Forest mensuration parameters derived from individual tree crown forest inventory method using airborne imagery and LiDAR

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Abstract

Precise forest inventory and mapping are needed for supervising the different functions of the forest (management, planning, biodiversity and carbon stock). The recent improvements in remote sensing tools in terms of precision allow the achievement of forest inventory at single tree level close to total field inventory. Based on an individual tree crown (ITC) forest inventory method using airborne images, the approach has been extended for deriving tree mensuration parameters (height and stem volume) thanks to LiDAR data. This methodology has been tested in south-eastern Belgium over 1500 hectares of forest combining airborne image, LiDAR and field measurements. Forest map and inventory have been produced with information on species, density, height, basal area and stem volume. Based on a stratified random sample, the overall accuracy of the tree crown discrimination of eight tree species have been assessed to 85 %. Forest mensuration parameters have been compared to field measurements over coniferous and deciduous stands with high precision in coniferous. Height estimations from LiDAR have been compared with ground-based laser-scanning over two stands, proving the robustness of LiDAR data over field measurements. These results will still be improved by the development of tree mensuration models dedicated to remote sensing approach and better exploitation of LiDAR in tree crown delineation processes.

Keywords: Forest mapping, Remote sensing, Image classification, Terrestrial laser-scanning, Forest management, Digital orthophotos, Stem volume, Basal area

1. Introduction

Forestry requires more and more precise inventory associated with forest map in order to guide forest management (wood selling, expertises, appraisal and monitoring), for forest planning (assessment of stem volume and its distribution) and specific applications including environmental monitoring (natural habitat description for specific management), wood energy and carbon stock. Classical forest inventory methods based only on field measurements are either (1) statistical inventory based on sample plots or (2) total field inventory. The first approach is generally adopted for large regions. However, spatial distribution of volume and tree species is lacking and the precision of estimated forest parameters is generally not sufficient for precision forestry. The second forest inventory method produces detailed information on forest stocks but is time-consuming and thus limited to very limited areas.

Thanks to recent improvements in remote sensing technologies, tree crowns can now be distinguished thanks to the very high spatial resolution of airborne or satellite images. The semi-automatic Individual Tree Crown (ITC) forest inventory developed by Gougeon (1995) has already proved its efficiency for forest inventory in North America. But, until now, this approach has not been assessed over European forests for operational forest management.

The real interest of single tree forest inventory is the estimation of forest mensuration parameters including height, basal area and stem volume. The measurement of these parameters on the field is quite hard and expensive over large areas. Light Detection And Ranging (LiDAR) instruments provides Digital Surface Model (DSM) and Digital Terrain Model (DTM) with high precision (below 15 cm). This is an interesting alternative for deriving tree measurements, often difficult to measure on the field. Several researches have been done for assessing LiDAR data (e.g. Maltamo *et al.* 2004; St Onge *et al*. 2004). Leckie *et al.* (2003a) have combined high-density LiDAR (2 points by m^2) and multispectral imagery using individual tree crown analysis over small Douglas-fir plots. They found that heights derived from LiDAR were underestimated versus ground reference with an average error of 1.3 m. The estimation of other forest mensuration parameters such stem volume and basal area is quite more complex and can be done by at different level, (1) stand level or (2) tree level. A new approach for estimating basal area and stem volume based on canopy geometric model is proposed by Chen *et al.* (2007). However, this efficient approach has been evaluated with only one tree species at plot level. Dedicated relations between tree crown and stem volum to such applications have been investigated but they are generally region-specific (Kalliovirta and Tokola 2005). At single-tree level, regional allometric equations (Dagnelie *et al.* 1999) have been produced but they have not been assessed yet with remote sensing data.

The objective of this study is to develop an operational method for estimating forest mensuration parameters based on an individual tree crown forest inventory method using remote sensing. This approach should combine mapping and inventory at single tree level over large areas using remote sensing technologies including airborne images, multi spectral analysis and LiDAR surveys, coupled with optimized field data collection by local teams. The performance of this methodology will be assessed over Belgian forests using data from airborne data acquisition and field survey.

2. Materials and method

2.1. Study area

The study area is located in south-eastern Belgium (50° 12'N; 5° 41' E). Forest covers about 1500 ha which accounts for 85% of the region area. The altitude of the study area ranges from 400 to 600 meters. The study region includes around 650 forest stands with average stand area of 2 hectares. The forest consists of mixed deciduous trees (*Fagus sylvatica and Quercus spp.* as dominant tree species) and coniferous trees (*Picea abies* and *Pseudotsuga menziesii* as dominant tree species). This region has been selected given its accessibility and stand diversity (coniferous and deciduous, small and large stands).

