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Monitoring rubber plantation expansion using Landsat data time series and a Shapelet-based approach

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ABSTRACT

The expansion of tree plantations in tropical forests for commercial rubber cultivation threatens biodiversity which may affect ecosystem services, and hinders ecosystem productivity, causing net carbon emission. Numerous studies refer to the challenge of reliably distinguishing rubber plantations from natural forest, using satellite data, due to their similar spectral signatures, even when phenology is incorporated into an analysis. This study presents a novel approach for monitoring the establishment and expansion of rubber plantations in Seima Protection Forest (SPF), Cambodia (1995–2015), by detecting and analyzing the 'shapelet' structure in a Landsat-NDVI time series. This paper introduces a new classification procedure consisting of two steps: (1) an exhaustive-searching algorithm to detect shapelets that represent a period for relatively low NDVI values within an image time series; and (2) a *t*-test used to determine if NDVI values of detected shapelets are significantly different than their non-shapelet trend, thereby indicating the presence of rubber plantations. Using this approach, historical rubber plantation events were mapped over the twenty-year timespan. The shapelet algorithm produced two types of information: (1) year of rubber plantation establishment; and (2) pre-conversion land-cover type (i.e., agriculture, or natural forest). The overall accuracy of the rubber plantation map for the year of 2015 was 89%. The multi-temporal map products reveal that more than half of the rubber planting activity (57%) took place in 2010 and 2011, following the granting of numerous rubber concessions two years prior. Seventy-three percent of the rubber plantations were converted from natural forest and twenty-three percent were established on non-forest land-cover. The shapelet approach developed here can be used reliably to improve our understanding of the expansion of rubber production beyond Seima Protection Forest of Cambodia, and likely elsewhere in the tropics.

1. Introduction

Tree crop plantations for commercial rubber, cocoa and oil palm are rapidly expanding in tropical regions (Tan et al., 2009; Ziegler et al., 2009; Gerber, 2011; Van Vliet et al., 2012). Rubber production in continental Southeast Asia has increased due to global demand by almost 2500% from approximately 300,000 ha in 1961 to over 8 million ha in 2014 (FAO, 2017). Rubber is harvested in the form of latex that is a popular material for various consumer products. The projected rubber demand may require another 4–8.5 million ha of land globally by 2024, threatening significant areas of Asian forest, including many protected areas (Warren-Thomas et al., 2015). Driven by high prices and the ever-growing international demand, the governments in Cambodia and Laos have allocated large areas of land for rubber plantation in the last decade (Dararath et al., 2011; Witness, 2013; Yem et al., 2015). By the end of 2012, 2.6 million ha of land in Cambodia were leased for tree crop production, more than half of this for rubber (Witness, 2013), and yet little information is available to conservation or management agencies to aid conservation planning in the region.

Concern is mounting in forest-biodiversity policy arenas because new rubber plantations largely occur at the expense of natural tropical forest (Chomitz and Griffiths, 1996; Angelsen, 1999; van Straaten et al., 2015; Vijay et al., 2016). The conversion of natural forest to monoculture plantations causes net carbon emission because of the loss of aboveground organic carbon stocks (Kongsager et al., 2013; van Straaten et al., 2015). Also, forest conversion to plantations results in biodiversity loss which reduces the functioning of forest ecosystems and ecosystem resilience (Bremer and Farley, 2010). As such, a reliable inventory of commercial rubber plantations is important to carbon management

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programs such as UN-REDD+[1] which must differentiate plantations from natural forests to conserve intact forest, reduce degradation, and mitigate carbon emissions (Sasaki and Putz, 2009). Additionally, the expansion of tree plantations into community-managed lands commonly leads to regional political conflicts over access to natural resources between commercial companies and local subsistence-level populations (Gerber, 2011; Witness, 2013). Characterizing the spatiotemporal pattern of tree plantation expansion can improve our understanding of the recent history of commercial tree production, and is therefore beneficial to land policy and management decision making (Carlson et al., 2012). In contrast to the recent advance made in 30 m global forest mapping and monitoring products (Hansen et al., 2013), freely distributed forest change products do not distinguish natural tropical forests from commercial plantations, which leads to a substantial underestimation of forest loss, and compromises their value for policy implementation (Li and Fox, 2011b; Tropek et al., 2014). Therefore, there is a pressing need to develop new approaches to map and monitor commercial tree plantations throughout the tropics in such a way that natural forest area is not over-represented and commercial plantations are not under-represented, as is the common case today (Peerbhay et al., 2013; Tropek et al., 2014; Chazdon et al., 2016).

