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Object-based classification of vegetation and terrain topography in Southwestern Amazonia (Brazil) as a tool for detecting ancient fluvial geomorphic features

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ABSTRACT

Reconstructing the evolution of large tropical fluvial systems over the geological time is challenging, particularly in areas such as the Amazonian lowlands where basic geological and geomorphological data are still scarce relatively to the large dimension of the region. In such areas, remote sensing data are useful for detecting ancient morphological features that may reveal past fluvial dynamics. In this study, we explored object-based image analysis (OBIA) in the Madeira-Purus interfluve, Southwestern Brazilian Amazonia, integrating geospatial data including Landsat satellite multispectral images, the digital elevation model (DEM) acquired during the Shuttle Radar Topography Mission (SRTM), and stream channels digitized from topographic maps. This approach provided the basis to categorize automatically classes with contrasting vegetation and/or topographic characteristics within the dense tropical forest over an extensive and relatively flat forested area. The main goal was to use these classes as a surrogate for the recognition of ancient geomorphic features consisting mainly of paleochannels that may help reconstructing fluvial history in space and time. Landsat optical images with stream vector were appropriate to classify open vegetation areas that grow over paleochannels, but failed to identify these objects when they were located over forested areas. However, the digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) was successful to detect these objects even in forested areas. Topographic survey undertaken in the field increased the classification reliability by demonstrating true terrain variations along transects measured across the paleochannels. Based on this technique, networks of dendritic paleochannels were mapped and related to ancient tributaries of the Madeira River that had their courses flowing opposite to main modern streams. This denotes a significant change in fluvial dynamics over time, most likely resulting from tectonic tilting.

1. Introduction

Fluvial sediment erosion and deposition in past geological times result in geomorphic features that can be still recognized over the modern landscape. These features, such as paleochannels, that are either in process of abandonment or fully abandoned (Goudie, 2004, p. 743) are important elements for reconstructing the ancient history of fluvial systems. In Amazonian areas, many fluvial channels abandoned over the Quaternary have increasingly been recorded in a number of publications (Iriondo and Suguio, 1981; Latrubesse and Rancy, 2000; Müller et al., 1995; Rossetti and Valeriano, 2007; Rossetti et al., 2007, 2008; Souza Filho et al., 1999). According to these authors, these paleomorphologies record multiple events of channel course dislocation and abandonment during the Quaternary as a result of either climatic fluctuations or tectonic reactivations. Despite the available studies, further efforts are still required to map the paleochannels in this region, particularly considering the remarkably large dimension and the complexity of the Amazon River and its floodplain. This type of investigation can help detect landscape changes and analyze their controlling factors.

The analysis of Amazonian paleochannels has relied on aerial photographs, and, more recently, side-looking airborne radar and satellite remote sensing products. The latter represents a quick and low cost alternative for mapping these features on a regional scale. The use of remote sensing for the recognition of paleochannels in tropical areas is not new (Yashpal et al., 1980; McCauley et al., 1982; Ramasamy et al., 1991). Mapping and detecting of abandoned channels and meanders in tropical regions have been successfully conducted with the use of satellite multispectral images derived from optical sensors (*e.g.*, Landsat TM and ETM+)

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(Mitra et al., 2005). This approach is based on differencing spectral values over ancient fluvial morphology to allow interpretation of recent events such as channel migration and avulsion, and the overall evolution of drainage systems. However, optical images do not succeed in detecting slight changes in vegetation and/or topographic contrasts, which can be also related to relics of paleochannels preserved within forested Amazonian areas (Rossetti, 2010).

The use of synthetic aperture radar (SAR) to detect paleochannels in arid environments has some advantages over optical imagery due to its sensitivity to structural and dielectric properties, such as water content and surface roughness parameters (Paillou et al., 2009). Studies have also demonstrated that over forested tropical areas the use of digital elevation model (DEM) obtained from interferometric synthetic aperture radar (InSAR) data can improve significantly the detection of paleochannels over other remotely-sensed images (Almeida-Filho and Miranda, 2007; Rossetti, 2010). Particularly, the DEM generated by InSAR during the Shuttle Radar Topography Mission (SRTM) can reveal vegetation and/or topographical contrasts related to ancient fluvial morphologies (Rossetti et al., 2007). These contrasts can be explained by the interaction of the InSAR C-band (5.6 cm) with the vegetation canopy (Kellndorfer et al., 2004; Valeriano et al., 2006). The relatively limited penetration of the C-band under dense vegetation cover might either enhance or diminish slight topographic gradients over paleochannels located in the extensive Amazonian flatlands (Hayakawa et al., 2010; Mantelli et al., 2009). These contrasts may be also a product of detectable changes of biomass elements, which has been previously associated with abandoned depositional sites (Rossetti et al., 2012). Hence, multiple remote sensing data should be used in a complementary manner for vegetation and terrain characterization in Amazonian areas as a potential tool for detecting fluvial geomorphic features such as paleochannels.

