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Floristic composition and across-track reflectance gradient in Landsat images over Amazonian forests

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ABSTRACT

Remotely sensed image interpretation or classification of tropical forests can be severely hampered by the effects of the bidirectional reflection distribution function (BRDF). Even for narrow swath sensors like Landsat TM/ETM+, the influence of reflectance anisotropy can be sufficiently strong to introduce a cross-track reflectance gradient. If the BRDF could be assumed to be linear for the limited swath of Landsat, it would be possible to remove this gradient during image preprocessing using a simple empirical method. However, the existence of natural gradients in reflectance caused by spatial variation in floristic composition of the forest can restrict the applicability of such simple corrections. Here we use floristic information over Peruvian and Brazilian Amazonia acquired through field surveys, complemented with information from geological maps, to investigate the interaction of real floristic gradients and the effect of reflectance anisotropy on the observed reflectances in Landsat data. In addition, we test the assumption of linearity of the BRDF for a limited swath width, and whether different primary non-inundated forest types are characterized by different magnitudes of the directional reflectance gradient. Our results show that a linear function is adequate to empirically correct for view angle effects, and that the magnitude of the across-track reflectance gradient is independent of floristic composition in the non-inundated forests we studied. This makes a routine correction of view angle effects possible. However, floristic variation complicates the issue, because different forest types have different mean reflectances. This must be taken into account when deriving the correction function in order to avoid eliminating natural gradients.

1. Introduction

Amazonian rain forests, especially the non-inundated ones, were traditionally considered rather homogeneous in terms of species composition (Encarnación, 1985; Pires and Prance, 1985; Salo et al., 1986). More recently, however, several authors have shown that plant species composition in these forests is significantly related to physical and chemical characteristics of soils at different spatial scales, from local to regional (Tuomisto et al., 1995; Ruokolainen et al., 1997, 2007; Tuomisto et al., 2003a,b,c; Phillips et al., 2003; Costa et al., 2005; Duque et al., 2005; Kinupp and Magnusson, 2005; Bohlman et al., 2008; Kristiansen et al., 2012; Figueiredo et al., 2014). These findings have increased the need for a more detailed identification and mapping of spatial variation in plant species composition to support rainforest conservation and land use planning efforts. Interpretation of satellite imagery with high spatial resolution (10–100 m), such as Landsat, is crucial for such mapping to be possible over large areas.

Remote sensing of tropical rain forests is associated with several challenges, one of the most obvious being the persistent cloud cover in these high-rainfall regions. Another challenge is that reflectance differences among forest types are often subtle (Sesnie et al., 2010; Higgins et al., 2015). This makes it necessary to utilize the 8-bit satellite imagery (such as Landsat TM/ETM+) up to its radiometric limits, which in turn makes the interpretations more prone to errors due to radiometric distortions (Toivonen et al., 2006; Higgins et al., 2011). The importance of a careful radiometric and atmospheric correction is therefore evident.

In recent years, especially since the opening of the Landsat archive (Wulder et al., 2012), considerable effort has been put to the operational development and distribution of atmospherically

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corrected surface reflectance products (Roy et al., 2010; Ju et al., 2012). Because of the narrow field of view of Landsat (7.5° each side of nadir), the bidirectional reflectance distribution function (BRDF) effects are often ignored in the atmospheric correction, and a Lambertian behavior of the surface is assumed (Masek et al., 2006; Ju et al., 2012; Roy et al., 2014). However, studies over Amazonian forests have demonstrated that directional scattering, which gives rise to an across-track gradient in digital number, can be strong (Nagol et al., 2015), and hence nullify the spectral separability of different forest types (Toivonen et al., 2006) or suggest the existence of vegetation patterns where none exist (Ruokolainen and Tuomisto, 1998).

Several authors have suggested methods for BRDF correction of Landsat imagery. Roy et al. (2008) developed a multi-temporal data fusion for Landsat and MODIS using the MODIS BRDF/Albedo land surface characterization product (Schaaf et al., 2002) to correct directional effects in Landsat, and variations on this approach have since been evaluated over different sites (Li et al., 2010, 2012; Flood, 2013; Shuai et al., 2014). Given the vast areas covered by closed canopy, this method can be expected to be applicable over Amazonian forests in spite of the spatial resolution gap between both sensors. A more severe restriction is the persistent cloud cover in tropical areas. Generation of MODIS BRDF parameters assumes the availability of several cloud-free observations during a 16-day period (Schaaf et al., 2002). Even in the case of a cloudfree Landsat acquisition, the required number of MODIS observations during the adjacent days may not be reached. Furthermore, no MODIS BRDF parameters are available for the period before the start of MODIS operation in 2000. A different approach was suggested by Flood et al. (2013) for Landsat TM/ETM+ imagery over Eastern Australia. This method exploits the availability of multi-temporal acquisitions over this region to calculate BRDF parameters at the Landsat spatial resolution. Consequently, it is not applicable in areas with only occasional cloud-free conditions.

