Remote Sensing of Environment 175 (2016) 32–42

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

On the interest of penetration depth, canopy area and volume metrics to improve Lidar-based models of forest parameters

Cédric Véga [a,*], Jean-Pierre Renaud [b], Sylvie Durrieu [c], Marc Bouvier [c]

[a] Institut National de l'Information Géographique et Forestière, Laboratoire de l'Inventaire Forestier, 11 rue de l'Ile de Corse, 54000 Nancy, France
[b] Office National des Forêts, pôle RDI, 11 rue Ile de Corse, 54000 Nancy, France
[c] UMR TETIS Irstea-Cirad-AgroParisTech/ENGREF, Maison de la Télédétection en Languedoc-Roussillon, 500, rue J.F. Breton BP 5095, 34196 Montpellier Cedex 05, France

ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form 20 December 2015
Accepted 30 December 2015
Available online 7 January 2016

Keywords:
Lidar
Forest inventory
Penetration depth
Area and volume metrics
Area-based approach
Basal area
Aboveground volume

ABSTRACT

We proposed a new area-based approach to process Lidar point clouds and develop new sets of metrics to improve models dedicated to predict forest parameters. First, we introduced point normalization based on penetration depth below the outer canopy layer to avoid biases introduced by ground normalization and canopy surface heterogeneity during metric computation. Second, we proposed computation of area and volume metrics from canopy surface models computed from both first and last returns to better characterize the 3D plot heterogeneity. The set of proposed metrics were combined with traditional ones, based on point height above ground level, to measure their contribution to models of basal area (BA) and aboveground volume (AGV). The modeling framework included a wide range of forest types, canopy structures and Lidar characteristics. Models were developed for all sites grouped together or separately. In each case, the set of metrics was submitted to a hierarchical clustering process to select the best variables to be included in the models that were further established using a best-subset method. Overall, the introduction of the proposed metrics allowed a reduction in models root mean squared error from −0.06% to 19.58% according to forest types and target forest parameters. Best improvements were achieved for broadleaved forests, showing the potential of the proposed metrics to efficiently characterize the structure of such porous forest canopies.

1. Introduction

Airborne Laser Scanning (ALS) is a state of the art remote sensing technology for describing forest environments. ALS acquisitions are based on light detection and ranging (Lidar) principles (Baltsavias, 1999). ALS systems combine a micropulse laser scanning system, either multi-echo or full-waveform, a global positioning system (GPS) and an inertial measurement unit to produce high precision measurements of the Earth's surface (Baltsavias, 1999). Owing to the ability of the laser signal to provide information from several targets on its trajectory, Lidar can penetrate through forest canopies, thus providing 3D multi-echo point clouds or waveforms describing the 3D structure of both the vegetation structure and the ground below it (Reutebuch, McGaughey, Andersen, & Carson, 2003). Due to partial occlusions, the deeper the laser beam penetrates into the vegetation, the more the signal is attenuated.

One of the interests of ALS data for forest applications lies in the demonstrated relationship between the vertical distribution of the laser hits within the canopy and the vertical distribution of foliage (Magnussen & Boudewyn, 1998). For large scale applications, ALS point cloud analyses mainly rely on area-based approaches and statistical analyses of height distributions of laser hits above the ground level (Hyyppä et al., 2008). Such distributional metrics (DM) are most of the time computed taking into account the rank of the returns (Næsset, 2004). While first returns provide insights on the outer canopy structure, last returns distribution describes the maximum penetration of the signal within the vegetation layer. From these two height distributions, large sets of metrics have been considered, including height percentiles, density metrics, and distribution moments such as mean, skewness or coefficient of variation, among others (Zhao, Popescu, Meng, Pang, & Agca, 2011; Magnussen, Næsset, & Gobakken, 2013). DM have been successfully used as predictors of key forest inventory variables like stand density, basal area, volume or biomass (Means et al., 2000; Lim & Treitz, 2004; van Aardt, Wynne, & Oderwald, 2006). And area-based approaches using such DM were further integrated within National Forest Inventories of northern countries (Næsset, 2004).

The use of DM has been found to be a robust approach enabling to predict forest inventory variables for a wide range of both Lidar data acquisition and forest conditions (Jakubowski, Guo, & Kelly, 2013; Disney et al., 2010; Bater et al., 2011; Magnussen, Næsset, & Gobakken, 2010; Hopkinson, 2007). However, DM-based approaches have limits. First, a central issue remains the overall site-dependencies of models built on

---

* Corresponding author.
E-mail address: cedric.vega@ign.fr (C. Véga).

