Towards automated characterization of horizontal and vertical forest structure using multi-seasonal airborne laser scanning

Leiterer, Reik ; Schaepman, Michael E ; Morsdorf, Felix

Abstract: We present a method to characterize the vertical layering of forests in space and time based on vertical echo distributions from airborne laser scanning. We further demonstrate successful scaling from local to regional areas, including assessment of transferability, robustness and operational use of the method.

Towards automated characterization of horizontal and vertical forest structure using multi-seasonal airborne laser scanning

Reik Leiterer, Michael E. Schaepman, Felix Morsdorf

Remote Sensing Laboratories, University of Zurich, Winterthurerstrasse 190, CH-8057, Zurich, Switzerland.

Highlights: We present a method to characterize the vertical layering of forests in space and time based on vertical echo distributions from airborne laser scanning. We further demonstrate successful scaling from local to regional areas, including assessment of transferability, robustness and operational use of the method.

Key words: *Canopy, Large-scale, Automatic, Forestry, Operational, ALS*

Introduction

Forests cover approximately one third of Earth's total land area and are one of the most biologically diverse terrestrial ecosystems on Earth [1]. Moreover, they form habitats maintaining the majority of terrestrial biodiversity and provide a wide range of valuable ecosystem goods and services, including food, timber, and climate moderation. Understanding and monitoring forest ecosystems and their underlying processes allows the projection of biogeochemical and -physical cycles under e.g. changing climate conditions, and is essential for supporting forest management, conservation biology and ecological restoration [2]. The forest structure is considered a particularly crucial constituent of forest ecosystems functioning and processes as it e.g. influences the energy fluxes between the atmosphere and forests, serves as an indicator to determine forest stand resistance to disturbances, enables the estimation of the conservation potential for biodiversity, or allows the identification of recruitment limitations [3]. Airborne laser scanning (ALS) systems are suitable for providing not only horizontal information about the forest structure, but also detailed vertical information based on the physical measurement principles of active sensing and canopy gap fraction [4]. Forest structure information includes geometric variables such as variation in the canopy height and canopy volume, as well as biophysical variables such as fractional canopy cover [5]. Existing approaches for forest structure characterization often require a large amount of prior information at a pre-defined spatial scale and/or rely on manual processing steps, which again require prior information about stand characteristics. Therefore, most of these approaches are limited in their transferability to other sites due to necessary local calibration of the applied models, and they tend not to be directly comparable.

To overcome these limitations, we developed an automated and transferable grid-based approach to provide quantitative descriptions of canopy structure at different scales, where retrievals are based solely on ALS data [6]. Previously developed and tested on a small patch of ALS data (800 ha) from 2010, we transferred the developed method to a much larger scale (180'000 ha) using a different ALS data set in order to prove the transferability, robustness and near-operational use of the developed approach. The area is subject to different forest management practices (from natural situations to highly intensive regimes with silvicultural interventions) and contains a variety of forest types.

Study area and data

The ALS data were acquired in 2014 for the Kanton Aargau, Switzerland, under defoliated (or leaf-off) and foliated (or leaf-on) conditions, covering an area of approximately 1800 km2 (approx. 20 and 40 echoes/m2 for forested areas, respectively). A three-dimensional point cloud was obtained composed of planimetric coordinates (x and y), ellipsoidal heights (z) and the echo type, as well as the physical characteristics of the reflecting object (echo amplitude and width). The topographically corrected point cloud was derived by extracting ground returns from the point cloud and calculating the digital terrain model using an ordinary kriging method [6]. The height aboveground was then calculated for each echo of the point cloud by subtracting the interpolated DTM value at the corresponding horizontal echo location.

Forest inventory data were collected with forest structure information, such as tree species, tree height, forest cover or canopy stratification (e.g., number of canopy layers) as well as information about ground cover and understory vegetation [7]. The forest inventory data were used for validation only.

Methods

One of the essential features in the applied method is the histogram of the vertical echo heights (percentage of echoes per vertical bin) within a given horizontal grid cell. This histogram can be interpreted as a kind of synthetic waveform reflecting various forest structure features.

We derived the histograms both, on a small scale (1x1m) to take account of small-scale variations in the forest structure and on a coarser scale (20x20m) according to the size of the forest inventory plots. The histograms were calculated for the leaf-off and the leaf-on data independently as well as for the combined data. For the histogram based on the combined data, we calculated the following ALS metrics on the coarse scale: i) $canopy_{var}$ - the small-scale variation of the histograms within the coarse grid cell; and ii) $canopy_{lay}$ – the amount and the extent of vertical canopy layers, whereby a canopy layer was considered to have a minimum vertical extent of ≥3m and the spacing between two layers needs to be ≥3m, following the forest inventory specifications. $Canopy_{lay}$ was classified afterwards according to the amount of layers into '1-layered', '2-layered' and 'multi-layered' canopies.

Using the leaf-off and the leaf-on histograms, we calculated $canopy_{diff}$ – the differences in the percentage of points in the top canopy layer, whereby the extent of the top canopy layer was indicated by $canopy_{lay}$. Based on the leaf-on data only, we calculated $canopy_{cov}$ – the ratio between echoes from the forest ground/ forest floor and echoes from the forest canopy above, as a proxy for the percentage forest cover. $Canopy_{var}$ and $canopy_{diff}$ were afterwards classified into significant variations/differences and non-significant variations/differences using the *p*-value with a significance level set to $p \leq 0.05$. Significant changes in $canopy_{var}$ means a high variability in the vertical structure on a small-scale and thus a less good representation of the vertical structure in the coarse-scale histograms in contrast to a homogenous vertical structure, indicates by non-significant variations. Significant differences in $canopy_{diff}$ indicate deciduous vegetation, whereas non-significant differences indicate evergreen vegetation. Table 1 gives an overview about the resulting forest structure classes.

