Supplementary Materials: A Density-Based Algorithm for the Detection of Individual Trees from LiDAR Data

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1. Literature Review for the Classification of Individual Tree Detection Approaches

Table S1 shows an extensive, albeit not exhaustive, list of the main methods that have been proposed so far for the identification of individual trees from LiDAR data. This review begins from the 2000s, when active remote sensing devices began to be widely used in forestry [1,2], and only considers the applications of the traditional airborne discrete-return LiDAR systems, neglecting the multi-spectral [e.g., 3] and the full-waveform ones [e.g., 4–6]. The algorithm classification (AC), which is reported in the first column of Table S1, refers to the classification described in Section 1 and displayed in Figure 1 of the companion manuscript.

We remark that the list does not include the recent branch of Terrestrial Laser Scanning (TLS) systems. While Airborne Laser Scanning (ALS) systems provide complementary information for forest inventory in terms of tree number, areal stem density and tree height over large areas (up to the regional scale), TLSs give high point density data and allow for three-dimensional tree reconstruction, but can investigate relatively small areas [see 7–10, for further details].

Table S1. Methods described in the literature (2001-2019) for the identification of individual trees starting from LiDAR data. Part of the information is taken from Lu *et al.* [11]. AC refers to the approach classification shown in Figure 1 of the companion manuscript; FT is the forest type (C coniferous, D deciduous, O other); LC is the leaf condition (ON - OFF); PD is the point density (points·m^{-2}); - means not-specified.

AC	Short description	Reference	FT	LC	PD
A.1.1	Local maxima method applied after a convolution filter.	Hyyppä *et al.* [12]	C	ON	8.0 - 10.0
A.1.1	Local maxima method whose spatial scale is selected by choosing the parabolic surface that leads to the smallest residuals when fitting the CHM.	Persson *et al.* [13]	C - D	-	-
A.1.1	Local maxima method applied to the CHM created by performing Gaussian smoothing at different scales.	Brandtberg *et al.* [14]	D	OFF	12.0
A.1.1	Local maxima method with variable window size determined as an allometric function of the height of the local maximum.	Popescu and Wynne [15]	C - D	ON	0.5
A.1.1	Local maxima method applied to smoothed CHMs to detect the treetops. Pouring algorithm for the crown segmentation.	Heurich and Weinacker [16]	C - D	-	10.0
A.1.1	Local and quasi-maxima selection and removal of the non-trees by means of an adaptive filter.	Pitkänen *et al.* [17]	C - D	-	10.0
A.1.1	Local maxima method applied after smoothing filters.	Weinacker *et al.* [18]	C - D	-	-
A.1.1	Comparison between the used of the local maxima method applied to the CHM and the canopy maxima model (CMM) to select the treetops. Marker-controlled watershed for the crown segmentation.	Chen *et al.* [19]	D	ON	9.5
A.1.1	Local maxima method applied to smoothed CHMs to detect the treetops. Watershed for the crown segmentation.	Koch *et al.* [20]	D	ON	5.0 - 10.0
A.1.1	Local maxima method applied after smoothing filters. Region-growing algorithm for the crown segmentation.	Solberg *et al.* [21]	C	ON	5.0
A.1.1	Local maxima method to detect the treetops. Region-growing algorithm to delineate the crowns.	Pang *et al.* [22]	C - D	-	1.6 to 7.0
A.1.1	Local maxima method applied to smoothed CHMs to detect the treetops. Watershed for the crown segmentation.	Maltamo *et al.* [23]	C	ON	4.0
A.1.1	Local maxima method applied after a curvature-based smoothing filter. Marker-controlled watershed for the crown segmentation.	Yu *et al.* [24]	C - D	ON	2.6
A.1.1	Local maxima method applied to smoothed CHMs to detect the treetops. Adaptive filtering algorithm for the crown segmentation.	Ene *et al.* [25]	C - D	ON	10.4

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Table S1. – *Continued from previous page*

