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Fusing Landsat and SAR time series to detect deforestation in the tropics

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ABSTRACT

Fusion of optical and SAR time series imagery has the potential to improve forest monitoring in tropical regions, where cloud cover limits optical satellite time series observations. We present a novel pixel-based Multi-sensor Time-series correlation and Fusion approach (MulTiFuse) that exploits the full observation density of optical and SAR time series. We model the relationship of two overlapping univariate time series using an optimized weighted correlation. The resulting optimized regression model is used to predict and fuse two time series. Using the MulTiFuse approach we fused Landsat NDVI and ALOS PALSAR L-band backscatter time series. We subsequently used the fused time series in a multi-sensor change detection framework to detect deforestation between 01/2008 - 09/2010 at a managed forest plantation in the tropics (*Pinus caribea*; 2859 ha). 3-monthly reference data covering the entire study area was used to validate and assess spatial and temporal accuracy. We tested the impact of persistent cloud cover by increasing the per-pixel missing data percentage of the NDVI time series stepwise from ~53% (~6 observations/year) up to 95% (~0.5 observation/year) while fusing with a consistent PALSAR time series of ~2 observations/year. A significant linear correlation was found between the Landsat NDVI and ALOS PALSAR L-band SAR time series observables for logged forest. The multi-temporal filtered PALSAR HVHH backscatter ratio time series ($HVHH_{mt}$) was most strongly correlated with the NDVI time series. While for Landsat-only the spatial and temporal accuracy of detected deforestation decreased significantly with increasing missing data, the accuracies for the fused NDVI-PALSAR case remained high and were observed to be above the NDVI- and PALSAR-only cases for all missing data percentages. For the fused NDVI-$HVHH_{mt}$ time series the overall accuracy was 95.5% with a 1.59 month mean time lag of detected changes. The MulTiFuse approach is robust and automated, and it provides the opportunity to use the upcoming data streams of free-of charge, medium resolution optical and SAR satellite imagery in a beneficial way for improved tropical forest monitoring.

1. Introduction

Forest change is one of the major processes of global land-cover change (Foley et al., 2005). In particular tropical regions have been undergoing rapid changes in forest cover since the 1980s (Achard, Stibig, & Eva, 2010; Achard et al., 2014; Gullison et al., 2007; Hansen, Potapov, & Moore, 2013; Hansen et al., 2008; Stern, 2007; van der Werf et al., 2009). These changes are regarded as one of the major sources of greenhouse gas emissions (Harris et al., 2012; Zarin, 2012). Consistent and accurate detection of tropical forest changes is fundamental to reliably estimating greenhouse gas emissions and successful implementation of climate mechanisms such as REDD + (Herold & Skutsch, 2011; Pelletier, Ramankutty, & Potvin, 2011; UNFCCC, 2009). To assess historical and future changes in forest area and carbon stocks, satellite-based remote sensing at medium spatial resolution (10–30 m) supported by field observations is the appropriate tool for most tropical countries (Sy, Herold, Achard, & Asner, 2012) that currently lack sufficient national forest monitoring capacities (Romijn, Herold, Kooistra, Murdiyarso, & Verchot, 2012).

Current and anticipated optical and SAR satellite missions (Fig. 1) have been listed as core missions by the CEOS Space Data Coordination Group (CEOS, 2014). Their aim is to support systematic worldwide forest monitoring by providing long term medium resolution time series data with a free and open data policy (GFOI, 2013a). There has been some temporal overlap between different optical and SAR satellite systems available for forest change assessments. However, varying overlapping periods, uncoordinated observation strategies, and user-unfriendly data policies and data access procedures have resulted in data from different satellite missions rarely being used in combination to track forest changes in the tropics. With a data archive spanning over 40 years, Landsat provides the longest and most sophisticated record of medium spatial resolution satellite imagery (Roy et al., 2014). For many tropical countries, very limited or no observations are available for the 1980s and 1990s due to a non-global observation strategy (Goward, Arvidson, & Williams, 2006) and a lack of available ground stations in the past (Arvidson, Goward, Gasch, & Williams, 2006). Since the mid-1990s a number of optical and C- and L-band radar

