Data for investigating structural complexity of individual Scots pine trees

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Abstract
Tree functional traits together with processes such as forest regeneration, growth, and mortality affect forest and tree structure. Forest management inherently impacts these processes. Moreover, forest structure, biodiversity, resilience, and carbon uptake can be sustained and enhanced with forest management activities. To assess structural complexity of individual trees, comprehensive and quantitative measures are needed, and they are often lacking for current forest management practices. Fractal analysis and a single scale, independent metric called box dimension offer means for assessing structural complexity of individual trees. Terrestrial laser scanning (TLS) point clouds provide three-dimensional (3D) information on trees that can be utilized in generating the box dimension metric. This data set includes information needed for generating the box dimension from 741 individual Scots pine (*Pinus sylvestris* L.) trees from 9 sample plots with different thinning treatments located in southern boreal forests. The thinning treatments include two intensities of thinning and control treatment (i.e., no thinning treatment since the establishment). The data set can be used in characterizing structural complexity of individual Scots pine trees of various size as well as assessing effects of various thinning treatments on it.

Keywords: box dimension, growth and yield, forest management, silviculture, terrestrial laser scanning, ground-based LiDAR, forest ecology, tree structure

Background and summary

Trees are interacting with each other and that affects their functioning and structure. Tomlinson (1983) has pointed out that development of trees and their structure can therefore enhance our understanding about forest structure. Thus, investigations on individual trees are important. Trees occupy three-dimensional space and tree architecture can be characterized based on growth dynamics and branching patterns (Tomlinson 1983). Tree structure, on the other hand, can be characterized by using morphological measures such as crown dimension (e.g., volume, surface area) and stem attributes (e.g., diameter at breast height (DBH), height, height of crown base) (Pretzsch 2014).

Terrestrial laser scanning (TLS) provides 3D point clouds enable generation of stem and crown attributes (Seidel et al. 2011, Liang et al. 2012, Bayer et al. 2013, Calders et al. 2013, Metz et al. 2013, Juchheim et al. 2017, Saarinen et al. 2017, Calders et al. 2018, Georgi et al. 2018, Saarinen et al. 2020). Nevertheless, objective and quantitative measures for structural complexity of individual trees are needed to better understand relationship between forest structural diversity and ecosystem services such as biodiversity, productivity, and carbon uptake (Hardiman et al. 2011, Messier et al. 2013, Puettmann et al. 2015, Zenner 2015).

Seidel (2018) presented an approach where fractal analysis of Minkowski-Bouligand dimension (or box-counting dimension, i.e., changes in number of boxes required covering an object when the boxes are made more defining) was applied in characterizing structural complexity of individual trees. The box dimension is determined as a relationship between the number of primitives of varying size needed to enclose all 3D points of a tree and the inverse of the primitive size. The box dimension is scale-independent and can theoretically vary between one and three, one being a cylindrical, pole-like object and three corresponding solid objects such as cubes (Figure 1).

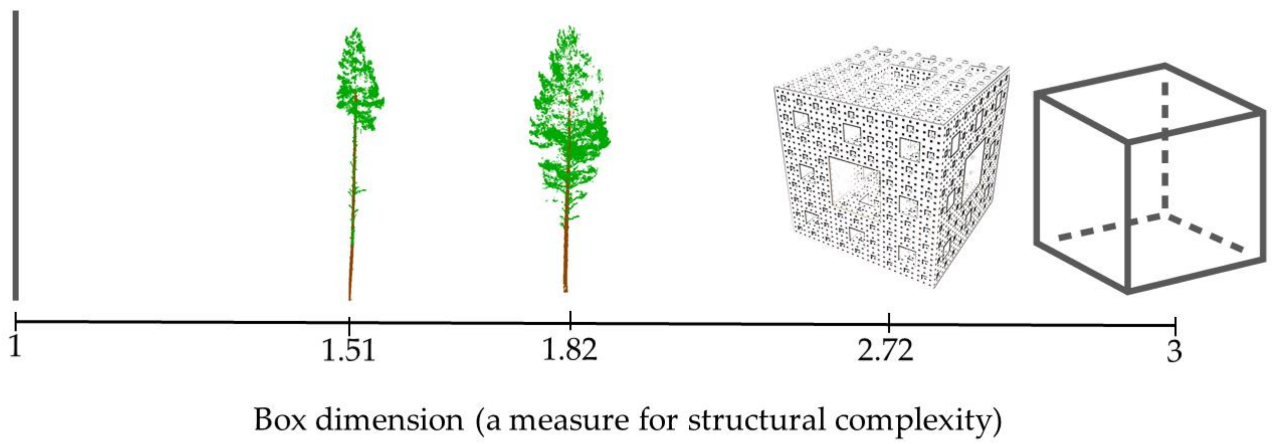

Figure 1. Examples of objects with box dimension ranging from one (cylindrical pole) to three (solid cube) in between two real-life trees and a Menger sponge (box dimension = 2.72). Modified after Figure 1 in Seidel et al. (2019).