AC	Short description	Reference	FT	LC	PD
A.1.1	Local maxima method applied to filtered CHMs to detect the treetops. Marker-controlled watershed algorithm for the crown segmentation.	Jing *et al.* [26]	C - D	ON	45.0
A.1.1	Local maxima method to detect the treetops. Region-growing algorithm for the crown segmentation.	Dalponte and Coomes [27]	C	ON	48.0
A.1.1	Local maxima method applied with different treetop window sizes and over unsmoothed and smoothed CHMs.	Silva *et al.* [28]	D	ON	-
A.1.2	Local curvature method to detect the treetops applied after that Gaussian filters generate a multi-scale representation of the CHM on the basis of the dominant size of the crowns.	Bian *et al.* [29]	D	-	8.9 - 13.9
A.2.1	Morphological operations to isolate the treetops by means of conical/elliptical structures that compose the three-dimensional CHM.	Andersen *et al.* [30]	C	-	3.5
A.2.1	Morphological filtering methods applied together with methods that fill the missing data and remove the outliers.	Chen [31]	-	-	-
A.2.1	Extended maxima transformation of the morphological image-analysis methods applied to the CHM.	Kwak *et al.* [32]	C - D	-	1.8
A.2.2	Watershed algorithm applied to the CHM for the crown segmentation. Local maxima method applied to each crown to detect the treetops.	Hirata *et al.* [33]	O	ON	40.5
A.2.2	Watershed algorithm applied to a smoothed CHM. Interpolation of the cloud points underlying the CHM to find the understory canopies and re-application of the watershed algorithm.	Duncanson *et al.* [34]	D	ON - OFF	18.0
A.2.2	Watershed algorithm applied to the CHM after smoothing and morphological operations.	Zhao *et al.* [35]	C - D	-	-
A.2.3	Valley-following approach applied to the CHM after smoothing filters.	Leckie *et al.* [36]	C	ON	2.0
A.2.3	Identification of individual trees through the convolution of a mexican hat wavelet over the CHM (i.e. spatial wavelet analysis).	Falkowski *et al.* [37]	C	ON	0.3
A.2.3	Iterative combination of watershed and morphological algorithms to delineate the crown material.	González-Ferreiro *et al.* [38]	D	ON	8.0
A.2.3	Detection of the contour of the individual trees by applying a graph theory-based algorithm.	Wu *et al.* [39]	C	ON	7.8 - 12.5
B.1	Local maxima method to detect the treetops that are subsequently used as seeds for the k-means clustering.	Morsdorf *et al.* [40]	C	-	30.0
B.1	Region-growing algorithm applied downward and starting from the treetops that have been previously detected by a local maxima algorithm.	Tiede *et al.* [1]	C - D	ON - OFF	10.0
B.1	Adaptive multi-scale filter and region-growing algorithm.	Lee *et al.* [41]	C	ON	14.2
B.1	Region-growing algorithm applied downward and starting from the treetops that have been previously detected by a local maxima algorithm.	Richardson and Moskal [42]	C	-	>4.0, >8.0
B.1	Region-growing algorithm with adaptive threshold that starts from the treetops that have been previously detected by a local maxima method.	Li *et al.* [43]	C	ON	>6.0
B.1	Morphological and watershed methods applied to the CHM for the crown segmentation. Refinement of segmentation and tree counting through a cloud-based approach.	Hu *et al.* [44]	C - D	ON	40.0
B.1	Multi-scale segmentation realized using point kernels of different size. Choice of the best set of apices from the segmented trees and final crown segmentation by using the selected apices as seed point and applying an adaptive neighbourhood algorithm.	Véga *et al.* [45]	C - D	-	10.0 - 17.8
B.1	Local maxima method to detect the treetops within each horizontal slice of the point cloud and k-means clustering for the crown identification and segmentation.	Kandare *et al.* [46]	C - D	-	60.0
B.1	Local maxima method to detect the treetops within each horizontal slice of the point cloud and k-means clustering for the crown identification and segmentation.	Ayrey *et al.* [47]	C - D	ON - OFF	5.0 to 21.0
B.1	Region-growing algorithm combined with morphological segmentation.	Ma *et al.* [48]	C	ON	4.0

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Table S1. – *Continued from previous page*

AC	Short description	Reference	FT	LC	PD
B.2	Detection of the points belonging to the trunks by looking at their intensity value. Identification of the individual trunks starting from the bottom and according to a clustering method.	Lu *et al.* [11]	C - D	ON - OFF	10.28
B.2	Treetops identification through a local curvature method applied to locally fitted surfaces and tops used as markers for watershed segmentation of the crowns. Detection of the treetops below the upper canopy layer by estimating the verticality of the points' distribution.	Mongus and Žalik [49]	C - D	-	25.6 to 96.6
B.3	Computation of the number of points in a column with windows of specific size for each point. Conversion of the points into a raster with cells of specific size and peaks detection after smoothing.	Rahman and Gorte [50], Rahman *et al.* [51]	C - D	OFF	70.0
B.3	Clustering approach based on the adaptive mean-shift algorithm running on previously defined layers.	Ferraz *et al.* [52]	C - O	ON	9.9
B.3	Treetops identification from the CHM and use of the tops as starting points for the angular analysis of the point space to detect sub-dominant trees.	Paris *et al.* [53]	C	ON	5.5 - 15.5

Abbreviations

The following abbreviations are used throughout the supplementary material:

AC	Approach Classification
ALS	Airborne Laser Scanning
C	Coniferous species
CHM	Canopy Height Model
CMM	Canopy Maxima Model
D	Deciduous species
FT	Forest Type
LC	Leaf Condition
LiDAR	Light Detection And Ranging
O	Other species
PD	Point Density
TLS	Terrestrial Laser Scanning

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