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Bidirectional texture function of high resolution optical images of tropical forest: An approach using LiDAR hillshade simulations

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ABSTRACT

Quantifying and monitoring the structure and degradation of tropical forests over regional to global scales is gaining increasing scientific and societal importance. Reliable automated methods are only beginning to appear; for instance, through the recent development of textural approaches applied to high resolution optical imagery. In particular, the Fourier Transform Textural Ordination (FOTO) method shows some potential to provide non-saturating estimates of tropical forest structure, including for large scale applications. However, we need to understand more precisely how canopy structure interacts with physical signals (light) to produce a given texture, notably to assess the method's sensitivity to varying sun-view acquisition conditions. In this study, we take advantage of the detailed description of canopy topography provided by airborne small footprint LiDAR data acquired over the Paracou forest experimental station in French Guiana. Using hillshade models and a range of sun-view angles identical to the actual parameter distributions found for Quickbird™ images over the Amazon, we study noise and bias in texture estimation induced by the changing configurations. We introduce the bidirectional texture function, which summarizes these effects, and in particular the existence of a textural 'hot spot', similar to a well-known feature of bidirectional reflectance studies. For texture, this effect implies that coarseness decreases in configurations for which shadows are concealed to the observer. We also propose a method, termed partitioned standardization, that allows mitigating acquisition effects and discuss the potential for an operational use of VHR optical imagery and the FOTO method in the current context of international decisions to reduce CO_2 emissions due to deforestation and forest degradation.

1. Introduction

Assessing the biophysical parameters of tropical forests is becoming an important economic and political endeavor, notably because of the role of these ecosystems in the carbon cycle (IPCC, 2007; Lewis et al., 2009; Malhi et al., 2008; Wright, 2005). Canopy structure, in particular, is an essential feature because it regulates the microclimate, e.g., light and moisture levels (Cochrane, 2003), within the forest as well as the interactions between the forest and the macroclimate through the exchange of energy, water vapor and other gases with the atmosphere (Bonan, 2008). The size distribution of tree crowns and the spacing between them is thought to be linked allometrically to a number of dynamical and structural forest parameters such as recruitment and mortality rates, trunk diameter distribution and biomass (Chave et al., 2005; Enquist et al., 2009). Canopy structure also reflects disturbance history and the level of forest degradation (Weishampel et al., 2007). Obtaining precise information about the structure of a forest's 'folded surface' (Birnbaum, 2001) could help advance various activities spanning the quantification of forest degradation, carbon stocks and dynamics, the water cycle and forest resilience to natural hazards, such as fire and invasive species.

Remote sensing data and methods have been successfully used to characterize and monitor forest structure and biomass in temperate and boreal ecosystems. However, repetitively assessing high biomass levels and complex structures such as those found in tropical forests over significant extents remains problematic, due to signal saturation of both reflectance (Huete et al., 2002) and backscattering signatures (Le Toan et al., 2004), as demonstrated by radiative transfer modeling studies (Gastellu-Etchegorry et al., 1996; Proisy et al., 2000). Alternatively and quite promisingly, the potential for high resolution images to be used for mapping forest structure is being explored through the development of crown detection algorithms (Asner et al., 2002; Gougeon & Leckie, 2006; Palace et al., 2008) and the analysis of canopy textural properties. For the latter, canopy surface properties are investigated using semivariograms (Bruniquel-Pinel & Gastellu-

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Etchegorry, 1998; Song & Woodcock, 2003; St-Onge & Cavayas, 1997), lacunarity indices (Frazer et al., 2005; Malhi & Roman-Cuesta, 2008) or 2D Fourier spectra (Barbier et al., 2010; Couteron et al., 2005; Proisy et al., 2007). Whatever the method used, it is now quite clear that the derivation of forest parameters using such approaches requires spatial resolutions finer than 4 m (Proisy et al., 2007). Indeed, the 'green carpet' (Asner et al., 2002) provided by medium resolution imagery then translates into a more informative image consisting of sunlit and shadowed canopy areas (Couteron et al., 2005). Designing and testing methods of textural characterization is therefore critical for processing such information on canopy conditions into meaningful information pertaining to forest structure.

Profiting from the Google Earth™ digital globe interface, Barbier et al. (2010) demonstrated that processing a large number of images (i.e., a set of 200 Quickbird™ high resolution images) is no longer a limit for such studies. It is indeed possible to automate the flow of computational operations needed to consistently map canopy texture and to develop approaches that are largely independent of the values of both the mean and variance of the images and therefore of problematic atmospheric corrections (Song & Woodcock, 2003). Fourier-based textural ordination (FOTO) of high resolution images (Couteron et al., 2005; Proisy et al., 2007) was shown to meet these requirements. It aims to identify the main gradients of textural variation by coupling 2D Fourier spectra describing the spatial frequency distribution of image variance in canopy scenes with principal component analysis (PCA). The resulting indices (i.e., scores for the main PCA axes) allow canopy structure to be described in terms of mean apparent crown size or canopy heterogeneity (Barbier et al., 2010). Indeed textural index values obtained from real-world Quickbird images proved to be consistent with those obtained from simulated images (applying the DART radiative transfer model of Gastellu-Etchegorry (2008) to simple templates of forest structure), thereby validating the model inversion (Barbier et al., 2010). Independent case studies using field datasets have also shown that FOTO canopy texture indices were correlated with several important parameters characterizing forest structure, such as mean trunk diameter (DBH), mean tree height, stand density, and even biomass (Couteron et al., 2005; Proisy et al., 2007).