2.2 Data acquisition

2.2.1 Airborne survey and pre-processing

One airborne survey was performed for both image and LiDAR acquisition with Falcon II system. This combined acquisition limits aerial flight costs and increase the data consistency having the same flight configuration. However, an offset should be found for defining appropriate acquisition period, between leaves on (for reliable trees species discrimination) and leaves off (for producing reliable DTM). The most appropriate period was selected at the start of vegetation period for having leaves of deciduous trees but not to dense for acquiring sufficient

LiDAR points from the ground. Over the study region, the flight survey was performed in May 2006 with average flight altitude around 1200 meters.

The airborne image, acquired from line-scanner camera, includes four spectral bands (Blue, Green, Red and Near-InfraRed (NIR)) with 50 cm spatial resolution. High quality airborne image is crucial for tree crown forest inventory as this image is the key element for tree crown delineation and tree species classification. The airborne survey should be done in clear sky weather conditions and limited time period. These two conditions are crucial in order to obtain aerial image with homogenous radiometry. After data collection, two pre-processings steps are required to produce digital orthophotos. First, the orthorectification is based on the DSM produced by the LiDAR and some reference points from the field. The precision of planimetric accuracy relies on these points. Over the study area, the absolute accuracy of the digital orthophotos was below 0.5 m. Secondly, relative radiometric corrections have been performed between flight bands in order to obtain homogenous radiometry over the whole region of interest.

LiDAR data were acquired with average point density of 4 points by m² and height accuracy below 15 cm. The sensor is a discrete return LiDAR system with laser pulse rate of 83 000 Hz. Based on point clouds, both DSM and DTM have been produced at 1 m spatial resolution. The grid used for processing stages has a higher resolution than the final grid. The elevation assigned to the final grid shall be the most relevant, namely the highest value for DSM and the lowest value for DTM (Löffler 2003). Due to acquisition in "leaves on" conditions, the raw DTM has been interpolated using bilinear interpolation over zones without ground altitude information. The Canopy Height Model (CHM) has been derived from the subtraction between DSM and interpolated DTM.

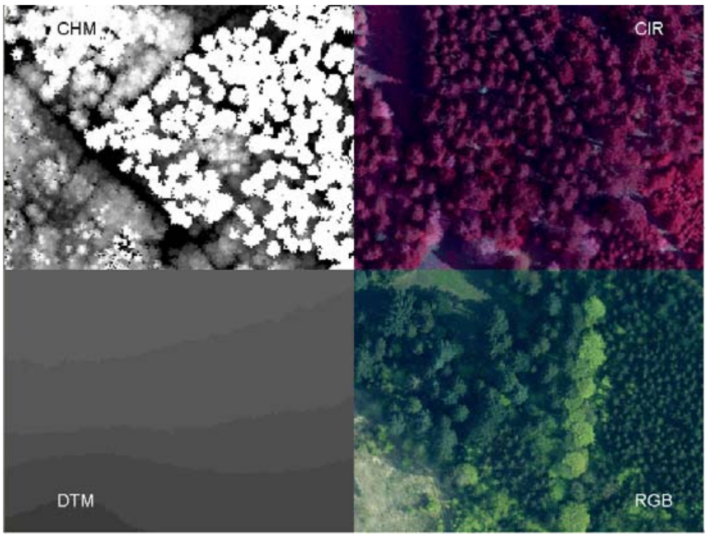

Figure 1: Extract of the airborne data acquisition including LiDAR and imagery

2.2.2 Field survey

Field measurements are required for calibrating the forest inventory method to the region of interest. However, the number of sample plots is considerably reduced compared to a classical systematic sampling thanks to preliminary photo-interpretation of the aerial image. Plots are visually selected in order to cover all species and age classes of interest and to be dispersed over the study area. The main purpose of this field survey is to define training sites for the image classification. These plots also provide information for forest mensuration estimation using LiDAR. Sample plots are circular with average diameter of 40 m (0.12 ha) where its center is localised using GPS. Over the study area, the field campaign has been done in October 2007 over 42 plots.

2.3 Image processing

The methodology of image processing for identifying tree crowns and their species has been adapted from Gougeon (1995, 2000). This method called Individual Tree crown (ITC) analysis is based on the delineation of each tree crown prior to tree-species classification. This semi-automatic approach is divided in three separate steps: tree crown delineation, classification and estimation of some forest inventory parameters.

