Remote Sensing of Environment 124 (2012) 534–541

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Improving species-specific plot volume estimates based on airborne laser scanning and image data using alpha shape metrics and balanced field data

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ARTICLE INFO

Article history:
Received 13 February 2012
Received in revised form 2 June 2012
Accepted 3 June 2012
Available online 6 July 2012

Keywords:
LiDAR
Forest inventory
Nearest neighbor
Computational geometry

ABSTRACT

Airborne laser scanning (ALS) data with sparse point densities are increasingly used for forest growing stock estimations. The area-level point distributions derived by ALS are not considered informative on tree species, however, and the required information is typically produced using an additional data source, such as spectral images. We developed new volumetric and structural features (so called alpha shape metrics), hypothesizing that these could produce additional information on the species-size variation as compared to the previously used ALS and image features. These metrics were tested in the prediction of species-specific, plot-level volume using the Most Similar Neighbor imputation method and a data set consisting of altogether 426 training and 142 validation field plots. The considered forest area was dominated by Scots pine, while Norway spruce and deciduous trees formed the other two species groups to be distinguished. The developed metrics improved the species-specific estimates by 13–30 or 2–4 percentage points compared to features based on ALS data alone or a combination of the ALS and image features, respectively. The metrics had a higher importance when the reference data insufficiently covered the species-size variation within the area. Although the estimates produced using a combination of the ALS and image data had a superior accuracy compared to those produced by the ALS data alone, the results indicate that species-specific estimates may be further improved by developing computational features based on ALS data.

1. Introduction

Especially in the Nordic countries, forest inventory methods based on the use of airborne laser scanning (ALS) are currently replacing the conventional field inventories because of their better accuracy and cost efficiency (Maltamo et al., 2011b). ALS-based forest inventories have been performed in Norway since 2002 (Næsset et al., 2004) and in Finland, flight campaigns to collect ALS data for forestry purposes were expected to cover 3 million hectares in 2011 (Maltamo et al., 2011b).

Operational ALS inventories are most often carried out using an area-based approach, in which the prediction is made for a group of trees (i.e. plots, segments or grid cells), employing the relationships between local field reference data and predictor features derived from the airborne data (e.g. Næsset, 2002; van Aardt et al., 2006; Packalén & Maltamo, 2006, 2007). An alternative approach is to use individual trees as the basic unit of the assessment (e.g. Hyyppä et al., 2001; Popescu et al., 2003), which is typically not preferred by the forest community due to higher data acquisition costs and the uncertainty related to tree detection and estimation (Maltamo et al., 2011b).

One of the biggest challenges in the ALS-based inventories has been the distinguishing between tree species, which is required by forest management systems that use species-specific growth and yield models, or involve different treatment schedules depending on species. Because Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] H. Karst.) constitute more than 80% of the growing stock of Finland (Korhonen et al., 2006), for example, the minimum requirement for a remote sensing based inventory system (Packalén, 2009) is to separate these species and a broad group of deciduous trees consisting mainly of birches (*Betula* spp. L.) with minor proportion of aspen (*Populus tremula* L.), alders (*Alnus* spp. P. Mill.), willows (*Salix* spp. L.), and rowan (*Sorbus aucuparia* L.).

Although the ALS-based height and density features (Næsset, 2002) used in the growing stock estimation may produce information also on species (Hudak et al., 2008), the ALS data are usually not considered an adequate information source with this respect (e.g. Törmä, 2000). Instead, the species recognition task is solved most often using additional spectral image data, such as aerial (Packalén & Maltamo, 2006, 2007) or satellite images (Wallerman & Holmgren, 2007). Still, the accuracies of the species-specific estimates cannot be compared to those of total stand attributes. Although the images are usually available in the Nordic countries for the purpose of visual forest stand delineation (e.g. Eid et al., 2004; Koivuniemi & Korhonen, 2006; Ståhl et al., 2011), using them as additional data complicates

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doi:10.1016/j.rse.2012.06.002

the inventory system and includes difficulties from the operational point of view (Packalén, 2009).

Contrary to the area-based estimation, the height and intensity distributions may be highly informative on the species when considered at the individual tree level (e.g. Ørka et al., 2009). Using classification features derived from ALS data alone, the recent Scandinavian studies have reported an up to 95% accuracy of separating individually delineated pine and spruce trees (Holmgren & Persson, 2004) and 88–90% accuracies when considering the three species groups together (Holmgren et al., 2008; Korpela et al., 2010). The sparse density data (hereafter "sparse" refers to <1 measurements × m^{-2}; cf. Maltamo et al., 2011b) used for the area-based estimation do not allow tree delineation (Kaartinen & Hyyppä, 2008), but the results obtained in the tree-level studies encourage developing plot-level features that would, at least implicitly, allow the distribution of the point data into individual objects (trees / tree groups) within the plot.