Although forest management affects growing conditions of trees as well as their size and shape (Mäkinen & Isomäki 2004, Saarinen et al. 2020), it is unclear how forest management affects structural complexity of conifers. Here, TLS point clouds were utilized in voxelizing individual Scots pine trees with varying size of voxels for box dimension metric. This data set can be utilized in characterizing structural complexity of individual Scots pine trees of various size as well as assessing effects of various thinning treatments on it.

Materials and methods

Study site and data acquisition

The study area consists of three study sites dominated by Scots pine established and maintained by Natural Resources Institute Finland (Luke). All study sites are in southern boreal forest zone and characterized as mesic heath forest (i.e., Myrtillus forest site type according to Cajander (1913)). At the time of the establishment (1 in 2005, 2 and 3 in 2006), the stand age was 50, 45, and 59 years for 1, 2, and 3, respectively. The first thinning (removal ~30% of stems) had been carried out for all study sites in the early 1990s. Nine rectangular sample plots (size from 1000 and 1200 m^2) were placed at each study site resulting in a total of 27 sample plots.

The experimental design of the study sites includes two varying levels of thinning intensity (i.e. moderate and intensive) and one plot at each study site remained as a control plot where no thinning has been carried out since the establishment of the sites. One plot at each study site was left as a control plot where no thinning has been carried out since the establishment of the sites. Thinning intensity was defined as the remaining basal area whereas thinning type determined which trees (based on a crown class) were removed. The remaining relative stand basal area after moderate thinning was ~68% of the stocking before thinning and intensive thinning reduced the stocking levels down to 34%. Suppressed and co-dominant trees were removed Additionally, unsound and damaged trees (e.g., crooked, forked) were removed. Other thinning treatments were also carried out but here we concentrated on 3 plots with moderate, 3 plots with intensive, and 3 plots with no treatment since establishment. Distribution of thinning treatments to sample plots within the three study sites is presented in Table 1.

Table 1. Thinning treatment of the sample plots in the three study sites.

Study site	Moderate	Intensive	No treatment
1	9	8	4
2	2	5	3
3	5	3	7

The TLS data acquisition was carried out with a Trimble TX5 3D phase-shift laser scanner (Trible Navigation Limited, USA) operating at a 1550-nm wavelength and measuring 976,000 points per second, delivering a hemispherical (300° vertical x 360° horizontal) point cloud with an angular resolution of 0.009° in both vertical and horizontal direction with a maximum range of 120 m (resulting a point distance approximately 6.3 mm at 10-m distance) and beam divergence of 0.011°. All three study sites were scanned between September and October 2018 by using a multi-scan approach to ensure point cloud completeness. Eight scans were conducted at each sample plot with two scans on two sides of a plot center and six auxiliary scans closer to the plot borders (see Figure 1 in Saarinen et al. 2020). Artificial targets (i.e., white spheres with a diameter of 198 mm) were placed around each sample plot to be used as reference objects for registering the eight scans into a single, aligned coordinate system with a FARO Scene software (version 2018). A LAStools software (Isenburg 2019) was used to remove topography from the point clouds by applying a point cloud normalization workflow presented by Ritter et al. (2017).

Stem point extraction from TLS data

First, plot-level TLS point clouds were segmented to identify points from individual trees. Local maxima from canopy height models (CHMs) with a 20-cm resolution were identified using the Variable Windom Filter approach (Popescu & Wynne 2004) whereas the Marker-Controlled Watershed Segmentation (Meyer & Beucher 1990) was applied to delineate crown segments. A point-in-polygon approach was applied for identifying all points belonging each crown segment. To identify points originated from stem and crown within each crown segment, a point cloud classification procedure by Yrttimaa et al (2020) was used. The classification of stem and non-stem points assumed that stem points have more planar, vertical, and cylindrical characteristics compared to non-stem points representing branches and foliage (Liang et al. 2012, Yrttimaa et al. 2020). The method by Yrttimaa et al. (2019, 2020) is an iterative procedure beginning from the base of a tree and proceeding towards treetop. More detailed description of the point cloud classification workflow can be found in Yrttimaa et al. (2019, 2020). The result of this step was classified 3D point clouds for each individual tree (n=741) within the 9 sample plots.

