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Retrieving structural and chemical properties of individual tree crowns in a highly diverse tropical forest with 3D radiative transfer modeling and imaging spectroscopy

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ABSTRACT

Spatial and temporal information on the structural and chemical properties of tropical forest canopies are key to understanding ecosystem processes. However, such information is usually limited to field studies performed at the plot level (~1 ha). The combination of imaging spectroscopy with physically based radiative transfer (RT) models holds great promise for generalizing and extrapolating insights from plot-based studies to whole landscapes. Here, we tested the capacity of a simplified 3D RT approach to retrieve the structural and chemical traits of individual tree crowns (ITCs) from a highly diverse tropical forest. We first produced two datasets called measured and simulated. The measured dataset was composed of ITC reflectance extracted from sunlit imaging spectroscopy pixels. The simulated dataset was produced using a look-up-table approach and the discrete anisotropic radiative transfer (DART) model. We then compared the simulated and measured reflectances of ITCs in terms of shape difference by computing the spectral angle. The results showed small disagreements between the simulated and measured reflectances. Such differences impacted neither the spectral variability nor the spectral regions recognized as useful for species discrimination, showing that the spectral angle was a suitable measure of spectral similarity. Simulation robustness was assessed by comparing model parameters obtained by inversion to imaging spectroscopy vegetation indices and the proportion of non-photosynthetic vegetation (NPV), green photosynthetic vegetation (GV) and shade estimated within ITCs. DART canopy structural parameters were related to NPV (R^2 = 0.71), GV (R^2 = 0.78) and shade (R^2 = 0.55). DART canopy foliar parameters such as chlorophyll and carotenoids were related to the ratio of TCARI/OSAVI (R^2 = 0.80) indices and the simple ratio between reflectances at 515 nm and 570 nm (R_{515}/R_{570}) (R^2 = 0.54), respectively. Species-related differences in NPV, GV and shade were explained by variations in crown architectural characteristics. The simulation framework employed in this study can be applied to retrieve structural and chemical traits of ITCs from other areas in which high-resolution imaging spectroscopy data are available.

1. Introduction

Tropical forests are key Earth biomes. They harbor at least two-thirds of the world's terrestrial biodiversity (Gardner et al., 2009) and provide ecosystem services for humanity such as carbon (C) storage with 55% of the global forest C stock (Pan et al., 2011) and nutrient cycling with fixation of 70% of terrestrial nitrogen (Wang and Houlton, 2009). Most of our knowledge about the dynamics of tropical forests comes from field measurements performed at the plot level (~1 ha), but data that encompass broader spatial extents are needed to better understand the complex structure and functions of these important ecosystems. Remote sensing holds great promise for generalizing and extrapolating insights emerging from plot-based studies to whole landscapes (Asner et al., 2015b). Plant canopy foliage exhibits multiple interactions with solar radiation from the visible to the shortwave infrared regions of the electromagnetic spectrum (VSWIR, 400–2500 nm).

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These interactions are related to leaf functional traits involved in the production of carbohydrates such as photosynthetic pigments (e.g., chlorophylls, carotenoids and anthocyanins) and others that provide defense against herbivory or physical hazards, such as cellulose and lignin (Wright et al., 2004). Thus, information is increasingly needed about spatial and temporal variation in canopy foliar properties related to ecosystem function and processes (Asner and Martin, 2016).

Imaging spectroscopy, also known as hyperspectral remote sensing, has proven to be a pivotal technology that can fill this need. Imaging spectroscopy has emerged as a promising way to map tropical forest canopy diversity (Féret and Asner, 2014; Laurin et al., 2014; Schäfer et al., 2016), to identify species at the individual tree crown (ITC) level (Clark et al., 2005a; Féret and Asner, 2013; Baldeck et al., 2015; Ferreira et al., 2016) and to estimate canopy chemical properties (Asner and Martin, 2009; Asner et al., 2015a, 2015b; Chadwick and Asner, 2016). Imaging spectroscopy data are acquired by sensors capable of measuring reflected radiation from the forest canopy over a spectral continuum of many narrow bands, which allows detection of subtle variations in the spectral response of tree species. Such variations are induced by canopy chemical traits and biophysical properties such as the leaf area index (LAI), but vegetation is not the only contributor to the variability in canopy reflectance: illumination, geometry of acquisition, background (understory plants, litter, soil, etc.) and atmospheric effects also influence the signal finally measured by the sensor (Asner, 1998; Huesca et al., 2016). This fact challenges our ability to retrieve canopy traits or information regarding biodiversity from imaging spectroscopy, particularly in tropical environments in which the canopy is spectrally and structurally very complex. A better understanding of diffusive and absorptive processes occurring within the canopy of tropical forests and influencing canopy reflectance is needed to address these issues. Radiative transfer models (RTMs) are valuable tools for improving our understanding of these processes and their influence on the electromagnetic signal.