The manual delineation of paleochannels on remote sensing images can be time consuming. Despite the satisfactory results of this kind of effort, the development of new techniques is important to optimize the mapping of paleochannels over large regions, such as in Amazonia. One of the most recent developments on image classification consists of object-based image analysis (OBIA). OBIA consists in delineating different geospatial data into multiple objects corresponding to homogeneous regions in remote sensing images (Benz et al., 2004). This involves specific image segmentation algorithms that allow the use of information related to image object characteristics in the classification processes. These characteristics are intrinsic to objects (spectral, textural or geometrical properties) or rely on topological and semantic properties related to their contextual information (*e.g.*, connectivity, proximity), even if they belong to different hierarchical levels. Previous studies have successfully applied this method to map contemporary fluvial morphologies in tropical environments (Hamilton et al., 2007). Moreover, the use of OBIA has improved the possibility of combining various remote sensing products that differ in spectral characteristics and/or spatial resolution. This technique allows the interpreter to explore the characteristics of multiple geospatial data during image classification, thus increasing the ability to discern geomorphic features (Dragut and Blaschke, 2006). In addition to the interpreter knowledge, machine learning decision tree algorithms consist of a simple and quick approach to help classifying remote sensing images from a predictive model based on training samples (Otukei and Blaschke, 2010).

The present study discriminates areas of open vegetation from dense tropical forest, as well as classifies small vegetation and/or topographic contrasts within the dense forest of one area in southwestern Brazilian Amazonia. This was achieved by combining geospatial data through OBIA and detailed topographic survey as a surrogate for delineating paleochannels.

2. Study area

The study was undertaken over a 40,000 km^2 area within the Madeira-Purus interfluve in the Southwestern Brazilian Amazonia, where several patches of open vegetation occur. These patches have been identified as grassland and/or shrubland savanna (also locally known as *campinarana*) in sharp contrast with woodland savanna and dense tropical forest (RadamBrasil, 1978) (Fig. 1). The term savanna will be used in this paper to discriminate naturally occurring open vegetation from anthropic deforestation (not-savanna) which can also be found within the study area. Located between the states of Rondônia and Amazonas, this area has average annual temperature and precipitation ranging from 24 °C to 26 °C and 2250 mm to 2750 mm, respectively. The average elevation is 86 m, with elevations as high as 213 m along gently dissected plateaus.

Geologically, the study area is located in the southeast of Solimões Basin, which consists of a structure formed due to intraplate rifting during the Paleozoic, and strike-slip motion during the Late Jurassic in response of the Andean uplift (Jordan, 1995). The sedimentary fill is up to 3800 m thick and includes Paleozoic to Quaternary deposits (Caputo, 1991). At the surface, the study area consists of Plio-Pleistocene deposits of the Içá Formation and unnamed Pleistocene–Holocene deposits (Rossetti et al., 2005).

3. Materials and methods

The mapping and morphological characterization of detectable vegetation and/or altitudinal contrasts for the study area were mostly based on analysis of freely available remote sensing data. These included Landsat-7/ETM+ optical images (accessed from http://landsat.usgs.gov/) and SRTM-DEM for South America (accessed from ftp://e0srp01u.ecs.nasa.gov/srtm/).

The Landsat images obtained from the United States Geological Survey (USGS) global archive (Woodcock et al., 2008) included Path/Row 232/65, 232/66, 233/65 and 233/66 from 2000 to 2001, which are closer to the DEM data (see below). These optical images have a Level 1 Terrain (L1T) processing, meaning that the data had been radiometrically and geometrically corrected and orthorectified (USGS, 2013). Bands on the blue and green region, as well as the thermal bands were excluded from the analysis.

The SRTM data used in this study consisted of the ~90 m ground resolution DEM generated from C-band InSAR (Rabus et al., 2003), which represents terrain elevation added to a parcel of tree canopy heights (Kellndorfer et al., 2004).

Additionally, digitized drainage data from 1:100,000 topographic maps (accessed from http://mapas.mma.gov.br/) were used to represent the drainage network. Sample synthetic color images available from Google Earth (Yu and Gong, 2012) were used as a reference to characterize vegetation classes. These images have degraded resolution and are derived from hybrid high spatial resolution orbital sensors from the year 2010 and later.

3.1. Data pre-processing and transformations

The Landsat images were mosaicked, with linear stretch and histogram equalization being applied for each of the multispectral bands. Equalization was made only visually for each multispectral band during mosaicking aiming to minimize strong brightness contrasts among the images resulting from different satellite track lines. Transformation using principal component analysis (PCA) was performed on the mosaicked Landsat images to decrease variance of the image spectral values (Mather, 2004, p. 149).