Attribute for structural complexity

Box dimension was used for assessing structural complexity of the individual trees. Box dimension is a structural measure derived from TLS point clouds representing each tree. First, one box including all TLS points of each tree was fitted (i.e., initial box) in which the edge length of the box was tree height and then boxes of different sizes (i.e., tree height/2, tree height/4, tree height/8, tree height/16, tree height/32, tree height/64, tree height/128) were fitted to point clouds of each tree and the number of fitted boxes of each size was saved. Finally, the box dimension for each tree can be defined as a slope between natural logarithm of 1/(box edge length of certain size/edge length of initial box) and natural logarithm of number of boxes including boxes of certain size (Figure 2). Please note that the box dimension is not included in the data set but anyone using the data should calculate that for possible further analyses.

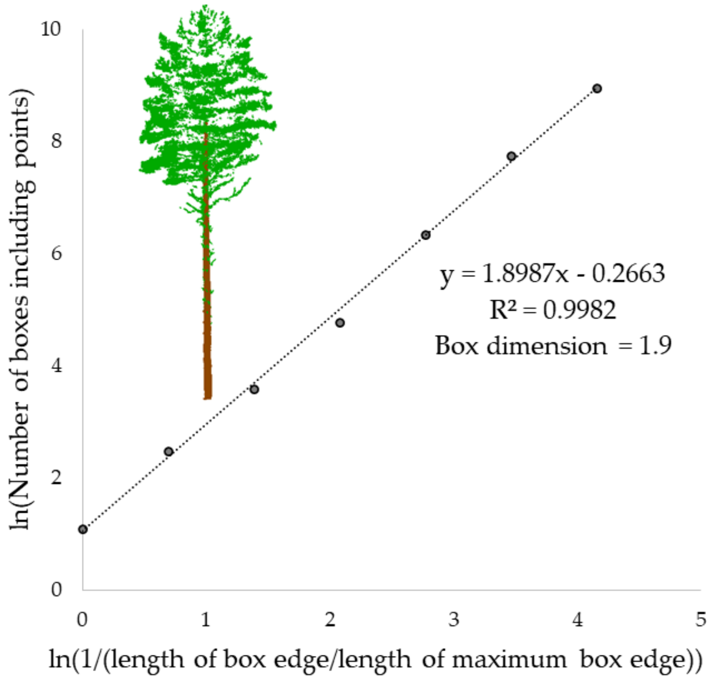

Figure 2. The definition for the box dimension for a Scots pine, the slope of the fitted straight line (1.90) equals the box dimension whereas the intercept (-0.27) is a measure of tree size and coefficient of determination (R^2=1.0) self-similarity (Dorji et al. 2019). Modified after Figure 1 in Seidel et al. (2018).

Data Records

This data set includes a packed zip file. The zip file includes text files of size and number of voxels (boxes) for each tree within the 9 sample plots from the three test sites. The title of the text files includes the information on the study site and the plot within the study site. The text files contain information on size and number of voxels generated for each tree within the plot from the TLS point clouds. The column "h" is the height of each tree in meters above ground indicating the maximum size of the initial voxel. Columns "h/2", "h/4", "h/8", "h/16", "h/31", "h/64", and "h/128" indicate voxels of certain size as a relation to the initial voxel size (i.e., tree height). The column "treeID" includes tree identification number. "plotID" refers to the plot number within a test site, and "trial" refers to study site. The columns are separated by space. There are two rows for each tree within a text file describing the voxel size (row name "size") and number of voxels of that size (row name "N"). Information on tree, plot, and study site identification are identical for both rows. Based on the study site and plot number, files from different thinning treatments can be identified by using the information in Table 1.