RTMs are physical models that describe photon transport mechanisms acting within the canopy (leaves, branches, twigs, etc.) and the background and are capable of simulating the spectral response of forest areas. Once a physical model produces realistic simulations, it can be used to estimate biophysical and biochemical vegetation traits from canopy reflectance in different ways. RTMs are known to be more generalizable than data-driven models adjusted with measurements because they can simulate remote sensing data in a variety of acquisition and environmental conditions (Myneni et al., 2002; Verrelst et al., 2015) and are less prone to bias induced by the sampling strategy of measured data. A large number of RTMs exist, differing by their complexity and by the hypotheses upon which they rest. Operational regional monitoring requires computationally efficient RTMs and procedures applicable to satellite imagery acquired by sensors with coarse-to-moderate spatial resolution (MODIS, Thematic Mapper). Such applications usually rely on hypotheses about the homogeneity of the vegetation stand, which makes one-dimensional (1D) RTMs particularly appropriate, because they describe vegetation as a turbid medium to statistically represent light interactions in a given volume (e.g., group of leaves, atmosphere or water) (Verhoef et al., 2007; Jacquemoud et al., 2009; Houborg et al., 2015). In the case of heterogeneous canopies characterized by complex architectures, including substantial shadowing effects and variations in branching pattern, three-dimensional (3D) RTMs are more appropriate (Schneider et al., 2014; Gastellu-Etchegorry et al., 2015) because they can deal with explicitly described canopy structures. The level of details and type of information required by the existing 3D RTMs to describe this canopy structure may vary depending on the model in use and objectives pursued. A number of models featuring integration of canopy architecture have been developed (for a recent review refer to Widlowski et al., 2015), including the discrete anisotropic radiative transfer (DART) model (Gastellu-Etchegorry et al., 2015).

DART is currently one of the most comprehensive 3D RTMs and has been widely used to simulate the radiative transfer of forest canopies, helping to interpret the radiometric signal measured by remote sensors. Simulations of various types of forested ecosystems have been performed so far from alpine forests to diverse tropical forests for ecological and forestry purposes (Gastellu-Etchegorry et al., 1996; Schneider et al., 2014). These simulations comprised a wide range of remotely sensed data (including imaging spectroscopy data and very high spatial resolution data) to generate textural and spectral information. Malenovský et al. (2008) used DART to investigate the influence of woody elements on the canopy spectral response and the LAI retrieval of a Norway spruce (*Picea abies*) forest. Simulations were performed in the 450–800 nm spectral range and compared with top of canopy (TOC) reflectance acquired by an airborne imaging spectroscopy sensor. The authors highlighted the importance of including woody elements in radiative transfer-based approaches to retrieve LAI, particularly when individual tree crowns were considered. In the same study area, DART was successfully used by Malenovský et al. (2013) to retrieve leaf chlorophyll content from imaging spectroscopy. For this purpose, they simulated the imaging spectroscopy data in a spectral region sensitive to chlorophyll absorption located between 650 and 720 nm; then, they inverted the model using artificial neural networks. In tropical environments, Barbier et al. (2010) used DART to verify the relationship between canopy textural attributes and crown diameters and quantify the impact of satellite image acquisition parameters (viewing and illumination angles) on the results of the FOTO method (Couteron, 2002) that was applied to determine crown size and heterogeneity. Morton et al. (2016) used DART to build a 3D Amazon forest scene and study the diurnal and seasonal variability in light utilization. The model was parameterized with high-density light detection and ranging (LiDAR) data and in situ measurements. A realistic representation of the forest stand permitted the authors to investigate the influence of the forest structure on light interactions occurring within the canopy.

To investigate the potential and limitations of the various types of remote sensing data for applications dedicated to the retrieval of canopy chemical traits and biophysical properties of forest ecosystems using 3D RTMs, researchers require the ability to produce realistic and accurate simulations of the remote sensing signal. The realism and accuracy of these modeling tools should then be compatible with the level of details available to run the simulations. Thus, forward modeling studies are necessary to gain knowledge on model limitations, costs required for realistic simulations and photon transport mechanisms contributing to the variability in canopy reflectance. Moreover, forward modeling provides an efficient way to identify spectral regions showing high fidelity or discrepancies between measured and simulated data. This information helps to select suitable spectral ranges to be used when applying the model to retrieve a certain canopy variable and to improve the model itself (Schlerf and Atzberger, 2006; Zeng et al., 2016).

State-of-the-art 3D RTMs, such as DART, handle the description of many factors that influence the signal measured by a remote sensor. This ability makes it a powerful tool for understanding light diffusion processes that set up the radiation field of forest canopies. However, a very comprehensive description requires a large amount of information to parameterize the many parameters controlling all possible scattering mechanisms in the scene, which is usually not fully available. Therefore, performing 3D modeling of complex heterogeneous canopies requires a certain number of assumptions and trade-offs to establish the optimal description level for each factor based on available information and, importantly, to fully understand the effects resulting from default values set for variables missing experimental measurements.

To date, little is known about the performance of 3D RTMs for simulating airborne imaging spectroscopy data acquired over diverse tropical forests. Ideally, simulating the spectral response of individual tropical trees would require a detailed parameterization of the 3D crown architecture, which can be derived from high-density airborne or terrestrial LiDAR and extensive field measurements (Morton et al.,