One potential technique for tackling this problem is presented by Vauhkonen et al. (2008, 2009), who used computational volumetric and structural features to quantify the allocation of foliage in the tree crowns, thus differentiating between the species and improving the stem diameter estimates. The technique is based on a 3D triangulation of the point cloud, in which a predefined parameter alpha (Edelsbrunner & Mücke, 1994) is used as a size-criterion to determine the level of detail in the obtained triangulation (see Fig. 1). In the approach, the simplexes of the underlying triangulation are compared with the specified alpha value, and those which have an empty circumscribing sphere with a squared radius larger than the defined alpha value are removed (see Edelsbrunner & Mücke, 1994 for details).

The result obtained by the previously described "alpha shape approach" is highly dependent on the alpha parameter, which should be set to correspond the applied point density, for example. However, especially in the case of the area-based estimation, this parameterization can be done feasibly because a local field sample is typically collected to fit the applied estimation method to each remotely sensed data set (Maltamo et al., 2011b). So far, the alpha shape approach has been tested only in tree-level applications in which the trees have been separately detected and delineated in the data (Vauhkonen et al., 2008, 2009, 2010a, 2010b). Provided the alpha parameter can be set correct with respect to the plot-level spacing of the trees (Fig. 1), we assume that volumetric and structural features related to individual trees can be extracted also from sparse density, plot-level data. We hypothesize that these features provide more information and improve the prediction of species and size related forest attributes as compared to height distribution metrics (Næsset, 2002) typically used in the plot-level estimation.

The purpose of this study was to test the performance of the alpha shape metrics calculated from sparse density ALS data in a plot-level prediction of species-specific volume. We tested the potential of these metrics to improve the results compared to either ALS features alone or features derived from a combination of the ALS and image data.

2. Material and methods

2.1. Study area and field data

The study area was located in Kuortane in western Finland (62°47 N, 23°31′E) and covered about 22,000 ha. It is a typical managed boreal forest area dominated by coniferous tree species, of which Scots pine is the main species with 81% coverage. Norway spruce and deciduous trees, mainly birches, usually occur as an admixture. The area is characterized by fairly simple morphology and only slight variations in elevation as compared to more southern Europe.

The field data for this study were collected in two separate campaigns. The first data set was collected in 2006, when a network of field plots with a radius of 9 m was placed in the area following an intensified systematic cluster sampling design of the Finnish National Forest Inventory (NFI). This data set was used and described in detail by Maltamo et al. (2009b). According to them, the systematic sampling design was not optimal for collecting a representative reference data with respect to species and size distribution of the area. To balance the previous data set, a set of new plots was subjectively placed on the area and measured in 2009. The locations of the new sample plots were based on visual interpretation of the species-specific volume map produced by Maltamo et al. (2009b). The aim was to obtain more plots dominated by spruce and deciduous species. Thus the placement of the new plots did not follow the earlier NFI design, but the plots were arranged in clusters of irregular shapes using a 50 m minimum distance between the plot centre points.

In both field campaigns, all sample plots were positioned with a differential GPS. The measurements included diameter at breast height ($d_{1.3}$), tree and storey class and tree species (Scots pine, Norway spruce or deciduous) for each tree with $d_{1.3}$ > 5 cm. In each plot, one tree representing the median diameter in each storey class and species was selected as a sample tree. The sample trees were measured for height (h) using a Vertex hypsometer, and in 2009, all

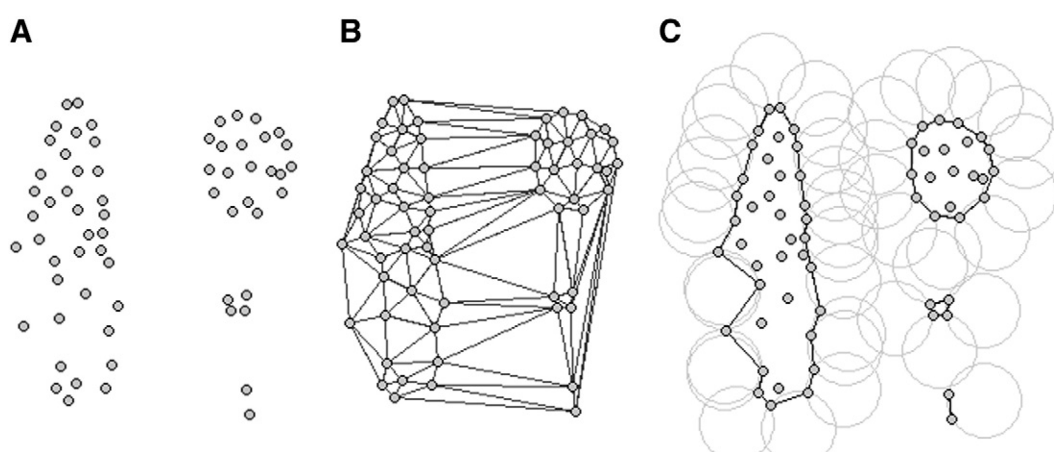

Fig. 1. A schematic diagram describing the computation of the alpha shape metrics: a point cloud with an even vertical profile (A); a triangulation based on it (B); and an alpha shape with four separate components extracted using the applied alpha value, which is illustrated using grey circles (C). Note that this example is drawn in 2D for ease of visualization, and the interpretation may therefore differ from the actual analysis carried out in 3D.