Technical Validation

At the sample plot level, TLS point clouds were co-registered with a mean distance error of 2.9 mm and standard deviation 1.2 mm, mean horizontal error was 1.3 mm (standard deviation 0.4 mm) and mean vertical error 2.3 mm (standard deviation 1.2 mm) (Saarinen et al. 2020) indicating high geometric accuracy of the point clouds. When similarly collected point clouds have been used to automatically measure tree diameters at multiple heights along a stem, root mean square error less than 1 cm can be expected in boreal forest conditions (Liang et al. 2018).

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Conflicts of Interest
The authors declare no conflicts of interest.

References
Bayer, D., Seifert, S., Pretzsch, H. 2013. Structural crown properties of Norway spruce (Picea abies [L.] Karst.) and European beech (Fagus sylvatica [L.]) in mixed versus pure stands revealed by terrestrial laser scanning. Trees 27: 1035-1047. https://doi.org/10.1007/s00468-013-0854-4

Cajander, A.K. 1913. Ueber Waldtypen. Acta Forestalia Fennica 1: article id 7526. https://doi.org/10.14214/aff.7526

Calders, K., Lewis, P., Disney, M., Verbesselt, J., Herold, M. 2013. Investigating assumptions of crown archetypes for modelling LiDAR retursn. Remote Sensing of Environment 134: 39-49. https://doi.org/10.1016/j.rse.2013.02.018

Calders, K., Origo, N., Disney, M., Nightingale, J., Woodgate, W., Armston, J., Lewis, P. 2018. Variability and bias in active and passive ground-based measurements of effective plant, wood and leaf area index. Agricultural and Forest Meteorology 252: 231-240. https://doi.org/10.1016/j.agrformet.2018.01.029

Dorji, Y., Annighöfer, P., Ammer, C., Seidel, D. 2019. Response of Beech (Fagus sylvatica L.) Trees to Competition—New Insights from Using Fractal Analysis. Remote Sensing 11: 2656. https://doi.org/10.3390/rs11222656

Georgi, L., Kunz, M., Fichtner, A., Härdtle, W., Reich, K.F., Strum, K., Welle, T., von Oheimb, G. 2018. Long-term abandonment of forest management has a strong impact on tree morphology and wood volume allocation pattern of European beech (*Fagus sylvatica* L.). Forests 9: 704. https://doi.org/10.3390/f9110704

Hardiman, B.S., Bohrer, G., Gough, C.M., Vogel, C.S., Curtis, P.S. 2011. The role of canopy structural complexity in wood net primary production of a maturing northern deciduous forest. Ecology 92: 1818-1827. https://doi.org/10.1890/10-2192.1

Isenburg, M. 2019. LAStools—Efficient LiDAR Processing Software, (version 181001 academic); rapidlasso GmbH: Gilching, Germany. Available online: http://rapidlasso.com/LAStools [accessed on December 19, 2019].

Juchheim, J., Annighöfer, P., Ammer, C., Calders, K., Raumonen, P., Seidel, D. 2017. How management intensity and neighborhood composition affect the structure of beech (*Fagus sylvatica* L.) trees. Trees 31(5): 1723-1735. https://doi.org/10.1007/s00468-017-1581-z

Liang, X, Litkey, P., Hyyppä, J., Kaartinen, H., Vastaranta, M., Holopainen, M. 2012. Automatic Stem Mapping Using Single-Scan Terrestrial Laser Scanning. IEEE Transactions on Geoscience and Remote Sensing. 50: 661-670. https://doi.org/10.1109/TGRS.2011.2161613

Liang, X., Hyyppä, J., Kaartinen, H., Lehtomäki, M., Pyörälä, J., Pfeifer, N., ..., Wang, Y. 2018. International benchmarking of terrestrial laser scanning approaches for forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing 144: 137-179. https://doi.org/10.1016/j.isprsjprs.2018.06.021

Mäkinen, H., Isomäki, A. 2004. Thinning intensity and long-term changes in increment and stem form of Scots pine trees. Forest Ecology and Management 203: 21-34. https://doi.org/10.1016/j.foreco.2004.07.028

Messier, C., Puettmann, K.J., Coates, K.D. (Eds) 2013. Managing forests as complex adaptive systems – Building resilience to the challenge of global change. Routledge, Oxford, UK. 353 p.

Metz, J., Seidel, D., Schall, P., Scheffer, D., Schulze, E.-D. 2013. Crown modelling by terrestrial laser scanning as an approach to assess the effect of aboveground intra- and interspecific competition on tree growth. Forest Ecology and Management 310: 275-288. https://doi.org/10.1016/j.foreco.2013.08.014

Meyer, F., Beucher, S. 1990. Morphological segmentation. Journal of visual communication and image representation 1(1): 21-46.

