, 2015b) mainly because of increased temporal availability of medium spatial resolution satellite data in recent years. Mapping deforestation from medium spatial resolution satellite data at sub-annual scales is beneficial because it provides opportunity for timely detection of small deforestation events that cannot be detected from coarse spatial resolution data. Currently, however, detecting deforestation from medium spatial resolution satellite data at sub-annual scales is challenging especially in forests that exhibit strong seasonality in their photosynthetic activity. Satellite images from medium spatial resolution satellite sensors are often not acquired regularly in all parts of the globe. Methods (e.g. DeVries et al., 2015; Verbesselt, Zeileis, & Herold, 2012; Zhu & Woodcock, 2014), which are used to detect deforestation at sub-annual scales from satellite image time series, account for seasonality in the time series using a seasonal model. The use of a seasonal model is based on an assumption that there is an identifiable seasonal pattern in the time series which can be described mathematically (Cleveland, Cleveland, McRae, & Terpenning, 1990). However, this assumption may not always hold if the time series is for satellite images which are not acquired at regular interval, or have wide temporal gaps due to persistent cloud cover (Asner, 2001). Oftentimes, however, a seasonal model is still used to account for seasonality in such image time series (DeVries et al., 2015; Zhu & Woodcock, 2014). Yet, we do not know if using a seasonal model to account for seasonality in satellite image times which are not acquired at regular interval affects our ability to detect deforestation events early.

Recently, time series from coarse resolution sensors (e.g. Moderate Resolution Imaging Spectroradiometer) have been used to derive the seasonal patterns when mapping deforestation at sub-annual scales from medium spatial resolution satellite data (Dutrieux et al.,

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2015).The approach of using time series from coarse resolution sensors to address the problem of seasonality in medium spatial resolution satellite data is novel and can be viewed as a synergistic way of using satellite data (De Sy et al., 2012; Reiche et al., 2015b; Zhang, 2010). The weakness of this approach, however, is its reliance on data from another sensor to account for seasonality in Landsat data. If the sensor producing data that are used to derive the seasonal pattern fails, the approach would also not work anymore. To avoid such situation, methods that can address the issue of seasonality in image time series without using data from other satellite sensors to derive the seasonal pattern are critically needed and should be developed.

Instead of using a seasonal model to account for seasonality in image time series, we can potentially use spatial context. Here, spatial context refers to spatial neighbourhood of a focal pixel — the pixel which is being processed. There are several ways we can use spatial context to address the challenge of seasonality in image time series. For example, we can assume that pixels within a spatial neighbourhood of a focal pixel are likely to exhibit temporal dynamics similar to that of the focal pixel. Based on this assumption, we can simply calculate similarity between values of the neighbouring pixels and the focal pixel at each time step, resulting into a time series of similarity measures (Lhermitte, Verbesselt, Verstraeten, & Coppin, 2011). Similarity measures calculated during the growing season are likely to be similar to those calculated during senescence. In this way, deforestation can then be mapped from the time series of similarity measures. To calculate similarity measures in a consistent manner, however, reference pixels need to be selected and such pixels themselves should remain stable for the period under consideration. The challenge, however, is on how to keep the same cohort of reference pixels throughout the entire time series because, at some time steps, selected reference pixels might be affected by clouds, and would be masked out by cloud masking algorithm. Such challenge makes the method of calculating similarity measures to minimise the seasonal variations in image time series cumbersome. Another spatial context method that can be used to tackle the problem of seasonal variations in image time series is the one applied in vegetation regeneration studies. In such studies, regeneration of vegetation after fire is usually characterised from satellite data by calculating the ratio between burned plot pixels and un-burned plot pixels at each time step, resulting into the so-called regeneration index time series (Lhermitte et al., 2011). In a simplistic view, such method can be viewed as local normalisation of pixel values using spatial context. The problem with such method, however, is that pixels which are similar to the focal pixel prior to a fire event should be used as a reference when calculating regeneration index (Lhermitte et al., 2011). Such requirement has some crucial advantages, but is equally problematic because if the reference pixels happen to be disturbed at some subsequent time steps they can no longer be useful references. A new method that does not require selection of reference pixels when using spatial context to tackle the problem of seasonal variations in image time series is, therefore, desirable.