From these promising results, the systematic use of the FOTO method at regional or continental scales requires a thorough examination of how and to what extent FOTO texture indices may be influenced by variation in acquisition parameters across scenes such as sun height and sensor viewing angles. Changes in these parameters may induce sensible textural variations, as tree crowns and associated shadows may seem bigger or smaller in different configurations. This may disrupt the consistency of any kind of texture measure based on a set of scenes acquired over heterogeneous lighting and viewing conditions. Such heterogeneities are unavoidable if the scene array is to cover extensive areas. Preliminary tests (Barbier et al., 2010) were performed on the basis of a correlation analysis of the textural properties of Quickbird images and their acquisition parameters, and also using the DART radiative transfer model (Gastellu-Etchegorry, 2008) applied on simple templates of 3D forest structure. In both approaches, the influence of acquisition parameters was shown to be small but significant. However, a correction method, based on a partitioned standardization of Fourier spectra according to bins of similar acquisition configurations, showed good potential to mitigate instrumental discrepancies.

The aim of the present study is to reach a broader level of understanding of the effects of acquisition parameters on FOTO-based texture quantification and to further test our mitigation method. We ground the methodological analysis in real-world patterns of rainforest canopies by taking advantage of the accurate altimetric description of the canopy provided by airborne light detection and ranging data (LiDAR, Lefsky et al., 2002; St-Onge et al., 2008; Vega & St-Onge, 2008), allowing for a detailed study of the interactions between lighting/viewing angles and canopy structure. Despite its prohibitively high cost over large spatial scales, airborne LiDAR indeed provides unprecedented forest structural information (Asner, 2009). We therefore produced a digital surface model (DSM) at a pixel size of 1 m, using LiDAR data acquired over a large rainforest track (300 ha) in French Guiana. This canopy topography model served to derive equivalents of 2D panchromatic optical images via hillshade simulations, with varying viewing and sun lighting angles and over diversified actual canopy structures.

The sensitivity of texture values obtained from the FOTO analysis of the hillshade models was then assessed and analyzed. The influence of the acquisition parameters was summarized in a bidirectional texture function (BTF), a concept analogous to the bidirectional reflectance distribution function or BRDF (Gastellu-Etchegorry et al., 1999; Gerard & North, 1997; Kimes, 1983; Nicodemus, 1965). Although the term of BTF has already been introduced for computer graphics purposes (Dana et al., 2007, 1999), textures were previously treated as a databank of images of sampled structures acquired under different conditions of observation and illumination but not quantified using quantitative texture indices as proposed in the present study. To our knowledge, the only similar attempt in the context of remote sensing applications is a recent contribution (Goodin et al., 2004) that investigated the effects of solar and viewing angles on the observed spatial structure of a tallgrass prairie, quantified through variograms. However, the range of scales considered (>1 m between sampling points) was not compatible with the scales at which individual grass stumps or leaves could have affected the observed structural patterns.

2. Data

2.1. Study site

The study was conducted over an area of 300 ha of lowland *terra firme* rain forest, located within and around the Paracou Experimental Station (5°18′ N, 52°23′ W) in French Guiana. The station was established in 1984 by the French Agricultural Research Centre for Development (CIRAD) for silvicultural research within natural forest stands (http://arlequin.cirad.fr/arlequin/english/index.php, last consulted: July 23, 2009). The total number of stems and associated basal area ranged from 575 to 665 stems per hectare and 29.3 to 33 m² per hectare, respectively. A set of 14 permanent plots of 9 ha each were managed with contrasted silvicultural treatments and a 25 ha reference plot was delimited to study the natural forest (Gourlet-Fleury & Houllier, 2000). Silvicultural treatments ranging from severe to highly selective logging regimes provided an important diversity of forest structure and consequently of canopy texture. A floristic survey revealed about 546 different plant species belonging to 57 families, with a dominance by *Caesalpiniaceae*, *Lecythidaceae*, *Chrysobalanaceae* and *Sapotaceae* (Sabatier & Prévost, 1990).

The climate in the study area is equatorial, characterized by mean annual rainfall and temperature around 3040 mm and 26 °C, respectively. It is marked by a dry season from mid-August to mid-November and a shorter dry period in March (Gourlet-Fleury et al., 2004). The moderate undulating topography consists of a succession of small elliptical hills ranging from 100 to 300 m in diameter and 20 to 35 m in elevation above sea level. Slopes vary from 25 to 45%. Soils are mostly shallow ferralitic, developed on schists and sandstones on the hills and bottomlands, respectively (Delcamp et al., 2008).

2.2. LiDAR data

The light detection and ranging (LiDAR, Lefsky et al., 2002) data were acquired over the study site using the ALTOA system (http://www.altoa.fr/) on October 20, 2004 as part of the CAREFOR research project. This system includes a portable Riegl laser rangefinder (LMS6Q140i-60) mounted onboard a helicopter flying at a speed of 30 m s^{-1} about 150 m