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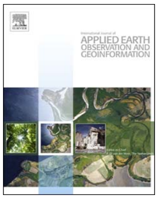

Classification of tree species based on longwave hyperspectral data from leaves, a case study for a tropical dry forest

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ABSTRACT

Remote sensing of the environment has utilized the visible, near and short-wave infrared (IR) regions of the electromagnetic (EM) spectrum to characterize vegetation health, vigor and distribution. However, relatively little research has focused on the use of the longwave infrared (LWIR, 8.0–12.5 μm) region for studies of vegetation. In this study LWIR leaf reflectance spectra were collected in the wet seasons (May through December) of 2013 and 2014 from twenty-six tree species located in a high species diversity environment, a tropical dry forest in Costa Rica. A continuous wavelet transformation (CWT) was applied to all spectra to minimize noise and broad amplitude variations attributable to non-compositional effects. Species discrimination was then explored with Random Forest classification and accuracy improved was observed with preprocessing of reflectance spectra with continuous wavelet transformation.

Species were found to share common spectral features that formed the basis for five spectral types that were corroborated with linear discriminate analysis. The source of most of the observed spectral features is attributed to cell wall or cuticle compounds (cellulose, cutin, matrix glycan, silica and oleanolic acid). Spectral types could be advantageous for the analysis of airborne hyperspectral data because cavity effects will lower the spectral contrast thus increasing the reliance of classification efforts on dominant spectral features. Spectral types specifically derived from leaf level data are expected to support the labeling of spectral classes derived from imagery.

The results of this study and that of Ribeiro Da Luz (2006), Ribeiro Da Luz and Crowley (2007, 2010), Ullah et al. (2012) and Rock et al. (2016) have now illustrated success in tree species discrimination across a range of ecosystems using leaf-level spectral observations. With advances in LWIR sensors and concurrent improvements in their signal to noise, applications to large-scale species detection from airborne imagery appear feasible.

1. Introduction

Environmental monitoring techniques have widely used the visible (VIS; 0.4–0.7 μm), near and shortwave infrared (NIR: 0.7–1.4 μm; SWIR: 1.4–2.5 μm) regions of the electromagnetic (EM) spectrum for remote sensing of vegetation. Each of these spectral regions provides different information based on the interaction of light with the internal foliar components. For instance, in the VIS, *chlorophyll a* reflects in the green (495–570 nm) and absorbs in the red and blue (620–750 nm and 450–495 nm, respectively), and indices have been created that capture this information aimed to indicate photosynthetic capacity and productivity (Kiang et al., 2007). In the NIR, which is also known as the NIR plateau, vegetation is strongly reflective (Clark et al., 2003; Kiang et al., 2007; Kokaly et al., 2009) and the NIR reflectance is driven by leaf thickness and internal morphology and a few studies have used these traits to successfully classify species in the same site and season (Zhang et al., 2006; Castro-Esau et al., 2006; Castro-Esau and Sanchez-Azofeifa, 2008; Sanchez-Azofeifa et al., 2009). Additionally, spectral features in the NIR resulting from organic bonds of plant biochemical material are detectable in dried and ground matter and are potentially more promising in species classification (Clark et al., 2003); these features in living, fresh leaves are masked due to internal scattering from the cell walls and strong absorption features from water (water absorption: 0.98 &1.3 μm; Kokaly and Clark, 1999; Clark et al., 2003). The SWIR region is exploited for the estimation of leaf water content and leaf dry matter content (Kokaly and Clark, 1999; Clark et al., 2003; Cheng et al., 2011). In regards to the discrimination of species, all three regions have limitations: 1) pigments in the VIS are generally not taxonomically unique; 2) the NIR has limited success in one site, in one season and a saturation with a large number of species (Castro-Esau et al., 2006; Hesketh and Sanchez-Azofeifa, 2012) and cellular biochemical features in the NIR that are potentially species specific can be

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masked in living and fresh leaves (Clark and Roberts, 2012; Clark et al., 2003); and 3) water content varies with individual and is also not inherently discernible between species. These issues have encouraged new investigations into alternative regions of the EM spectrum for taxonomic discrimination.

A relatively under-explored yet promising region of the EM spectrum for species identification is the long-wave infrared (8.0–12.5 μm; LWIR; Salisbury 1986). The LWIR has been used extensively in chemotaxonomic characterization of vegetation in the fields of biochemistry and chemistry (Kacuráková, 2000; Wilson et al., 2000; Szymanska-Chargot et al., 2015). Infrared (vibrational) and Raman spectroscopy have been used to identify plant constituents, compound abundances and starch-deficient mutants (Salisbury 1986; McCann et al., 1992; Séné et al., 1994; Chen et al., 1998; Wilson et al., 2000). However, for the purpose of remote sensing, vegetation was thought to be featureless in the LWIR until the pioneering work of Salisbury (1986) who reported different spectral responses for four tree species albeit low overall reflectance and spectral contrast. Salisbury (1986) hypothesized that the observed spectral variability could be due to surface hydrocarbons and the waxy cuticle.