The tree crown isolation is based on a valley approach which separates shaded areas from sunlit areas and then isolates tree crowns based on intensity gradient (Leckie *et al.* 2003b). This algorithm starts with low value areas and follows any valleys in image brightness. Large shaded areas without trees are also removed based on specific masks in order to avoid false tree tops. Valleys are also created between tree crowns, thus producing segments of valley and crown material. Finally, the boundaries of each segment of crown material are refined to produce segments or isolations (isols), which generally represent tree crowns and sometimes clusters of crowns.

Supervised classification is performed for identifying tree crown species and producing the ITC forest map based on tree crown delineation. Spectral signatures are defined using information from field survey. The multispectral information of each isol is summarized and compare with spectral signatures. The algorithm is based on maximum likelihood classifier using minimum and maximum thresholds. The purity of these spectral signatures is crucial because it affects the accuracy of the classification. In order to reduce inter-classes confusion, the study region can be segmented in sub-regions based on stand composition, topography or radiometry differences. Spectral signatures for five coniferous classes (Spruce, Douglas-fir, Larch, Fir and Pine) and four deciduous classes (Beech, Oak, Birch and other deciduous trees) were computed in study area for producing the ITC forest map.

Several stand-based forest inventory parameters can be derived directly from this ITC forest map without LiDAR information. The forest stand can be delineated from the aerial image or provide by other GIS data. The estimated parameters include density (number of trees by hectares), canopy closure (in percent), species distribution (in cover percentage), and average tree crown diameter (in meters). This information is provided both globally at stand level or by tree species included in the stand.

2.4 Forest mensuration estimation

LiDAR gives information about forest canopy structure which are used for estimating forest mensuration parameters including dominant height, basal area and stem volume. These parameters are derived thanks to relations between remote sensing data and field measurements. Two types of approach have been assessed using the CHM produced from LiDAR data. Relations can be computed at (1) stand level or (2) tree level defined by the ITC tree crown delineation.

2.4.1 Stand level approach

The stand level approach consists in global estimation of forest mensuration parameters for each forest stand. Dominant height is estimated on the field by the height of the 100 higher trees by hectares. In order to derive height of the dominant tree over each 100 m², a new CHM, called *maxCHM*, is computed on 10 meters raster cells and deriving the maximum height value. Based on stand delineation, dominant height is derived from the mean value of all *maxCHM* cells included in the stand polygon.

Basal area and stem volume are estimated using a new metric called canopy geometric volume defined by Chen *et al.* (2007). This metric is computed by the geometric volume for a polygon under the CHM. The regression model is calibrated with field inventory based on local tree mensuration method compared on canopy geometric volume based on LiDAR over sample stands. Over the study area, two different regressions (one for coniferous and one for deciduous) have been derived.

2.4.2 Tree level approach

Starting from the tree crown delineation produced by the ITC classification, tree mensuration parameters can be estimated at single tree level using LiDAR information. The estimation of tree height can be done by intersecting tree crown delineations over the CHM and deriving the highest height value under tree crown shape. Allometric equations are required to derive basal area and stem volume from the tree crown diameter. Several relations are provided by Dagnelie *et al.* (2007) for estimating DBH from tree crown diameter and stem volume from DBH and height. It is important to note that these allometric equations have been derived from on-the-field measurements which were not dedicated to remote sensing applications. The species information required for these species-specific relations is provided by the ITC classification. Thanks to these relations, basal area and stem volume are computed for each tree and summarized by stand.

2.5 Field validation

In order to assess the performance of this methodology, a field survey has been performed in November 2007 over several sample plots and some entire stands. The ITC classification has been first assessed by visual interpretation using random stratified sampling of 265 sites. A subset of 37 validation sites, different from training sites, focused on sites hard to qualify by photo-interpretation, has been described on the field. For assessing the accuracy of tree mensuration parameters, total inventories have been performed on entire stands, both coniferous and deciduous. Total inventories were preferred to plot inventory in order to avoid errors due to extrapolation of plot information.

The assessment of tree height estimations is complex and three methods of height estimation have been compared. First, height can be estimated thanks to LiDAR data extracted at tree top. Second, a classical and rapid method for height measurement on the field is performed with a laser instrument called vertex. Finally, height can be measured thanks to terrestrial laser scanner survey providing 3d information from the ground.
This last technique of height estimation can be considered as the reference as it provides very high precision measures. The equipment included Leica HDS 300 laser-scanner, theodolite and RTK-GPS. The measurements have been performed over two different stands, coniferous and deciduous. The laser-scanner point density is about 400 points by m² at a distance of 30 meters from the laser source. The theodolite measurements provide information of the tree location at breast height. The laser-scanner information has been analysed for deriving tree heights which have also been estimated by vertex instrument on the field.