http://dx.doi.org/10.1016/j.rse.2015.12.039

these metrics, thus requiring local calibration to select the most explanative variables for a given site and a given ALS data set (Ni-Meister et al., 2010; Vincent et al., 2012). Magnussen et al. (2013) also pointed out the dependency of percentile and density metrics to both plot size and ALS point density and proposed to use only metrics independent of these parameters such as height distribution cumulants. As highlighted by Zolkos, Goetz, and Dubayah (2013), ALS-based model performance is influenced predominantly by forest type, impact of topography on stand structure, as well as plot size. Second, while height distribution provides information on the complexity of the canopy vertical structure, it fails in describing its horizontal arrangement. Such a limit may explain the low level of the generalization of models based on classical DM to predict forest parameters (Bouvier, Durrieu, Fournier, & Renaud, 2015). Bouvier et al. (2015) thus suggested going beyond the usual vertical distributions in order to better handle plot horizontal heterogeneity together with vertical structural heterogeneity. Several metrics described in the literature have the potential to provide information on horizontal heterogeneity. Among them, the rumple index, defined as the ratio of the outer canopy surface area to the ground surface area (Parker et al., 2004; Kane et al., 2010) has been proposed to capture the heterogeneity of the outer canopy surface with respect to the plot area, and turned out to be sensitive to the 3D structure of the canopy trees (Kane et al., 2010). Other authors suggested considering the crown volume, which entails identifying live crown bases and gaps within the canopy. To that aim, and using vertical canopy profiles derived from large footprint full-waveform data, Lefsky et al. (1999) introduced the concept of canopy volume profile (CVP). The CVPs were used to capture the spatial organization of the vegetation material in voxels and to characterize the vertical distribution of various canopy structures. Similar methods were also used for ALS data at plot or tree levels using return frequency in height intervals along the canopy column (Asner et al., 2011; Coops et al., 2007; Popescu & Zhao, 2008; Riaño, Meier, Allgöwer, Chuvieco, & Ustin, 2003; Vepakomma, St-Onge, & Kneeshaw, 2011; Hollaus, Wagner, Schadauer, Maier, & Gabler, 2009). However, when volumetric or voxel-based approaches are applied to ALS data the choice of spatial resolution (Magnussen et al., 2013; Vepakomma et al., 2011), and the choice of approaches used for surface interpolation and filtering (Liu & Dong, 2014; Vepakomma et al., 2011; Véga & Durrieu, 2011; Ben-Arie, Hay, Powers, Castilla, & St-Onge, 2009) may become an issue.

Metrics describing the vertical heterogeneity of vegetation, e.g. DM of point heights and densities, and those describing its horizontal counterpart, like the rumple index (Kane et al., 2010), the volume under the canopy (Hollaus et al., 2009), or the variance of outer canopy height model (Magnussen, Næsset, Gobakken, & Frazer, 2012), are complementary and should be used jointly to provide a more thorough description of vegetation 3D structure and to increase model accuracy. However, just combining the two kinds of metrics may still be limited. All the aforementioned metrics are in fact derived after converting point elevations into heights above the ground. In our opinion, processing point cloud by subtracting the ground elevation from the elevation of aboveground points, may introduce errors in point cloud geometry over slope areas. The inner geometry of points belonging to a same tree will be distorted if the ground topography varies under the area covered by the tree crown (Véga et al., 2014; Saremi, Kumar, Turner, & Stone, 2014).

To correct this, we introduced here a new family of ALS metrics, based on an alternative way to normalize point clouds. Instead of normalizing the vertical point coordinates with respect to the ground elevation (i.e. $h = z - Ground$), we proposed to compute more directly the level of signal penetration within the canopy (i.e. $p = Canopy\ elevation - z$). We venture the hypothesis that the resulting point cloud and the metrics that can be derived from it, e.g. DM computed from the vertical distribution of penetration depths (Fig. 1), would be a good complement to usual height-based metrics and would contribute to improve the robustness of plot-level ALS-based models. Working on these new point clouds has two advantages. First, it can be computed directly from Z values thus minimizing impacts of DTM on the point distribution within the vegetation (Khosravipour, Skidmore, Wang, Isenburg, & Khoshelham, 2015; Véga et al., 2014). Second, while height distributions mix information from both the outer and inner canopy structure, penetration metrics remove the variability associated with the outer canopy surface, thus providing insights on the inner canopy structure. In addition to penetration depth metrics, we also proposed a computation of the rumple index and introduced new forms of canopy volumes applied not only to height (h) but also to elevation data (z), that benefits from information from both first and last returns. Here again, we ventured the hypothesis that z information may help minimize the effect of terrain on point cloud distribution, thus offering an improved description of canopy structure in slope areas.

The objective of the paper was therefore to demonstrate how traditional ALS metrics derived from the usual h-distributions (DM, cumulants, rumple index and surface volumes) could be efficiently complemented by the use of new ones (derived from z and p-distributions) to build improved ALS-based models of basal area (BA), and aboveground volume (AGV), in a range of forest types and ALS acquisitions.

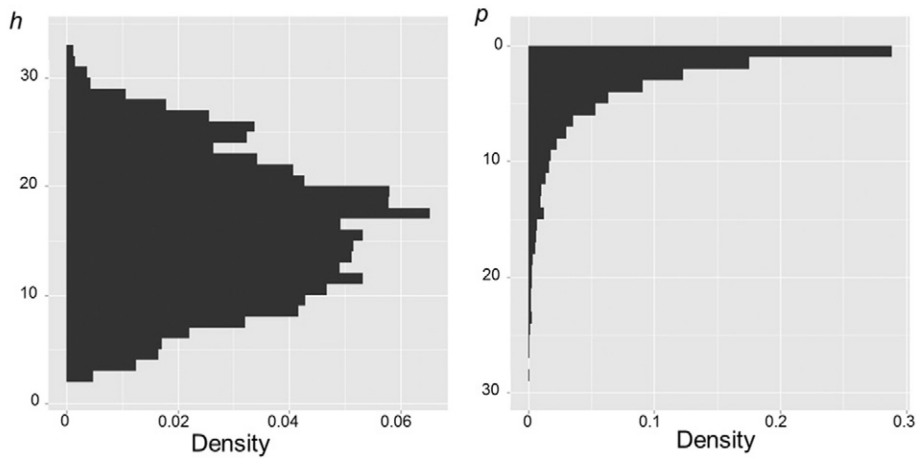

Fig. 1. Example of h (>2 m) (left) and p (>0) (right) distributions over a mixed mountainous plot.