Popescu, S. C., Wynne, R. H. 2004. Seeing the trees in the forest. Photogrammetric Engineering & Remote Sensing 70(5): 589-604. https://doi.org/10.14358/PERS.70.5.589

Pretzsch, H. 2014. Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures. Forest Ecology and Management 327: 251-264. https://doi.org/10.1016/j.foreco.2014.04.027

Puettmann, K.J., Wilson, S.McG., Baker, S.C., Donoso, P.J., Drössler, L., Amente, G., Harvey, B.D., Knoke, T., Lu, Y., Nocentini, S., Putz, F.E., Yoshida, T. Bauhus, J. 2015. Silvicultural alternatives to conventional even-aged forest management – what limits global adoption? Forest Ecosystems 2: 8. https://doi.org/10.1186/s40663-015-0031-x

Ritter, T., Schwarz, M., Tockner, A., Leisch, F., Nothdurft, A. 2017. Automatic mapping of forest stands based on three-dimensional point clouds derived from terrestrial laser-scanning. Forests 8 (8): 265. https://doi.org/10.3390/f8080265

Saarinen, N., Kankare, V., Vastaranta, M., Luoma, V., Pyörälä, J., Tanhuanpää, T., Liang, X., Kaartinen, H., Kukko, A., Jaakkola, A., Yu, X., Holopainen, M., Hyyppä, J. 2017. Feasibility of Terrestrial Laser Scanning for Collecting Stem Volume Information from Single Trees. ISPRS Journal of Photogrammetry and Remote Sensing 123:140-158. https://doi.org/10.1016/j.isprsjprs.2016.11.012

Saarinen, N., Kankare, V., Yrttimaa, T., Viljanen, N., Honkavaara, E., Holopainen, M., Hyyppä, J., Huuskonen, S., Hynynen, J., Vastaranta, M. 2020. Assessing the effects of stand dynamics on stem growth allocation of individual Scots pines. Forest Ecology and Management 474: 118344. https://doi.org/10.1016/j.foreco.2020.118344

Seidel, D. 2018. A holistic approach to determine tree structural complexity based on laser scanning data and fractal analysis. Ecology and Evolution 8: 128-134. https://doi.org/10.1002/ece3.3661

Seidel, D., Annighöfer, P., Stiers, M., Zemp, C.D., Burkardt, K., Ehbrecht, M., Willim, K., Kreft, H., Hölscher, D., Ammer, C. 2019. How a measure of tree structural complexity relates to architectural benefit-to-cost ratio, light availability, and growth of trees. Ecology and Evolution 9: 7134-7142. https://doi.org/10.1002/ece3.5281

Seidel, D., Leuschner, C., Müller, A., Krause, B. 2011. Crown plasticity in mixed forests–Quantifying asymmetry as a measure of competition using terrestrial laser scanning. Forest Ecology and Management 261: 2123-2132. https://doi.org/10.1016/j.foreco.2011.03.008

Tomlinson, P.B. 1983. Tree Architecture: New approaches help to define the elusive biological property of tree form. American Scientist 71: 141-149. Available at: https://www.jstor.org/stable/27851897 [cited July 3, 2020]

Yrttimaa, T., Saarinen, N., Kankare, V., Liang, X., Hyyppä, J., Holopainen, M., Vastaranta, M. 2019. Investigating the feasibility of multi-scan terrestrial laser scanning to characterize tree communities in southern boreal forests. Remote Sensing 11(12): 1423. https://doi.org/10.3390/rs11121423

Yrttimaa, T., Saarinen, N., Kankare, V., Hynynen, J., Huuskonen, S., Holopainen, M., Hyyppä, J., Vastaranta, M. 2020. Performance of terrestrial laser scanning to characterize managed Scots pine (*Pinus sylvestris* L.) stands is dependent on forest structural variation. ISPRS Journal of Photogrammetry and Remote Sensing 168: 277-287. https://doi.org/10.1016/j.isprsjprs.2020.08.017

Zenner, EK. 2015. Differential growth response to increasing growing stock and structural complexity in even- and uneven-sized mixed *Picea abies* stands in southern Finland. Canadian Journal of forest Research 46: 1195 – 1204. https://doi.org/10.1139/cjfr-2015-0400