4. Results

4.1 Individual tree crown forest inventory

A detailed forest inventory has been produced over an operational study case in eastern Belgium (Figure 2). This individual tree crown inventory is georeferenced, identifies tree location and species and provides tree mensuration estimations. Information is summarized at stand level for forest management and stored in database linked to cartographic data. Among numerous forest parameters provided by the inventory, tree species distribution, stem density, dominant height, stem volume and basal area are the main parameters. The estimation accuracy of these parameters has been assessed based on field validation survey.

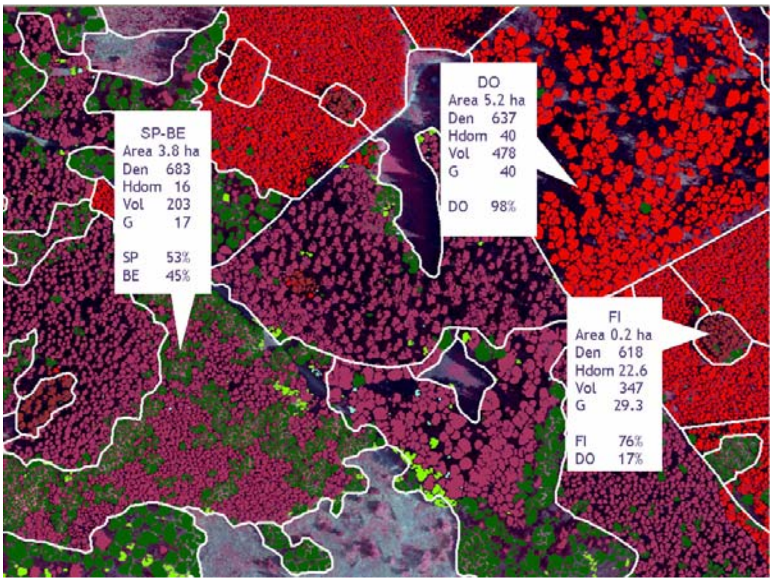

Figure 2: Forest map extract showing tree crown with color linked to species and stand-based forest mensuration parameters (Area in hectares (ha); Density (Den) in trees by ha; Dominant height (Hdom) in m; Volume (Vol) in m³ by ha and basal area (G) in m² by ha)

4.2 Tree species classification

The performance of the ITC classification has been assessed by comparing its tree crown species with trees analysed on sample field plots. Eight tree species, 5 in coniferous and 3 in deciduous, have been distinguished. High classification overall accuracy (85 %) has been obtained by the ITC classification assessed on more than 2000 tree crowns (Table 1). The accuracy is better for coniferous which have lower omission and commission errors than deciduous trees.

Table 1: Confusion matrix from the accuracy assessment of the ITC classification using field reference on sample plots (based on tree crown number; C.E. = Commission errors)

	Field reference										
ITC Classification	SP	DO	LA	FI	PI	BE	OA	BI	OD	Total	C.E. (%)
Spruce - SP	729	51		8		11	1			800	8.9
Douglas-Fir -DO		448		14		1				463	3.2
Larch - LA			86							86	0.0
Fir - FI				167						167	0.0
Pine - PI	8				136		11			155	18.6
Beech - BE	139	2	7	8		21	2	4	7	190	88.9
Oak - OA	5	3	1			2	25	12	14	62	59.7
Birch - BI								230		230	0.0
Other Decid. - OD		12								12	100.0
Total	881	516	94	197	136	35	39	246	21	2165	
Omission Errors (%)	17.3	13.2	8.5	15.2	0.0	40.0	35.9	6.5	100.0		85.1

4.3 Tree mensuration estimation

Estimations of forest parameters using stand level and tree level approaches based on remote sensing data have been compared to total field inventory over two representative stands, one coniferous and one deciduous (Table 2). The assessed parameters included stem density, dominant height, stem volume and basal area. The deciduous stand has been evaluated using only the stand level approach given the lack of tree mensuration models for some species which are required for the tree level approach.

For both stands, tree density measured on the field was very close to measurements by the ITC approach. Dominant height was also correctly estimated by the ITC approach and was even better using tree level approach than the stand level. The analysis of the other tree mensuration parameters, namely basal area and stem volume, revealed large differences between each forest inventory techniques. Stem volume of coniferous stand estimated from ITC-Stand was very close from field estimations. These differences are larger for the deciduous stand than for the coniferous one.