Satellite data provide a large-area, consistent, repeatable and cost-effective approach to mapping tropical forest extent (Coppin et al., 2004; Cutler et al., 2012; Roy et al., 2014; Dutrieux et al., 2015). Numerous remote sensing methods have been applied to map commercial tree plantations (Thenkabail et al., 2004; Santoso et al., 2011; Srestasathiern and Rakwatin, 2014; Konik and Bradtke, 2016). These methods can be categorized into two broad groups: *single-date image classification*, and *phenology-based classification*. Single-date studies delineate tree plantations using a single image, based on their spectral separability from natural forest. For example, Srestasathiern and Rakwatin (2014) used a variety of vegetation indices to map oil palm crowns in Thailand using pan-sharpened 0.6 m WorldView-2 imagery (90% detection accuracy for oil palm). However, while high-spatial resolution imagery can provide detailed maps, it is often impractical for large-area forest mapping due to their limited coverage and high cost (Rogan and Chen, 2004). Li and Fox (2011a) used Mahalanobis typicalities with a neural network algorithm to map rubber plantations in Thailand and China using 15 m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data with a low commission error (i.e., 2%) but high omission error (i.e., 24%) for rubber stands. Li et al. (2008) used maximum likelihood classification using 30-m Landsat Multi Spectral Scanner (MSS) and Enhanced Thematic Mapper (ETM) images to map natural forest, rubber plantation and shifting cultivation in Xishuangbanna, China, with an overall accuracy of above 80%. Despite the reported success of single-date approaches, in most cases separating plantations vs. natural forest is often unreliable and inconsistent due to their extreme spectral similarity, leading to a high level of uncertainty in the maps produced (Li and Fox, 2011a, 2011b; Dong et al., 2013).

The second group of studies focuses on characterizing the phenology of plantations using satellite imagery representing leaf-on and leaf-off images, because rubber (*Hevea brasiliensis*) has been adapted to tolerate months of drought stress in southeast Asia through deciduousness by dropping leaves in the dry season (late January and February). Dong et al. (2013) and Fan et al. (2015) reported that rubber plantations had distinct spectral signatures compared with natural forest in their leaf-on vs. leaf-off stages, and successfully used the Landsat imagery corresponding to these two stages to map rubber plantations in Yunnan and Hainan provinces in China, with an overall accuracy of 87% and 96% respectively. Similarly, Li et al. (2015) used the Normalized Difference Vegetation Index (NDVI), Land Surface Water Index (LSWI) and Normalized Burn Ratio (NBR) for delineating the change of phenology of rubber from bi-temporal Landsat-derived data in Xishuangbanna, southwest China, and achieved 90% overall accuracy. But the optical remotely sensed data for the leaf-on stage are often unavailable in the tropical region (e.g., our study region) due to the frequent cloud cover in the wet season (Dong et al., 2012). It is essential to develop a superior classification method with less practical constraint on the collection of the specific data for analysis.

A consistent and accurate mapping approach for tropical commercial tree plantations is desirable to reduce the present uncertainty when estimating forest degradation, carbon storage and biodiversity required by organizations such as UN REDD+ (Dong et al., 2013). A review of the tree plantation mapping literature reveals that a new approach is needed to: (1) overcome the spectral limitation of single-date approaches by using the freely available Landsat archive; and (2) avoid the issue of phenological spatial-temporal uncertainty associated with phenology-based approaches, and the presence of water vapor/clouds. In this paper, a shapelet-based approach is proposed to provide new insights for overcoming the challenges of commercial plantation mapping. The proposed approach is based on the assumption that rubber trees/-plantations have a time period of consistently low vegetation cover (or bare ground) due to land clearing and planting preparation (Beckschäfer, 2017), whereas mature natural forests have consistently high vegetation cover. The ability to detect this diagnostic time period in a Landsat NDVI time series could allow rubber plantations to be distinguished from natural forests. The temporal segment in a time series corresponding to this diagnostic time period fits into the concept of 'shapelets'. A shapelet refers to discrete, local patterns in a time series that are highly predictive of its class (Ye and Keogh, 2009; Zakaria et al., 2012; Papagiannopoulou et al., 2016). Previous studies have discussed two advantages for using a shapelet-based approach instead of entire time series for characterizing a time series: (1) producing more reliable classification results by ignoring 'unimportant' time points (Ye and Keogh, 2009, 2011; Grabocka et al., 2014; Hills et al., 2014); and (2) offering interpretable temporal features for events that are of interest to domain experts, such as conservation managers (Hills et al., 2014).

In this paper, we developed a framework for leveraging the concept of shapelets to address two objectives: (1) to develop and test a new method to map rubber plantation distribution in multitemporal Landsat data; and (2) to characterize historical rubber plantation events in the Seima Protection Forest, Cambodia between 1995 and 2015. For the first objective, we developed a new automated procedure for classifying rubber plantations vs. natural forest by detecting shapelets in a 20-year Landsat time-series. For the second objective, the shapelet approach was used to extract the following information: (1) year of plantation establishment; and (2) pre-conversion land-cover from detected shapelets, and validated the results by using the records from the REDD+ project report for this region (WCS, 2015).

2. Study area, image selection and preprocessing

2.1. Study area

A REDD+ conservation project area, Seima Protection Forest (SPF), is the study area for this study (Fig. 1). The SPF is located in eastern Cambodia in Mondulkiri and Kratie provinces, and covers 11,805 km^2 (WCS, 2015). The SPF was created by a Prime

[1] UN-REDD+: United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD+) (http://www.un-redd.org/).