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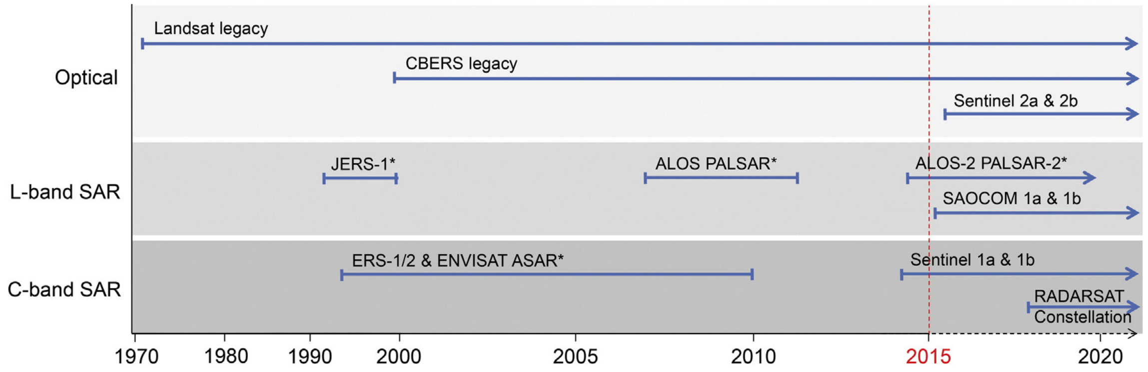

Fig. 1. Current and anticipated medium resolution optical and SAR satellite missions selected by CEOS Space Data Coordination Group as core missions to provide time series data in support of worldwide forest mapping. Important missions with non-core status due to restricted data access policy in 2014 are denoted with an asterisk (adapted from CEOS, 2014).

satellite constellations have provided an additional source of time series data. With the Landsat Data Continuous Mission (LDCM, Irons, Dwyer, & Barsi, 2012) and the planned launch of a multiple optical and SAR satellite systems in the next decade, the continuation of these data streams will be ensured and synergy across multiple data sources encouraged. Such efforts on multi-sensor synergies support the clearly defined goal of the responsible space agencies to increase the detail and accuracy of time series to assess forest changes in the tropics (Drusch et al., 2012; Irons et al., 2012; Suzuki, Kankaku, & Osawa, 2013; Torres et al., 2012).

After the opening of the Landsat archive (Woodcock et al., 2008) many studies demonstrated the operational capabilities of optical medium resolution satellite imagery for detecting changes and trends in forest cover from local to global scales (Achard et al., 2014; Carreiras, Jones, Lucas, & Gabriel, 2014; Griffiths et al., 2013; Hansen et al., 2013; Hirschmugl, Steinegger, Gallaun, & Schardt, 2014; Huang et al., 2010; Kennedy, Yang, & Cohen, 2010; Lehmann, Wallace, Caccetta, Furby, & Zdunic, 2013; Margono et al., 2012; Margono, Potapov, Turubanova, Stolle, & Hansen, 2014; Masek et al., 2013; Souza et al., 2013; Potapov et al., 2012; Zhu, Woodcock, & Olofsson, 2012; Zhu & Woodcock, 2014). The main limitation of optical remote sensing methods in tropical regions is the restricted data availability due to frequent cloud cover (Asner, 2001; Hirschmugl et al., 2014; Souza, Cochrane, Sales, Monteiro, & Mollicone, 2009; Souza et al., 2013). In fact, some tropical countries experience cloud cover exceeding the long-term yearly average frequency of 80% (Herold, 2009). Persistent cloud cover inhibits full optical coverage from Landsat-like sensors even when compositing is performed over a period of 1–2 years (Reiche et al., 2013; Souza et al., 2013). Overcoming this problem in forest change monitoring is still an open research issue (Romijn et al., 2012) that requires deliberate attention in order to provide more accurate and spatially consistent forest activity data which is key to making climate mechanisms such as REDD+ viable (Pelletier et al., 2011).