Table 2: Comparison of forest mensuration parameters estimated by the stand-level (ITC-Stand) and tree level (ITC-Tree) approach with total field inventory data from two validation stands.

Stand	Coniferous (8.6 ha)			Deciduous (2.5 ha)	
Inventory method	ITC-Stand	ITC-Tree	Field	ITC-Stand	Field
Density (nb trees/ha)	519	519	512	120	119
Dominant height (m)	25.1	25.6	25.8	28.5	28.2
Basal area (m^2/ha)	28.5	24.4	31.4	34.1	22.3
Stem volume (m^3/ha)	343	244	340	171	136

The tree level approach has been evaluated by comparing ITC-Tree estimations with field measurements. Large differences were found for basal area and stem volume estimations. The Diameter Breast Height (DBH) classes distributions have been analysed for both ITC-Tree and field inventories (Figure 3). The shift of DBH classes distribution of ITC-Tree to lower values can be explained by underestimation of the crown diameter having a direct impact on the estimations of basal area and stem volume.

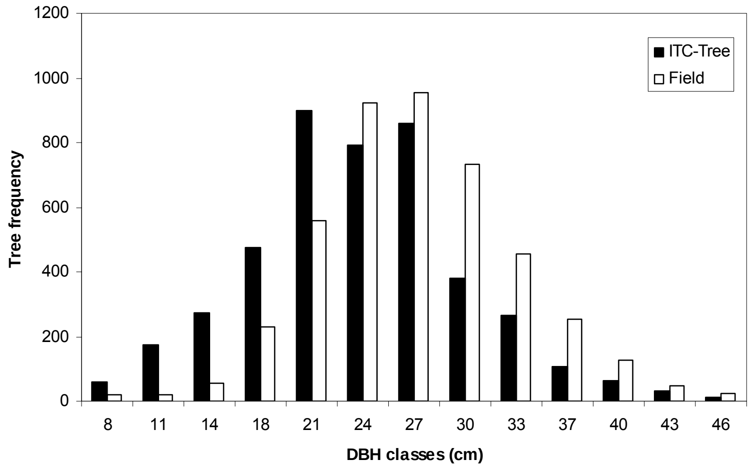

Figure 3: Comparison of stand distributions of Diameter Breast Height (DBH) derived from the ITC-Tree inventory and the field inventory over the coniferous validation stand.

4.4 Tree height comparison with terrestrial laser-scanner

The comparison of tree height estimations from LiDAR and field measurement based on vertex instrument have been compared with information extracted from high precision terrestrial laser scanner survey (Table 3). This comparison shows discrepancies in height estimations. These differences and RMSE are lower using LiDAR (mean height difference below the meter) than using vertex on the field. This proved the interest of using LiDAR for more robust height estimation required for reliable forest mensuration. Finally, these differences are smaller for coniferous than for deciduous.

Table 3: Comparison of tree height estimations based on (1) airborne laser scanner (LiDAR), (2) Vertex with terrestrial laser scanner measurements (RMSE: Root Mean Square Errors).

	Coniferous (0.14 ha, n=14)		Deciduous (0.44 ha, n=44)	
	Mean height difference (m)	RMSE	Mean height difference (m)	RMSE
1) Airborne - Terrestrial laser scanner	0.31	1.45	-0.71	3.95
2) Vertex - Terrestrial laser scanner	-1.18	2.09	-1.61	5.24

5. Discussion and conclusion

The originality of the present study is the integration of several new technologies in an operational tool for producing georeferenced forest inventory. The developed methodology includes individual tree crown forest inventory, optimized field survey with GPS and LiDAR. This first assessment of ITC technique over European forests is promising given its high classification overall accuracy (85%) for eight tree species. This study also has evaluated the potential of LiDAR data for deriving forest mensuration parameters based on relations between remote sensing and field information. Several parameters including stem density, dominant height, stem volume and basal area have been estimated with good accuracy at stand level by comparison with ground truth measurements.

This forest inventory methodology could still be improved at tree level for reaching higher precision thanks to new technologies or dedicated relations. Classification could use new hyperspectral sensors in order to cover larger range of tree species. The integration of LiDAR data together with the aerial image in tree crown isolation could also improve tree crown delineation and thus related forest mensuration estimation. Finally, specific field measurements are needed for developing tree mensuration models dedicated to remote sensing technologies. The proposed methodology is not focused only on forest management but also provides valuable information for several applications as the assessment of biodiversity reduction or the integration of the global warming impacts in adaptable forest management system.

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