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Spectral normalization of SPOT 4 data to adjust for changing leaf phenology within seasonal forests in Cambodia

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ABSTRACT

As cloud cover exacerbates the application of optical satellite data for forest monitoring in tropical wet and dry regions during the rainy season, data acquisition is mainly restricted to the dry season. When analyzing wide areas, large numbers of single scenes obtained at different times of the dry season are often handled. Such imagery is characterized by changes of spectral reflectance due to vegetation phenology, varying atmospheric effects and solar geometries. In order to allow batch processing with automatic classification techniques, inter-scene comparability is required and data have to be radiometrically normalized. Cambodia is characterized by a mixture of evergreen, semi-evergreen and deciduous forest types, the latter two experiencing at least partial leaf shedding over the course of the dry season. Using spatial medium resolution SPOT 4 data and a manually delineated base map a season adjustment model was developed. The model is adapting the land cover specific spectral signatures of a slave scene (acquired in the middle of the dry season with its seasonal forests defoliated) to an adjacent master scene (from the beginning of the dry season, showing the same forest types with leafs). The relative position of every pixel reflectance was determined in relation to the mean reflectance and its standard deviation for each land cover type and sensor band of the unadjusted slave scene. For seasonality adjustment these pixel reflectance values were transformed (rescaled) to the corresponding position in spectral space defined by the band mean reflectance and standard deviation derived from the corresponding land cover class of the master scene. While the variability of spectral profiles of the pixels in the slave scene is rescaled, the mean reflectance value of the land cover class in the slave scene is conformed to the mean reflectance of the corresponding land cover class in the master scene. The Transformed Divergence (TD) separability index was used to indicate the performance of the adjustment process by characterizing the spectral distance for each land cover type comparing a reference dataset to the uncorrected and to the seasonality corrected scene respectively. While the TD values of all forest types showed a sharp decline, highlighting the good performance of the model, the TD values of the agriculture/urban class remained high, indicating limited normalization of this heterogeneous land cover type. In order to further demonstrate the performance of the model, an object-based land cover classification was applied to the unadjusted as well as to the corresponding adjusted scene. A comparison of the results showed a highly significant improvement of overall accuracy from 32.2% to 75.8% when applying seasonality adjustment.

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1. Introduction

Tropical forest monitoring using optical satellite data is complicated due to often persistent cloud cover, strongly restricting satellite acquisition (Asner, 2001; Trigg, Curran, & McDonald, 2006). Gaps in the data record due to cloud cover have to be filled by other scenes of the same geographic position not affected by clouds but acquired at another point of time (Trigg et al., 2006; Wulder et al., 2008). Monitoring of larger areas using spatially medium or high resolution data can be very challenging due to the correlation between spatial resolution and revisit cycles for most satellite systems (Beuchle et al., 2011; Wulder et al., 2008). However, only such data are able to resolve small-scale land cover changes such as illegal logging activities (Fuller, 2006).

In contrast to the tropical rainforest climate of the inner tropics, areas at the outer margins of the tropical zone experience a more pronounced seasonality (Peel, Finlayson, & McMahon, 2007), with lower cloud frequency during the dry season (Wylie, Jackson, Menzel, & Bates, 2005), thus slightly enhancing the probability to obtain less cloud-affected scenes (Asner, 2001). However, the vegetation of the

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tropical wet and dry climates is characterized not only by evergreen tropical forests, but also includes semi-evergreen and deciduous forest types that undergo different leaf development stages over the course of the dry season due to events such as color-changes and leaf abscission (Richardson et al., 2013; Tanaka et al., 2008; Tani et al., 2007), later referred to as 'leaf phenology' throughout the paper. This results in a change of the spectral properties within seasonal forests detected by optical sensors (Huang et al., 2008; Laborte, Maunahan, & Hijmans, 2010; Schriever & Congalton, 1995). When monitoring vast areas using spatially medium or high resolution data, which requires a large amount of scenes, it is almost unavoidable that individual scenes stem from different stages of the season (FFPRI, 2012; Forestry Administration of the Royal Government of Cambodia, 2011; Wulder et al., 2003). The spectral properties of the single satellite scenes are further affected due to distinct solar geometries and varying atmospheric conditions prevailing at the different acquisition dates. In order to generate radiometrically consistent coverage, the single scenes are corrected for illumination (Gu & Gillespie, 1998; Richter, Kellenberger, & Kaufmann, 2009) and normalized using pseudoinvariant features that are independent of seasonal or biological cycles, thus matching scenes derived at different dates (Schott, Salvaggio, & Volchok, 1988). However, as image normalization generally requires next to same-season imagery (Canty & Nielsen, 2008; Cohen, Maiersperger, Spies, & Oetter, 2001), scenes with different leaf phenology of seasonal forests severely interfere with the application of established normalization processes, thus negatively affecting automatic land cover classification approaches. Helmer and Ruefenacht (2005, 2007) found that regression tree normalization shows best results in producing seamless cloud-filled imagery for vegetation undergoing seasonal changes, and in a later study the same technique was successfully used to map forest disturbance types (Helmer et al., 2010). An important prerequisite of that approach is the availability of overlapping cloud-free pixels (Helmer & Ruefenacht, 2007). Another approach by Roy et al. (2008) using multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS)–Landsat data fusion is restricted to relative radiometric normalization for surface features detectable at 500 m resolution. Even though detailed classification techniques for forest inventory under REDD+ (Reducing Emissions from Deforestation and Forest Degradation) are not yet specified and will strongly depend on various technical and economic factors (Hiepe & Kanamaru, 2008; Holmgren, 2008), automatic classification approaches have the advantage to better implement transparent and reproducible forest monitoring. Therefore, studies aiming to monitor larger areas based on optical medium or high resolution satellite data try to avoid the mixture of satellite scenes that are differently affected due to seasonal changes (Beuchle et al., 2011; Bodart et al., 2011; Franks, Masek, Headley, Gasch, & Arvidson, 2009), but this can be challenging if the number of available scenes covering a certain period of time is limited.

