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Relationships between the mineralogical and chemical composition of tropical soils and topography from hyperspectral remote sensing data

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Abstract

Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) data acquired in 1995 in the vicinity of Campo Verde, central Brazil, were analyzed to investigate the relationships between the mineralogical and chemical composition of different soil types and topography. Band depth analysis following the continuum removal separated areas of exposed soils from the other scene components. Principal component analysis (PCA) was applied to this subset of pixel spectra of exposed soils. The Spectral Feature Fitting (SFF) technique was used for mineral identification in the scene. Regression relationships between the silica/aluminum ratio and the absorption band depth values at 2210 nm (kaolinite) and 2260 nm (gibbsite), calculated from laboratory spectra after the continuum removal, were used to estimate the Ki index ($1.7SiO_2/Al_2O_3$) in AVIRIS spectra, an indicator of the degree of soil weathering in soil surveys. Results were plotted over an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-derived digital elevation model showing that several soil properties varied with surface elevation. Low reflectance soils (e.g., Rhodic Acrustox with negative first component (PC1) scores, clay texture and higher organic carbon, SiO_2, Al_2O_3, Fe_2O_3 and TiO_2 content) predominated at higher elevations and high reflectance soils (e.g., Ustic Quartzipsamments with positive PC1 scores, sand texture and lower content of these constituents) at lower elevations. In some portions of the study area, soil composition changed gradually from Rhodic Acrustox at higher elevations to Xanthic Acrustox at lower elevations, or from lower average soil reflectance (negative PC1 scores) and deeper kaolinite absorption band to higher average soil reflectance (positive PC1 scores) and deeper gibbsite absorption band. When applied to AVIRIS data, the laboratory-derived relationship between the Ki index and the depth of the 2210 and 2260 nm absorption bands showed a good correspondence with spectral fits for kaolinite and gibbsite. Kaolinitic areas were associated with high Ki values due to a high SiO_2 and low Al_2O_3 content, whereas gibbsitic areas corresponded to low Ki values and highly weathered soil surfaces due to a low SiO_2 and high Al_2O_3 content.

Keywords: Hyperspectral remote sensing; Tropical soils; AVIRIS; Topography; Mineral identification

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1. Introduction

The genesis of tropical soils usually results in highly weathered surfaces due to a desilification process or the removal of silica and an accumulation of aluminum (Moniz et al., 1982; Curi and Franzmeier, 1984, 1987; Macedo and Bryant, 1987; Baptista et al., 1998). Tropical weathered soils are characterized by the predominance of a relatively simple mineralogy composed of quartz, goethite, hematite, kaolinite, gibbsite and opaque minerals (e.g., ilmenite and magnetite) (Madeira Netto, 1993; Madeira et al., 1997). Except for quartz and opaque minerals, the other minerals display well-defined absorption bands in the Visible/Near Infrared (VNIR) region (goethite and hematite) and in the Shortwave Infrared (SWIR) interval (kaolinite and gibbsite) that can be detected by laboratory/field instruments (reflectance spectroscopy) or airborne/orbital imaging systems (hyperspectral remote sensing) with high spectral resolution.

Hyperspectral remote sensing provides new perspectives for the study of tropical soils due to the possibility of measuring, on a per-pixel basis, iron oxide and clay mineral absorption bands usually observed in laboratory spectra. Since landscape position influences some chemical and physical properties of tropical soils and their mineralogy (Curi and Franzmeier, 1984; Uhlmann et al., 1997; da Motta et al., 2002; Cunha et al., 2005), these measurements can be related to topographic data to aid soil mapping. In spite of the potential of hyperspectral data to add information for soil mapping, these data have not been widely used by the soil community. Examples of applications include Baptista et al. (1998), Palacios-Orueta and Ustin (1998), Ben-Dor et al. (2002), Galvão et al. (2001), Pizarro et al. (2001), Chabrillat et al. (2002) and Dehaan and Taylor (2004).

Most of the hyperspectral soil studies reported in the literature did not consider topography in their data analysis. The combined use of different techniques of spectral analysis (e.g., Principal Components Analysis (PCA), band depth analysis and Spectral Feature Fitting (SFF)) and their association with a Digital Elevation Model (DEM) may provide a better comprehension of the variation patterns of soil composition along toposequences. Such an approach may also include the potential determination of the Ki ratio ($1.7SiO_2/Al_2O_3$), a common index that indicates the degree of alteration or weathering in tropical soils. For a Brazilian latosol, this index is an indirect measure of the relative proportions of kaolinite and gibbsite (Resende and Santana, 1998) and can be estimated from reflectance values associated with the 2210 nm (kaolinite) and 2260 nm (gibbsite) absorption bands (Madeira Netto, 1993; Madeira et al., 1995; Baptista et al., 1998).

In this article, variations in soil types and in their mineralogical and chemical composition, detected from Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) data, were analyzed in relation to changes in topography obtained from an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-derived DEM. Using reference spectra from a spectral library, mineral identification of iron oxides and clay minerals was performed on a per-pixel basis with the SFF technique. Laboratory-derived regression relationships between the silica/aluminum ratio (Ki index) determined from chemical analysis and absorption band depth values were applied to the AVIRIS scene to characterize the degree of soil surface alteration and its relationship with mineralogy.

2. Study area

The study area (22 × 11 km) is located in the vicinity of Campo Verde in the state of Mato Grosso in central Brazil (Fig. 1). According to the Brazilian system of soil classification (Embrapa, 1999), the area is characterized by the presence of the following major soil types: dystrophic Red Latosol (Rhodic Acrustox in the Soil Taxonomy), dystrophic Red–Yellow Latosol (Typic Acrustox), dystrophic Yellow Latosol (Xanthic Acrustox), orthic Quartzarenic Neosol (Ustic Quartzipsamments) and concretionary Petric Plintosol (Petroferric Acrustox). A small occurrence of acriferric Red Latosol (Anionic Acrustox) was also observed in the study area. Henceforth, the Soil Taxonomy will be used to facilitate reading.

The natural vegetation is composed of savannas, which have been rapidly replaced by crops. The study area is dominated by agricultural activities that include the growing of soybeans, cotton and corn. As a result, most of the areas of exposed soils are plowed fields without the influence of physical or biogenic soil crusts. Dust also did not influence the spectral reflectance. The climate is tropical with a mean temperature of 21 °C. The annual rainfall may reach 1500 mm with a well-defined rainy season between December and May. The topography is gently undulating. The mean elevation is 705 m with minimum and maximum values of 480 m and 850 m, respectively.

3. Methodology

3.1. Data collection

3.1.1. Soil analyses

A total of 86 soil samples were collected in the study area (22 × 11 km) from both the surface (0–20 cm; 43