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Characterization of indicator tree species in neotropical environments and implications for geological mapping

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A B S T R A C T

Geobotanical remote sensing (GbRS) in the strict sense is an indirect approach to obtain geological information in heavily vegetated areas for mineral prospecting and geological mapping. Using ultra- and hyperspectral technologies, the goals of this research comprise the definition and mapping of Neotropical tree species that are associated with geological facies (here called geo-environments) as well as their spectral discrimination at leaf and crown scales. This work also aims to investigate the possible relationship between leaf and crown spectral and chemical properties. The study was developed at the Mogi-Guaçu Ecological Station, in the Cerrado domain, southeastern Brazil. Data from 70 sample units, such as sediment texture and species from inventories, were first analyzed through vectorial quantization using Self-Organizing Maps (SOM). Principal Component Analysis and Spearman's ranked correlation coefficients were used to define geo-environments and target-species, respectively. Biochemical and visible to shortwave infrared (VSWIR) point spectral data (350–2500 nm) were collected from the leaves of the target-species, during both rainy and dry seasons. Spectral data from target-species crowns were obtained from hyperspectral images (530–2.532 nm, ProSpecTIR-VS sensor) with 1 m spatial resolution, and acquired in the beginning of the dry season. These spectra were classified using Multiple Endmember Spectral Mixture Analysis (MESMA) with two endmembers (EMs). Based on the MESMA results with two EMs, the best dataset per target-species was chosen for pixel-based image unmixing with three EMs (target-species, other vegetation types and shade). From 121 species sampled in the field, two proved to be associated with floodplains (Alluvial Deposits sequence), two with hills and plateaus of the Aquidauna Formation (Carboniferous sedimentary rocks, Paraná Basin), and two more with a specific facies of the Aquidauna Formation that has a distinctive presence of coarse and very coarse sand. Five target-species were well discriminated at the leaf scale, reaching 90.0% and 85.0% of global accuracies in the rainy season and in the dry season, respectively. Accurate spectral discrimination appears to be linked to the considerable biochemical variability of their leaves in both seasons. Three species were discriminated at the crown scale, with 70.6% of global accuracy. When eight other landscape scale vegetation classes were included in the analyses, only *Qualea grandiflora* Mart. produced a satisfactory accuracy (61.1% and 100% of producer and user's accuracies, respectively). The spatial distribution of its fraction in the unmixed image, particularly, matches with the geological facies to which it was associated in the field. Ecological requirements for successfully mapping indicator species include broad and random distribution of the target-species' population, and singular physiological, phenological (and spectral) behavior at the imagery acquisition date. Our study shows that, even in tropical conditions, it is possible to use plant species mapping to support geological delineation, where rock exposures are typically rare.

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1. Introduction

Geobotany is an old science, commonly understood as a technique for mineral prospecting in vegetated terrains (e.g., Cannon, 1960, 1971; Brooks, 1972, 1983; Prasad, 1987). In a broader sense, it comprises the study of the physical and biological processes that are of interest to Earth Science (Ustin et al., 1999). According to those authors, Geobotany has the potential of providing a better understanding of phenology, abundance and the distribution of plants through holistic ecophysiological models, connecting plant behavior to edaphic conditions and geology.

In western culture, recognition of an association between a plant species and a specific rock type dates back to the 4th century B·C, credited to Theophrastus (Kruckeberg, 2002). However, there are practical difficulties related to this science by requiring both geological and botanical knowledge. Since the advent of multispectral remote sensing, Geobotany has gained increasing importance (Lyon and Lee, 1970; Ustin et al., 1999) in its strict and broad senses (e.g., Carranza and Hale, 2002; Higgins et al., 2011; Lammoglia and de Souza Filho, 2013; Sanches et al., 2013; Sirén et al., 2013; Hede et al., 2015; Wang et al., 2018).

The first Geobotanical Remote Sensing (GbRS) studies focused essentially on mineral deposits, as shown by various NASA Technical Reports (e.g., Arden Jr and Westra, 1977). Within the Cerrado biome (Brazilian tropical savanna), GbRS studies seem to be also focused on the characterization of particular mineralizing processes (e.g. Almeida-Filho and Castelo Branco, 1992; Almeida-Filho et al., 1996; Almeida-Filho and Vitorello, 1997), and hydrocarbon microseepage (e.g., Souza Filho et al., 2008). These studies highlighted geobotanical anomalies due to chemical stresses. However, the application of the tool in regional geology over common rocks is still rare. Evidence of association between Neotropical plant communities' distributions and common local geology has been found using multispectral remote sensing in western Amazon for example (e.g., Higgins et al., 2011, 2012, 2014a).