As automatic classifications are error-prone regarding inconsistent reflectance values within identical land cover classes derived from different scenes, the objective of our study was to reduce the effects of seasonality on the various vegetation types. This was tested for three adjacent, spatially medium resolution Système Pour l'Observation de la Terre (SPOT) 4 scenes in Cambodia, which have been acquired at different times during the dry season. As the influence of the season on the reflectance properties was analyzed for each separate land cover type, the land cover of the study area has to be known in advance for the definition of strata. Land cover base maps are usually available from previous land cover classifications and in our case we used a forest cover map of Cambodia, derived by the Forestry Administration (FA) of Cambodia. Based on the land cover and acquisition date-specific reflectance values, a model was developed to adjust the reflectance values of one SPOT scene as if acquired at the same time during the dry season as a reference scene. Finally, the performance of the model was tested using an object-based classification approach and classification results were validated and analyzed per single land cover types.

2. Materials and methods

2.1. Study site and satellite data

The study area comprises three adjacent SPOT 4 scenes, situated along the borderline of the four northeastern provinces of Cambodia: Kratie, Mondul Kiri, Stung Treng and Ratanak Kiri (Fig. 1a). The climate of the region is monsoonal, separated into a distinct tropical wet season from May to October with an average monthly precipitation of 262 $\pm$ 16 mm and a dry season from November to April with an average of 65 $\pm$ 9 mm precipitation per month (Data for Kratie 1997–1999; GAME-T2 DataCenter). The land cover of the study area is dominated by deciduous forests but also includes evergreen and semi-evergreen forests as well as agricultural areas.

SPOT 4 data have a medium spatial resolution of 20 m over 4 spectral bands (band 1: 790–890 nm; band 2: 610–680 nm; band 3: 500–590 nm; band 4: 1580–1750 nm). The scenes represent the two extreme leaf phenological stages of deciduous forests that occur over the course of the dry season—being still foliated at the beginning of the dry season in contrast to defoliated trees around the middle of the dry season. While the two eastern SPOT scenes stem from the same satellite overpass during the early dry season (28/11/2007), thus showing no seasonal changes between both scenes and experiencing comparable atmospheric conditions, the southwestern scene was acquired about 10 months before during the mid of the previous dry season on 30/01/2007, thus experiencing completely different leaf phenology. All three scenes are completely free of clouds and haze. Land cover changes are negligible during that period of time. About 22% (824 ha) of the southeastern early dry season SPOT scene is overlapping with the southwestern mid dry season scene.

Additional to the satellite imagery of 2007, ancillary data, describing the spatial distribution of the different land cover classes of the study area in a timely manner (depending on the rate of land cover change within a period of 1–5 years), must be available in order to analyze and adjust the seasonality per land cover type. In our study this data source is the official 2006 forest cover map of Cambodia, derived by the FA of Cambodia. The manually derived map shows a total of eight land cover classes: evergreen forest; semi-evergreen forest; deciduous forest; bamboo; other forest; wood shrub dry; wood shrub evergreen; non-forest. For accuracy assessment random sampling was used to select 100 points for field visits, of which only 83 points were accessible and the remaining had to be discarded. Additionally, cluster based sampling of aerial photos and very high resolution (VHR) satellite data was applied, in which 76 points were checked. The combination of both assessments shows an acceptable accuracy of 71% (personal comment Chivin Leng, Cambodia FA). Two of above land cover classes are mixed classes, combining different land cover types. The class of other forest generally consists of several different land cover types (highly degraded forest; various plantation areas; mangrove forest; inundated forest) with distinct spectral properties and seasonal characteristics. Our study area only shows degraded forests and plantation areas within that particular class. The non-forest class combines various agricultural lands, water bodies, and a minor extent of urban areas, all also present within the three SPOT scenes. However, our study area does not show any bamboo forest.

Georeferenced pictures of various land cover types were taken during two field surveys at the beginning and in the middle of the 2011/2012 dry season, which mainly served to better understand the prevailing land cover types of the study area.

2.2. Modifications of the land cover base map

As the land cover base map has been derived on a visual delineation of Landsat scenes, the borderlines between the single land cover classes do not follow the pixel edges of the SPOT data. For a correct analysis of the statistics of each land cover class it is crucial that the polygons of the

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