The increasing availability of freely available time series data for large areas provides the opportunity to benefit from multiple satellite observation sources. In order to fully realize the potential of these time series and to tackle the problem of frequent cloud cover in the tropics, a shift is needed from traditional bi-temporal change detection approaches (Coppin, Jonckheere, Nackaerts, Muys, & Lambin, 2004; Lu, Mausel, Brondizio, & Moran, 2004), in which many changes are missing and the timing of changes is disregarded, to time series based change detection methods (Hansen & Loveland, 2012; Lu, Li, & Moran, 2014) which are capable of exploiting the full temporal detail of available archives (Irons et al., 2012; Verbesselt, Zeileis, & Herold, 2012).

A number of methods for analysing the entire temporal detail of optical time series have been introduced in recent years and successfully applied to detect natural and human induced forest change (Kennedy et al., 2010; Potapov et al., 2012; Verbesselt, Hyndman, Newnham, & Culvenor, 2010; Verbesselt et al., 2012; Zhu & Woodcock, 2014; Zhu et al., 2012). However, a number of shortcomings have been identified for these methods. First, all introduced methods were demonstrated with imagery from a single optical sensor, and only in areas where a large number of observations were available. Second, the performance of the methods in tropical regions under persistent cloud cover was not investigated. Finally, annual mapping resolution validated with independent reference was not exceeded. Often the Landsat time series data itself has served as reference data.

Synthetic Aperture Radar (SAR) data are not affected by cloud cover and provide continuous time-series information. For most tropical countries, however, the density of C- and L-band observations is low, with only a small number of images available per year (Rosenqvist, Shimada, Member, Ito, & Watanabe, 2007). Unlike optical sensors, SAR penetrates into the forest canopy and thus returns signal derived from its physical structure. In particular, multi-temporal L-band SAR backscatter provided by JERS (1992–1998) and ALOS PALSAR (2006–2011) have been proven suitable for detecting tropical deforestation (Almeida-Filho, Rosenqvist, Shimabukuro, & Silva-Gomez, 2007; Almeida-Filho, Shimabukuro, Rosenqvist, & Sanchez, 2009; Motohka, Shimada, Uryu, & Setiabudi, in press; Reiche et al., 2013; Rosenqvist et al., in press; Simard, Saatchi, Grandi, & Member, 2000; Thapa, Shimada, Watanabe, & Motohka, 2013; Whittle, Quegan, Uryu, Stüewe, & Yulianto, 2012), even at a global scale (Shimada et al., in press). Due to the high penetration depth of L-band into the canopy, disturbed and undisturbed forest are more enhanced compared to C-band (Luckman, Baker, Kuplich, da Costa Freitas Yanasse, & Frery, 1997; Ribbes et al., 1997). The main degrading factor for SAR data is SAR speckle resulting in poor radiometric resolution which negatively affects classification results (Quegan & Toan, 1998; Quegan & Yu, 2001). The most common method to reduce SAR speckle is bi-dimensional (spatial domain) SAR speckle filtering (Oliver & Quegan, 1998; Trouvé, Chambenoit, Classeau, & Bolon, 2003). Having time series data available allows additional speckle reduction in the temporal domain using a multi-temporal SAR filter. In contrast to conventional bi-dimensional SAR speckle filters that result in a trade-off between speckle-reduction and decreased spatial resolution, multi-temporal SAR filters reduce the SAR speckle with minimal loss of radiometric accuracy and spatial resolution of single channels (Quegan & Yu, 2001; Quegan, Yu, & Le Toan, 2000; Trouvé et al., 2003).

Multi-sensor data fusion (Zhang, 2010) approaches that combine SAR and Landsat-like optical sensors have clearly demonstrated an increase in forest mapping accuracy (Almeida-Filho et al., 2007; Erasmi & Twele, 2009; Kuplich, 2006; Lehmann et al., 2011; Lehmann et al., 2012; Reiche et al., 2013; Vaglio Laurin et al., 2013; Walker, Stickler, Kellndorfer, Kirsch, & Nepstad, 2010). Approaches that combine optical and SAR time series imagery for detecting forest changes (Lehmann et al., 2012; Reiche et al., 2013), however, are rather limited to date (Lu et al., 2014). Various challenges including accurate co-registration, dealing with spectral variation in the time series (Zhang, 2010) and