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Characterization of the horizontal structure of the tropical forest canopy using object-based LiDAR and multispectral image analysis

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ABSTRACT

This article's goal is to explore the benefits of using Digital Surface Model (DSM) and Digital Terrain Model (DTM) derived from LiDAR acquisitions for characterizing the horizontal structure of different facies in forested areas (primary forests *vs.* secondary forests) within the framework of an object-oriented classification. The area under study is the island of Mayotte in the western Indian Ocean. The LiDAR data were the data originally acquired by an airborne small-footprint discrete-return LiDAR for the "Litto3D" coastline mapping project. They were used to create a Digital Elevation Model (DEM) at a spatial resolution of 1 m and a Digital Canopy Model (DCM) using median filtering. The use of two successive segmentations at different scales allowed us to adjust the segmentation parameters to the local structure of the landscape and of the cover. Working in object-oriented mode with LiDAR allowed us to discriminate six vegetation classes based on canopy height and horizontal heterogeneity. This heterogeneity was assessed using a texture index calculated from the height-transition co-occurrence matrix. Overall accuracy exceeds 90%. The resulting product is the first vegetation map of Mayotte which emphasizes the structure over the composition.

1. Introduction

The sustainable management of forested areas requires good knowledge of various stands and their structure, based on information on the cover's height and heterogeneity. An inventory can be time-consuming and expensive and only provides localized data unsuitable for comprehensive mapping, in particular for highly fragmented forested spaces. Aerospace technologies offer an alternative, especially for tropical forests, which are usually inaccessible and exhibit great spatial variability.

The stands are traditionally distinguished by photo-interpretation of aerial photographs (stereoscopic or monoscopic) but this method is not easily reproducible (St-Onge et al., 2007). Satellite imagery provides a signal dependent on factors that are structure-related (composition, geometry, density) or unrelated (environment, solar elevation, viewing angle, atmospheric transmittance). Nevertheless, even with very high resolution multispectral imagery (Weishampel et al., 2000), it is difficult to extract height information. We can proceed indirectly by modeling shadow variations related to tree height and density of the canopy (Asner and Warner, 2003) or by extracting textural information on the canopy, combined with the main parameters of the stand structures (Couteron et al., 2005; Lévesque and King, 2003). The horizontal structure, which can be defined as the "spatial arrangement of trees and openings" (Pascual et al., 2008), is also difficult to determine because canopy openings are not easily detectable from aerial images or photos (Vepakomma et al., 2008). This is one of the reasons why secondary forests (>15 years) cannot be distinguished from primary forests (Tottrup et al., 2007).

InSAR (Interferometric Synthetic Aperture Radar) (Neeff et al., 2005) and LiDAR (Light Detection and Ranging) (Dubayah and Drake, 2000; Lefsky et al., 2002) directly provide height information. Results with LiDAR are better than those from InSAR; the reduced viewing angle of the former allows better height estimation (Andersen et al., 2003). So-called "topographic" LiDAR systems have a small swath and are therefore preferred for detailed ground mapping over a large area. This type of LiDAR is often used in the forestry domain to characterize stands and inventory forest resources. We distinguish, in general, between analyses at the individual tree scale which necessitate the delineation of tree

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crowns (Hyyppä et al., 2008; Véga and Durrieu, 2011) and surface approaches, conducted at the plot or stand scales (Maltamo et al., 2004; Næsset, 2007; Yu et al., 2010).

LiDAR data result in two major models: the Digital Terrain Model (DTM) and the Digital Surface Model (DSM), whose difference leads to the Digital Elevation Model (DEM). Even with a perfect DTM and a perfect DSM and, therefore, with a DEM of equivalent quality, we can only determine, with discrete feedback systems, the canopy's horizontal structure (height and heterogeneity of heights) and possibly its texture (Vincent et al., 2010). Therefore, multispectral data (aerial photographs, satellite images) can be very useful for discriminating between neighboring stands with similar heights and horizontal structure but which are of different types.

Considerable work along these lines has been done (Bork and Su, 2007) and a review of various possible approaches depending on the type of dendrometric parameter sought has been conducted by (Gachet, 2009). With a few notable exceptions (Ke et al., 2010; Straatsma and Baptist, 2008), this body of work – pixel-based or object-based – combines not LiDAR and multispectral data themselves but rather the classification results obtained in parallel from them.

The classification of images at high spatial resolution is often difficult because their high intra-class radiometric variability induces classes overlapping. Especially, for heterogeneous canopies, the result is highly fragmented (Gachet, 2009; Kim and Madden, 2006). An exhaustive review (Blaschke, 2010) identifies the flaws in the "pixel" paradigm and highlights the recent advances in OBIA (object-based image analysis) which, in particular, permit an improved detection of stand boundaries. A stand is considered as "a community of trees sufficiently uniform in composition, age and spatial arrangement as to be distinguishable from adjacent communities" (Sullivan et al., 2009).