As foreseen by Sabins (1999), the availability of hyperspectral sensors has also encouraged new GbRS investigations. Madritch et al. (2014) showed that the canopy visible to shortwave infrared (VSWIR) hyperspectral reflectance from genotypes of trembling aspen (*Populus tremuloides*) is directly correlated with soil traits and belowground processes in two ecoregions: the Great Lakes region and Western region of the United States. In Neotropical environments, Asner et al. (2005) found associations between canopy traits and the age of underlying substrate using hyperspectral vegetation indices from the Hyperion sensor. Vitousek et al. (2009) correlated variations in canopy nitrogen content and vegetation height to substrate age using airborne VSWIR hyperspectral and Light Detection And Ranging (LIDAR) data. Higgins et al. (2014b) observed clear relationships between vegetation species composition, VSWIR spectral response and LIDAR structural data on two different underlying sedimentary formations in a Central Panama broadleaf forest. However, the information that can be obtained through hyperspectral remote sensing goes beyond what has been shown so far in GbSR approaches at the Neotropical zone, which hosts hyper-diverse vegetation types.

Remote discrimination and mapping of plant species in hyper-diverse communities is not an easy task. The high inter-specific and intra-specific spectral variability of tropical formations is still poorly understood by the scientific community (Asner, 2008; Asner and Martin, 2008). The current consensus is that the success of species mapping in tropical environments is a result of the species-specific structural, biochemical, physiological and phenological characteristics, making it a distinct “optical type” in face of other neighbor species (Asner and Martin, 2008; Gamon, 2008; Ustin and Gamon, 2010). Spectral discrimination of Neotropical species at the individual tree crown level, which is possible only with sensors of fine spatial resolution, was achieved in 2005 by Clark et al. (2005) in Costa Rica. Later, Kalacska et al. (2007), Féret and Asner (2013), Somers and Asner (2014), Baldeck et al. (2015) and Ferreira et al. (2016) reported similar successes in tree species mapping.

However, understanding the characteristics related to a crown's reflectance and its spectral classification is a challenge that starts at the leaf level (Castro-Esau and Kalacska, 2008). Evidence is emerging that at the leaf level hyperspectral remote sensing detects not only species but functional, structural and phylogenetical properties, which may vary among species and functional groups (e.g., Clark et al., 2005; Gamon et al., 2005; Asner, 2008; Asner and Martin, 2009; Asner and Martin, 2016; McManus et al., 2016). Successful spectral discrimination of Neotropical species at leaf scales has been shown in the literature since the 2000's (e.g., Cochrane, 2000; Castro-Esau et al., 2004; Clark et al., 2005; Castro-Esau et al., 2006; Rivard et al., 2008; Féret and Asner, 2011; Hesketh and Sánchez-Azofeifa, 2012; Ferreira et al., 2013; Prospere et al., 2014).

Focusing on plant functional groups in Neotropical forests, recent advances comprise species discrimination at the leaf level from various habitats (e.g., Castro-Esau et al., 2004; Kalacska et al., 2007; Sánchez-Azofeifa et al., 2009) and successional stages (e.g., Alvarez-Añorve et al., 2012). Hesketh and Sánchez-Azofeifa (2012) studied leaf spectral variation within tree and liana species in the rainy and the dry seasons, in wet and dry forests of Central America, observing different seasonal responses and good discrimination in both seasons. Due to the high intensity of the species-specific spectral variations between seasons, the authors highlighted the necessity of leaf chemical analyses to strengthen the observed spectral variations.

A reasonable amount of studies on Neotropical species' spectral discrimination, both at leaf and crown scales, as well as on emergent trees mapping, can be found in the literature, as shown above. Nevertheless, studies focusing on geological indicator tree species are generally lacking.

Thus, the objective of this investigation is to characterize and map indicator tree species to support geological facies delineation in an ecological station in southeastern Brazil. Specifically, we aim (i) to discriminate, chemically and spectrally, the tree species at leaf scale in both rainy and dry seasons; (ii) to distinguish these species spectrally at the crown scale in the dry season; and (iii) to map the sub-pixel fraction of the species using high-spatial-resolution VSWIR hyperspectral images. In addition, we discuss the relationships between target-species leaf traits and leaf and crown spectral discrimination, the challenges on discriminating and mapping indicator tree species previously defined in the field, as well as the application of the method to geobotanical studies in hyper-biodiverse landscapes, as found in the Neotropics.

2. Materials and methods

2.1. Study area

The study area is the Mogi-Guaçu Ecological Station (MGES), located in the Mogi-Guaçu municipality, State of São Paulo, southeastern Brazil. The MGES is approximately 1230 ha (Fig. 1) consisting of large hills and a floodplain, with elevations between 560 and 700 m. Most of the soils are hydromorphic floodplain soils. The MGES includes approximately 17 km of the Mogi-Guaçu River. We chose this area because common sedimentary formations without geochemical anomalies compose the local geology. Thus, we could test our GbRS methodology, designed for local (and regional) geologic mapping. The MGES geology is composed of the Aquidauana Formation and alluvial deposits from the Mogi-Guaçu River (CPRM, 2006). The Aquidauana Formation (Carboniferous sedimentary rocks, Paraná Basin) is a fluviolacustrine stratum with reddish sandstones and siltstones and, in addition, conglomerates, diamictites, rhythmites and shales. The diamictites, which are also red in color, contain dispersed clasts, some with striations of glacial origin, indicating that they represent tillites. Despite this lithological diversity, Fúlfaro and Bjomberg (1993) observed that the soils developed on this formation are commonly sandy. The alluvial deposits