Ribeiro da Luz and Crowley (2007, 2010) and Ribeiro da Luz (2006) made important strides in LWIR vegetation research providing strengthening evidence towards Salisbury (1986) hypotheses. They identified the source of the spectral features to be from constituents on the leaf surface and showed that living leaves have LWIR spectral characteristics that could potentially discriminate tree species (Ribeiro da Luz and Crowley, 2007). Ribeiro da Luz and Crowley (2007) and Ribeiro da Luz (2006) found that biochemical and structural constituents of the leaf produce spectral features as a result of the molecular vibrations of functional groups in the compounds. Though there are many compounds influencing the LWIR spectra, a few common compounds were identified in the LWIR spectra: cellulose, xylan, cuticular waxes, cutin and silica (Ribeiro da Luz and Crowley, 2007; Ribeiro da Luz, 2006). The spectral features make up a “fingerprint” spectrum that may be unique to a particular tree species. Ribeiro da Luz and Crowley (2007) also found intra-specific variation in amplitude of discriminating features between development stages of the leaf and its location within the crown (sun versus shade leaves). This investigation will elaborate on the Ribeiro da Luz and Crowley (2007, 2010) and Ribeiro da Luz (2006) studies by applying some of their feature matching methods and their published compound library to a novel ecosystem, a tropical dry forest, characterized by a high species diversity providing access to a larger number of species and greater spectral diversity than investigated in the past. Since the work of Ribeiro da Luz and Crowley other complimentary investigations have explored the applicability of LWIR spectroscopy to the field of remote sensing. Ullah et al. (2012) collected directional hemispherical *reflectance* (*DHR*) and emissivity spectra of leaves in the laboratory to discriminate 13 temperate tree species by using band selection methods applied to mid-infrared (3.0–6.0 μm; MIR) and LWIR spectra. They suggested that 6 bands could be used to efficiently discriminate the tree species of their study. The same research group then used a longwave spectral imaging spectrometer (Telops hypercam) to evaluate the discrimination of leaves extracted from 8 plant species (Rock et al., 2016) seven of which were used in their prior study. Rock et al. (2016) obtained a 92% overall accuracy after temperature-emissivity separation which is relevant to airborne survey. Both studies did not take into consideration compound characterization as conducted by Ribeiro da Luz and Crowley (2007) and Ribeiro da Luz (2006). Our investigation adds to these investigations and the field of LWIR vegetation remote sensing as a whole by combining the species classification, spectral feature identification and compound characterization across a new ecosystem with a greater biodiversity.

A study examining species in high diversity biomes could provide a better picture of the LWIR spectral diversity and variability across tree species. In this investigation, LWIR remote sensing is applied to tropical dry forests (TDF). TDF is defined as an ecosystem that is dominated by deciduous trees (i.e.: at least 50%) and experiences a mean annual temperature of > 25 °C, a total annual precipitation between 700 mm and 2000 mm, and 3 or more dry months annually (Sanchez-Azofeifa et al., 2005). The abundance of endemic plant species and their location in the tropical latitudes supports the high diversity index found in these ecosystems (Sanchez-Azofeifa et al., 2005; Portillo-Quintero et al., 2015). A TDF will therefore provide a well-rounded data set to capture inter-specific and intra-specific variability with many more species than that of a temperate forest. TDFs also provide optimal canopy structure for LWIR remote sensing that is closed planophile canopies with wide and flat leaves that should lead to stronger spectral contrast, (Ribeiro da Luz and Crowley, 2010) of relevance to ensuing investigations based on airborne longwave infrared imaging as a continuity to this study. Using LWIR spectra of leaves from TDF tree species this investigation has three specific aims: i) to examine the extent to which tree species can be classified using their LWIR spectrum, ii) to identify the discriminating features and explore the spectral diversity through spectral groups (*i.e.* spectral types, ST) and iii) attempt to identify the source of some of the aforementioned features.

2. Materials and methods

2.1. Sample site and leaf collection

This investigation took place at the Santa Rosa National Park Environmental Monitoring Super Site in Costa Rica (10° 53′ N, 85° 38′ W, Fig. 1) over two consecutive wet seasons in 2013 and 2014. This site is a tropical dry forest with a mean annual precipitation of 1390 mm and a mean annual temperature of 25 °C (Kalacska et al., 2005). The dry season extends from December to April and the wet season from May to November. Data collection was conducted at two sites of secondary growth forest where the vegetation is roughly 50–60 years old. Samples were collected from two pre-existing plots of 1 ha and 20 m by 50 m (+10.8416, −85.6157 and +10.8299, −85.6142) everyday over the course of the peak of the wet season in each year. Trees greater than 0.05 m of diameter at breast height (DBH) (Batcheler, 1985) were previously identified at the species level. The top 26 tree species dominating the canopy were selected for sampling and all species were broad leaf (Table 1).

2.2. Leaf spectral measurements

Leaf samples were collected from each of 3 tree individuals per species for 26 species with a tree trimming pole (Table 1). One diffuse reflectance spectral measurement per leaf was collected. A total of 15 leaves were collected per individual tree in 2013 (9 sun leaves, 3 mid-canopy and 3 shade leaves) and 3 leaves per individual in 2014 (1 sun, 1 mid-canopy and 1 shade). The majority of the leaves that were collected were sun leaves because only well-exposed leaves on the outer canopy are going to be remotely sensed. A diffuse reflectance spectrum of each leaf sampled was acquired with the use of an Agilent 4100 ExoScan FTIR (Fourier transform infrared) spectrometer. This spectrometer has a spectral range of 2.5–15.4 μm (4000–650 cm^{-1}) and a resolution of 4 cm^{-1}. It is a portable spectrometer with a weight of 3.73 kg, designed for field measurements with minimal to no sample preparation. This spectrometer uses a temperature stabilized deuterated-triglycine sulfate (DTGS) detector. The Agilent Exoscan has interchangeable probes that alter the fashion in which the infrared light illuminates the sample. For this study, a diffuse reflectance probe with a diffuse reference cap for background collection was used. For this probe the IR light illuminates a field of view (FOV) of roughly 1.5 cm at an angle of 45 ° and the maximum depth of light penetration is between 20 and 50 μm, depending on the medium. Two instrument performance tests were conducted during background measurements and performed before collection of every leaf spectra. Signal to noise was assessed at