In this paper, our objectives were (1) to investigate how spatial context can be used to reduce seasonal variations in satellite image time series, and (2) to assess whether using spatial context to reduce seasonal variations in satellite image time series leads to earlier detection of deforestation events than when a seasonal model is used. To achieve these objectives, we proposed a new spatial context approach for reducing seasonal variations in satellite image time series, and compared the results from the spatial context approach to those where a seasonal model is used to account for seasonality. Normalised difference vegetation index (NDVI) (Tucker, 1979) derived from Landsat Thematic Mapper (TM 5) and Enhanced Thematic Mapper Plus (ETM+ 7) images spanning from April 1984 to December 2014 was used as an indicator of vegetation temporal dynamic. Deforestation events were detected using Breaks For Additive Season and Trend (BFAST, Verbesselt et al., 2012), a change detection method capable of detecting forest cover disturbances at sub-annual scales (Dutrieux et al., 2015; Reiche et al., 2015b). BFAST was first proposed by Verbesselt, Hyndman, Newnham, & Culvenor (2010) and later optimised by Verbesselt et al. (2012) for near real-time detection of disturbances from satellite image time series based on structural change monitoring framework (Chu, Stinchcombe, & White, 1996; Leisch, Hornik, & Kuan, 2000; Zeileis, Leisch, Kleiber, & Hornik, 2005). With BFAST, the history and monitoring periods are first defined. History period contains the historical data whereas the monitoring period contains newly acquired observation that should be assessed for disturbance. To assess the newly acquired observation for disturbance, regression coefficients are first estimated from the historical data, and subsequently used to predict the value of an incoming observation in the monitoring period. Approaches for testing for structural change in the time series (Chu et al., 1996; Zeileis et al., 2005) are then used to assess if the incoming observations are significantly different when compared to the prediction based on the history period. We hypothesised that deforestation events would be detected much earlier from the time series whose seasonality is reduced using spatial context than from time series whose seasonality is accounted for using a seasonal model.

2. Study area

Our study focused at two tropical forest sites, a humid and dry forest (Fig. 1). The humid forest site, covering an area of about 10,000 km^2, is located west of Ariquemes, Rondonia State, Brazil (centred at: 10.2952° S, 64.0478° W). The dry forest site, also covering 10,000 km^2, is located in south east of Santa Cruz de la Sierra, Bolivia (centred at: 18.388° S, 62.361° W). These two sites have similar rainfall pattern throughout the year, but the Brazilian site receive higher rainfall per month (Fig. 2). Compared to the Bolivian site, the study site in Brazil is closer to the equator, and this may explain why the rainfall per month is much higher. This high rainfall per month also means more cloud cover and atmospheric contamination in the satellite data. The forest at the Brazilian site exhibits weak seasonality in its photosynthetic activity, typical of an evergreen tropical forest (Fig. 3). In contrast, the forest at the Bolivian site is characterised by strong seasonality in its photosynthetic activity, typical of dry tropical forest (Fig. 3). Deforestation at the Bolivian site is dominated mainly by industrial agricultural expansion with large blocks of deforestation events whereas at the Brazilian site deforestation events are heterogeneous and correspond mostly to a process of colonisation. The forests at these two sites have varying degree of seasonality, thus providing an ideal opportunity to evaluate whether using spatial context to reduce seasonal variations in image time series is more beneficial than using a seasonal model when detecting deforestation at sub-annual scales.

3. Data and pre-processing steps

3.1. Landsat data and tree cover percent dataset

We used NDVI time series derived from terrain corrected (L1T) Landsat TM 5 and ETM + 7 images, spanning from April 1984 to December 2014. Landsat images were obtained from The United State of America's Geological Survey (USGS) Landsat Surface Reflectance (SR) Climate Data Records (CDR). Landsat SR CDR Products are atmospherically and geometrically corrected. In total, 448 L1T images were used at the Bolivian study site, and 228 L1T images at the Brazilian study site. Clouds and cloud-shadows were masked out using the Function of mask (Fmask) outputs (Zhu & Woodcock, 2012), which were distributed with Landsat SR CDR Products by The United State of America's Geological Survey (USGS). We masked non-forest areas using the Landsat tree cover continuous fields for 2005 (Sexton et al., 2013).To ensure that we do not analyse pixels with insufficient data, we also masked pixels which had less than 15 observations in their entire time series and less than 6 observations in the historical period — the period prior to year 2005.