In object-oriented mode, as in photo-interpretation, a segmentation process is undertaken before the actual recognition. This process partitions the image into disjoint sets called image objects. We have used the fractal approach developed by eCognition (Benz et al., 2004; Blaschke et al., 2000) where the segmentation is based on a region-growing algorithm initialized from each pixel (Zhou and Troy, 2008). This algorithm can not only process source data of different kinds and resolutions simultaneously but can also conduct a multi-scale image analysis (Baatz and Schäpe, 2000; Burnett and Blaschke, 2003; Sparfel et al., 2008).

This article's goal is to explore the benefits of using DSM and DTM derived from LiDAR acquisitions for characterizing the horizontal structure of different facies in forested areas (primary forests *vs.* secondary forests) within the framework of an object-oriented classification. The originality of the approach we develop lies not only (i) in considering the usefulness of raw multispectral data (photographs and images) combined with LiDAR data at the segmentation stage itself for improved delineation of stands, (ii) in using the heights co-occurrence variance to assess the canopy's horizontal homogeneity, but also (iii) in applying it to the tropics, where little work of this type has been carried out.

Studies using two or more successive segmentations at different scales (forests, stands, trees) involve, to our knowledge, only one data type per segmentation (Tiede et al., 2007). We, on the other hand, incorporate source data from different sources from the second segmentation stage to benefit from the complementarity between LiDAR and multispectral data. The supplementary thematic maps have also been incorporated.

The methodology described in this article was applied on the island of Mayotte, over a surface area of 375 km^2, to produce a land cover map to characterize terrestrial vegetation and to provide a reference map to guide forest protection policies.

2. Data

2.1. Study site

The island of Mayotte (Comoro Islands) is one of the last to have forest complexes in this part of the western Indian Ocean. These complexes are located mainly in five forest reserves which are under threat from land clearing and the proliferation of lianas (Fig. 1). Forested areas outside the reserves are poorly known and much more fragmented.

2.2. LiDAR-derived data

2.2.1. Acquisition and processing of LiDAR data

LiDAR data were acquired within the framework of the Litto3D project in October 2008 by the French National Geographic Institute (IGN) using an airborne OPTECH 3100 AE system. The aircraft's position and absolute orientation was determined by a positioning system consisting of a GPS receiver and an inertial unit. The parameters affecting the density of ground points were the aircraft's speed (80 m/s) and flight height (900 m), the maximum angle ($\pm 18^\circ$), the scan frequency (50 Hz) and the laser pulse frequency (100 kHz). Under these conditions, the average raw point density is two points/m^2 for a ground footprint size 80 cm in diameter. The positional accuracy is better than 0.5 m (RMSE) and the vertical accuracy is better than 0.20 m (RMSE) irrespective of the area under consideration.

All the echoes were recorded. IGN then proceeded to automatically and interactively filter the point cloud to extract the first and last returns. The first returns correspond to the first interception of the transmitted pulse which, in forested zones, is theoretically caused by the canopy's summit. The last returns usually correspond to the soil surface but this is not always the case, particularly in areas of dense vegetation where significant interactive processing (taking about 2 h/km^2) is required to verify and reclassify points. To filter 'ground' points, IGN resorted to TerraScan software (Terrasolid Ltd., Finland), using an iterative TIN method (Axelsson, 2000). From this filtering, a DSM and a DTM were created at 1 m $\times$ 1 m resolution.

2.2.2. Calculating the DEM and the DCM

There are several ways of defining the canopy. In this article, the canopy is defined as the collection of crowns touching the canopy surface (Bongers, 2001). Calculating the difference between the DSM and the DTM (Naesset, 1997) yielded a Digital Elevation Model (DEM), also at a spatial resolution of 1 m. In these forest areas, the DEM exhibits several irregularities (Van Leeuwen et al., 2010) caused by pixels whose values are much lower than those of their immediate neighbors. We did not undertake mean smoothing because, even though it eliminates the holes, it also changes all the image pixels (Ben-Arie et al., 2009). We chose instead to use a rank-order operator median filter: it retains the edges and does not blur them but does remove isolated lines and elements. It thus highlights homogeneous areas without altering stand boundaries and edges (Korhonen et al., 2011; Popescu et al., 2002). In addition, it reduces the influence of low-vegetation points (Holmgren and Persson, 2004). This median filter applied to the inside of a sliding 3 $\times$ 3 window allowed us to obtain a Digital Canopy Model (DCM) which constitutes the input data for the level 1 segmentation (Fig. 2).

2.3. Multispectral data

The working image was a SPOT 5 image, reference K161-J375, at a spatial resolution of 10 m, acquired on 30 June 2005 with a viewing angle of +5.50° and consisting of four spectral bands: green, red,