Table 1: Characterization of forest structure according the calculated ALS metrics.

$canopy_{diff}$	$canopy_{lay}$	$canopy_{var}$	$canopy_{cov}$
deciduous	1-layered 2-layered multi-layered	high variability of vertical structure vs. homogeneous vertical structure	continuous classification (1-100%)
evergreen	1-layered 2-layered multi-layered		

Each of the coarse-scale grid cells therefore contain information about the vertical structure and the seasonal variations of the canopy as well as information about the spatial variability of the canopy structure within the coarse-scale grid cell. For the practical application, we finally segmented the structural classes with eCognition into structural homogenous patches, which are comparable to the conventional stands used for forest management in the region.

Results

The validation shows promising results for the determined forest structure classes, particularly in terms of the seasonal ($canopy_{diff}$) and horizontal variation ($canopy_{var}$) in the vertical canopy structure. The overall accuracy for the $canopy_{var}$-based classification was 83%, whereby in average the classification performs better for the evergreen classes. The classification into deciduous and evergreen vegetation resulted in a high overall accuracy of 91%. The estimated forest cover $canopy_{cov}$ shows with $r^2 = 0.76$ a good correlation to the field data. For the vertical stratification of the canopy ($canopy_{lay}$) we reached an overall accuracy of 69%, whereby the lowest accuracy was determined for the multi-layered deciduous forest and the highest accuracies for the 1- and 2-layered evergreen forests. For more developed forest stands (mean tree heights > 30 m), the different forest management strategies are partially reflected in the specific forest structure. In addition, the effect of different forest types (i.e. mixed stands or pure stands) correlates well with $canopy_{var}$ and $canopy_{lay}$. These results nicely agree with the results we achieved with the data from 2010 on the small area and show the transferability of the developed method [6].

Discussion and conclusion

The proposed forest canopy structure characterization improves existing structure classification approaches as it adds a more detailed description of the vertical stratification of the forest canopy and their horizontal variability. For example, the consideration of the small scale variations of vertical canopy structure is an important indicator in terms of biodiversity estimations or habitat assessments. An advantage of the proposed method is the robust development and we showed, that it can easily be adapted and harmonized to different scales as well as applied to different ALS data sets with varying data characteristics.

The validation shows satisfying results, particularly in terms of the seasonal and horizontal variety of the vertical canopy structure. In general, the transition zones between forested and non-forested areas as well as between the specific forest types are problematic, as it is always difficult to determine borders of discrete classes while looking at a continuous, natural feature space. However, the accuracy assessment of $canopy_{lay}$ turned out to be very difficult. The subjective visual evaluation of the canopy stratification by the forestry experts includes a source of error and thus cannot be regarded as an error-free reference, but rather as source for a type of cross-comparison. Additionally, the canopy stratification approaches used in the forest inventory are more related to the composition of different tree development stages and less focused on the actual vertical foliage distribution. For example, received echoes from the vegetation in the lower canopy parts can be either from the forest floor, forest succession or caused by low branches of old growth trees. In terms of the ALS based canopy stratification, we are not able to differentiate between those different sources even if it would be addressed in different ways based on methods of forest inventory or forest management.

We conclude that our method can substantially improve the robustness and reliability of ALS based forest structure characterization and enables an efficient monitoring of forest structure. The proposed approach meets forest management requirements in terms of accuracy, spatial resolution and information content, and has the potential to be applied in a semi-automated fashion in the near future. The next steps will be to transfer the method to a variety of forests (boreal/tropical) to ensure unambiguous use of the application. Further, we plan to investigate the relationship and usability of the derived forest structure classes with different established forest ecosystem goods and services, such as biodiversity, forest stand resistance to disturbances and stand productivity.

References

[1] Pan, Y., Birdsey, R.A., Phillips, O.L., & B. Robert (2013): The Structure, Distribution, and Biomass of the World's Forests. Annual Review of Ecology, Evolution, and Systematics, 44, 593-622.

[2] Bonan, G.B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science, 320 (5882), 1444-1449.

[3] Shugart, H.H., Saatchi, S., & F.G. Hall (2010). Importance of structure and its measurement in quantifying function of forest ecosystems. Journal of Geophysical Research, 115 (4), 1-16.

[4] Wulder, M.A., J.C. White, R.F. Nelson, E. Næsset, H.O. Ørka, N.C. Coops, T. Hilker, C.W. Bater, & T. Gobakken (2012). LiDAR sampling for large-area forest characterization: A review. Remote Sensing of Environment, 121, 196-209.

[5] Morsdorf, F., Mårell, A., Koetz, B., Cassagne, N., Pimont, F., Rigolot, E. & B. Allgöwer (2010). Discrimination of vegetation strata in a multi-layered Mediterranean forest ecosystem using height and intensity information derived from airborne laser scanning. Remote Sensing of Environment, 114, 14031415.

[6] Leiterer, R., Morsdorf, F., Torabzadeh, H., Schaepman, M.E., Muecke, W., Pfeifer, N., & M. Hollaus (2012). A voxel-based approach for canopy structure characterization using full-waveform airborne laser scanning. International Geoscience and Remote Sensing Symposium (IGARSS), art. no. 6350691, 3399-3402.

[7] Schneider, F.D., Leiterer, R., Morsdorf, F., Gastellu-Etchegorry, J.-P., Lauret, N., Pfeifer, N., & M.E. Schaepman (2014). Simulating imaging spectrometer data: 3D forest modeling based on LiDAR and in situ data. Remote Sensing of Environment, 152, 235-250.