As an alternative to multi-sensor or multi-temporal approaches, empirical scene-based normalizations have been suggested by some authors (Toivonen et al., 2006; Hansen et al., 2008; Broich et al., 2011). These derive the relationship between the position of a pixel in the image and its digital number or reflectance through linear regression, and consecutively use this relationship to normalize the across-track gradient. This method relies on a number of assumptions. Firstly, it is assumed that the BRDF, and the brightness variation it gives rise to, is linear over a uniform land surface in Landsat's narrow field of view. Secondly, it is assumed that there are no east-west gradients in the imagery other than those caused by directional reflectance effects (Roy et al., 2016). Hansen et al. (2008) aimed to ensure this by deriving the regression coefficients only for forested pixels (as inferred from a MODIS forest mask), rather than for all pixels in the scene. However, not all forests are identical, and gradual or abrupt changes in floristic composition may exist and affect reflectance properties even within forested areas, and this could invalidate the empirical correction.

In this study, we investigate the reliability of empirical across-track reflectance gradient corrections for two regions in Peruvian and Brazilian Amazonia. First, we use in situ data on floristic composition to test if adequate corrections of Landsat TM/ETM+ imagery is obtained using simple linear models, and if variation in species composition of the forest confounds the correction. Then we test an earlier suggestion (Toivonen et al., 2006) that the radiometric gradient has different magnitudes over different kinds of forest in Amazonia. If different corrections are needed for different kinds of forest, the demand for ground truth data would increase and routine radiometric correction be severely hampered. We use a large image dataset combined with geological data (which acts as proxy for forest species composition) to quantify how much error is introduced if compositional variation in the forest is ignored. This will help in assessing whether or not these relatively simple, empirical angular normalization techniques are appropriate for a given application.

2. Study area and data sets

2.1. Study area

This study was conducted in tropical rain forests of the Amazonian lowlands in northern Peru and western Brazil (Fig. 1). The area is covered largely by undisturbed primary *terra firme* (non-inundated) forest under closed canopy. Areas that are sporadically, seasonally or permanently inundated occur along rivers. Climate is tropical, humid, and almost aseasonal. In the city of Iquitos, which is situated near the Peruvian study area, the mean monthly temperature is 25–27 °C throughout the year and annual precipitation is approximately 3100 mm (Marengo, 1998). The city of Eirunepé, near the Brazilian site on the Juruá River, experiences a mean monthly temperature of approximately 25 °C and an annual precipitation of 2195 mm (http://inmet.gov.br/portal/). Elevation ranges from 100 to 250 m above sea level in most of the study area, with a few precipitously hilly areas exceeding 400 m.

Two geological formations are exposed at the surface over most of the study area. These are known in Peru as the Pebas Formation and the Nauta Formation, and in Brazil as the Solimões Formation and the Içá Formation, respectively. For clarity, only the Peruvian names will be used here. The Pebas Formation consists of poorly weathered, relatively cation-rich (by Amazonian standards) clay sediments that were deposited under low-energy semi-marine or lacustrine conditions of the Pebas Embayment. The Nauta Formation consists of more weathered, cation-poor sediments with coarser texture that were deposited on top of the Pebas Formation under higher-energy deltaic to fluvial conditions (Räsänen et al., 1995; Rebata-H. et al., 2006; Hoorn et al., 2010). The cation concentration in the soils derived from the Pebas Formation is about one order of magnitude higher than that in the Nauta Formation. This difference in soils is reflected in the species composition of the primary *terra firme* forest, and gives rise to a plant species turnover of 80–90% across the geological boundary (Higgins et al., 2011). A third distinct unit of the *terra firme* landscape is formed by river terraces of sedimentary deposits from Andean origin dated from mid/late Pleistocene. In terms of sedimentation environment and soil nutrient content, the terraces are similar to the Nauta Formation. The main difference between the two is that terraces are practically flat in topography (Irion and Kalliola, 2009).

The digitized geological maps used in this study were obtained from the Instituto Geológico Minero y Metalúrgico (INGEMMET, http://www.ingemmet.gob.pe) and the Geological Survey of Brazil (CPRM, http://geobank.sa.cprm.gov.br). The boundaries between the Pebas and Nauta Formations in these maps were modified according to the discontinuity identified in Landsat imagery and Shuttle Radar Topography Mission (SRTM) elevation data (Higgins et al., 2011). The histograms in Fig. 2 show that, for both study sites, the Pebas Formation is characterized by slightly lower elevations with less steep slopes than the Nauta Formation. There is no difference in terrain orientation between the two formations in either site.

2.2. Floristic data

The surface reflectance of dense forests, as observed by satellite sensors operating in the optical domain, is mostly determined by properties of the forest canopy, including tree species composition. Because collection of field data on canopy species composition in