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Performance of vegetation indices from Landsat time series in deforestation monitoring

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ABSTRACT

The performance of Landsat time series (LTS) of eight vegetation indices (VIs) was assessed for monitoring deforestation across the tropics. Three sites were selected based on differing remote sensing observation frequencies, deforestation drivers and environmental factors. The LTS of each VI was analysed using the Breaks For Additive Season and Trend (BFAST) Monitor method to identify deforestation. A robust reference database was used to evaluate the performance regarding spatial accuracy, sensitivity to observation frequency and combined use of multiple VIs. The canopy cover sensitive Normalized Difference Fraction Index (NDFI) was the most accurate. Among those tested, wetness related VIs (Normalized Difference Moisture Index (NDMI) and the Tasselled Cap wetness (TCw)) were spatially more accurate than greenness related VIs (Normalized Difference Vegetation Index (NDVI) and Tasselled Cap greenness (TCg)). When VIs were fused on feature level, spatial accuracy was improved and overestimation of change reduced. NDVI and NDFI produced the most robust results when observation frequency varies.

1. Introduction

Between 2000 and 2012, global forest loss increased by approximately 2000 km^2 per year (Hansen et al., 2013). Deforestation contributed to around 8% of anthropogenic carbon emissions in the 2000 s (Tubiello et al., 2015), and despite forests remaining a sink, emissions from degradation were 0.80 Gt CO_2 yr^{-1} between 1990 and 2015 (Federici et al., 2015). Mechanisms such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) aim to reduce forest loss and increase carbon sequestration in forests (UNFCCC, 2016). Monitoring, Reporting and Verification (MRV) of REDD+ carbon stock changes is mandatory and requires consistent and long term monitoring of forests supported by field observations (Arino et al., 2012), (De Sy et al., 2012). The Landsat mission can be a key component of such MRV methodologies, as it provides long term medium resolution (10–60 m) remote sensing data (Gutman et al., 2008; Skole and Tucker, 1993; Townshend and Justice, 1988). The availability of free Landsat data (Woodcock et al., 2008) created a paradigm change in how Landsat data is used, away from bi-temporal analysis towards time series analysis (Hansen and Loveland, 2012). In addition, an increase in computational capacities (Evangelidis et al., 2014) resulted in forest change maps of unprecedented scale and resolution (Hansen et al., 2013). Time series analysis methods applied to Landsat data were inspired by previous developments of coarse spatial resolution systems such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) (Cihlar et al., 1997; Roerink et al., 2000; Verbesselt et al., 2010; Forkel et al., 2013; de Jong et al., 2012; Tucker et al., 2005). Compared to those missions, Landsat offers the longest running cross-calibrated globally consistent record of the Earth's surface at medium resolution. Since the opening of the archive, many studies demonstrated Landsat's capabilities for mapping forest cover and related changes (Hansen and Loveland, 2012), (Wulder et al., 2012; Roy et al., 2014; Loveland and Dwyer, 2012; Woodcock and Ozdogan, 2012; Trenberth et al., 2013; Pflugmacher et al., 2012) with an increasing density of Landsat time series (LTS) (Achard et al., 2014; Huang et al., 2010; Zhu et al., 2012; Broich et al., Apr. 2011; Cohen et al., 2010). Methods developed for temperate forests can often be characterized by a higher frequency of observations than in tropical areas which are characterized by persistent cloud cover (Romijn et al., May 2012). When large areas are under investigation, methods have to cope with very different observation frequencies, often requiring complex solutions (Broich et al., Apr. 2011). Empiri-

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cal studies show strong correlations between vegetation indices (VIs), and vegetation parameters such as biomass and canopy closure (Avitabile et al., 2012; Myneni and Hall, 1995). VIs are useful for assessing the amount and condition of vegetation, while suppressing noise, soil background and atmospheric effects (Jackson and Huete, 1991). VIs have become a standard for the interpretation of vegetation dynamics such as deforestation, and have been applied on LTS (Forkel et al., 2013; de Jong et al., 2012; Verbesselt et al., 2012). In this paper, we compare the suitability of different VIs for mapping deforestation when using the Breaks For Additive Season and Trend (BFAST) Monitor algorithm. BFAST recently emerged as a reliable tool to detect ecosystem disturbances such as droughts, fires and vegetation changes (Verbesselt et al., 2010, 2012; Hutchinson et al., 2015; Watts and Laffan, 2014) in agricultural (Atzberger, 2013) and forested landscapes (Schmidt et al., 2015; Lambert et al., 2013, 2015). Moreover, BFAST Monitor proved its robustness when applied to more infrequent time series such as Landsat, Landsat – SAR fused series or Landsat – MODIS fused series (DeVries et al., 2015a; Reiche et al., 2015; Dutrieux et al., 2015; Hamunyela et al., 2016; DeVries et al., 2015b). The observation frequency of a pixel's time series determines the ability of BFAST Monitor to describe the time series, and therefore affects its ability to detect deforestation. More observations can describe seasonality and deforestation with a higher temporal resolution and thus tend to be more accurate (Schultz et al., 2015, 2013). So far, the algorithm has only been applied to the Enhanced Vegetation Index (EVI), Normalized Difference Moisture Index (NDMI) and Normalized Difference Vegetation Index (NDVI) time series. The performance of BFAST Monitor when using other VIs has not yet been assessed. The goal of this study was to identify which VIs can detect deforestation in the tropics better when applying BFAST Monitor on LTS. Given the constraint of highly varying observation frequencies in the tropics we test the capacity of VIs to produce robust and consistent results while varying observation frequency. Since different VIs might have different success rates depending on the type of deforestation mapped, our study covers three areas in the tropics characterized by different forest change dynamics. In addition, we tested whether data fusion of multiple maps at feature level can provide increased mapping accuracy. Ensemble classification has proved useful in combining various mapping outcomes of various inputs to produce one highly accurate map, and among those classification algorithms, random forest is the most prominent (Pal, 2005; Ceamanos et al., 2010; Gislason et al., 2006). We addressed the following objectives:

- Identify the most spatially accurate VI for deforestation mapping when applying BFAST Monitor to LTS
- Understand the VI's spatial accuracy regarding its sensitivity towards observation frequency per site (Brazil, Ethiopia, Vietnam)
- Explore the potential of feature level data fusion of VIs to complement each other and increase accuracy

To address these objectives, three sites in Brazil, Ethiopia and Vietnam were investigated for recent forest changes (2010–2013) using a reference database.

2. Material and methods

Fig. 1 outlines the study. First, LTS were created in three sites (Brazil, Ethiopia, Vietnam) (Section 2.1), which were selected based on their differing ecosystem characteristics, frequency of observations, and deforestation types. Landsat data processing included screening of each image for clouds and their shadows as well as non-forest masking (Section 2.2). Eight VIs were computed for the time series of each site, the EVI, Global Environment Monitoring Index (GEMI), Normalized Difference Fraction Index (NDFI), NDMI, NDVI, Soil Adjusted Vegetation Index (SAVI), Tasselled Cap wetness (TCw), Tasselled Cap greenness (TCg) (Section 2.3). Each of the 24 resulting time series was then analysed for deforestation occurring between 2010 and 2013 using the BFAST Monitor method (Section 2.4). The spatial accuracy (hereafter referred to as accuracy) of each derived deforestation map was assessed using reference data based on high resolution imagery (Section 2.5). To understand the VIs sensitivity to the observation frequency a model was constructed depicting this relationship (Section 2.6). Feature level data fusion of the VI maps was then tested (Section 2.7).

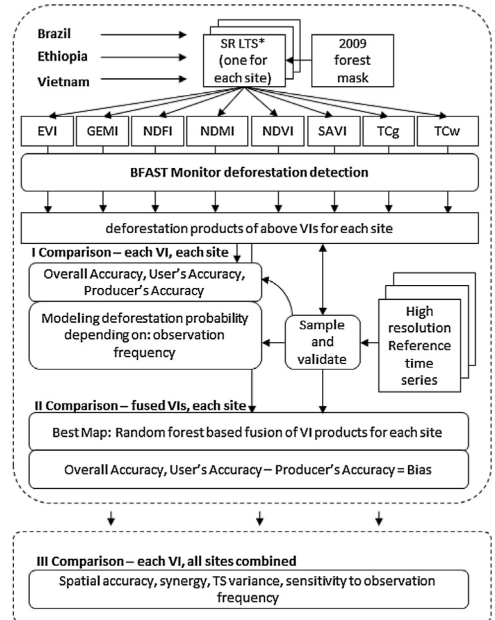

Fig. 1. Overview of the study setup. *SR LTS = Surface reflectance Landsat time series, TS variance and Synergy are explained in the caption of Fig. 7.

2.1. Study sites

Table 1 provides an overview of site properties and statistics of the time series used. The Brazil site is located within the municipality of Paragominas; its evergreen humid forest is managed and used for timber production. Gradual deforestation occurs as well as large patches of timber extraction. The climate is tropical equatorial with an average precipitation of 29 mm (June) to 391 mm (March), and the topography is flat. The Ethiopia site is part of the UNESCO Kafa Biosphere Reserve and deforestation is mainly driven by expansion of smallholder coffee plantations within mixed evergreen and dry-tropics forest production systems. Typically small incremental changes occur which gradually push back the forest boundary. The climate is tropical humid with an average annual precipitation of 1300 mm, and it has a rugged topography (Schmitt et al., 2010). The Vietnam site is situated in the highlands of Quang Nam province; the humid evergreen forest is little managed and natural forest is mainly removed for slash and burn agriculture. The climate is characterized by sudden heavy monsoon rains and has an average precipitation of 35 mm (February) to 425 mm (October) due to its situation on the boundary between the mesothermal climate in the north and the tropical conditions in the south (MONRE, 2006, 2007).