USAGE OF LIDAR DATA FOR LEAF AREA INDEX ESTIMATION

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Abstract

Leaf area index (LAI) can be measured either directly, using destructive methods, or indirectly using optical methods that are based on the tight relationship between LAI and canopy light transmittance. Third, innovative approach for LAI measuring is usage of remote sensing data, especially airborne laser scanning (ALS) data shows itself as a advisable source for purposes of LAI modelling in large areas. Until now there has been very little research to compare LAI estimated by the two different approaches. Indirect measurements of LAI using hemispherical photography are based on the transmission of solar radiation through the vegetation. It can thus be assumed that the same is true for the penetration of LiDAR laser beams through the vegetation canopy. In this study we use ALS based LiDAR penetration index (LPI) and ground based measurement of LAI obtained from hemispherical photographs as a reference in-situ method. Several regression models describing the corellation LAI and LPI were developed with various coefficients of determination ranging up to 0,81. All models were validated and based on the tests performed, no errors were drawn that would affect their credibility.

Key words: forest canopy, leaf area index, LiDAR, LiDAR penetration index, light regime

1 INTRODUCTION

The amount of light reaching the earth's surface in the forest area is mainly affected by the canopy of the tree layer, the rate of which is determined by the species composition of trees and more or less human interaction in terms of forest management. For successful modelling of vegetation growth, it is fundamental to understand the solar radiation regime in forests and its interaction with crown canopy [10].

Canopy can be characterized as an interface between the atmosphere and soil concentrating atmospheric carbon into biomass and releasing oxygen and water. Besides the arrangement of trees, the key factors determining the structure of the canopy include differences in their morphology and other factors, as well as the availability of light [27]. Among the most commonly used environmental indicators characterizing the structure of the canopy is the leaf area index (LAI). LAI is a key characteristic of the forest structure serving as the primary indicator for the exchange of matter and energy within the forest ecosystem. It is a dimensionless variable which is described as a total one-sided area of photosynthetic tissue per unit ground surface area [30]. Its definition is valid only for deciduous forests, and therefore Myneni et al. [19] defined the LAI as the maximum area of photosynthetic tissue per unit ground surface area. LAI depends on the species composition of the vegetation, its developmental stage, predominant habitat factors, seasonality and forest management. It is a dynamic parameter that changes from day to day (especially in spring and autumn) and is modified over the years due to the effects of physical and biological forces that are shaping and changing the forest environment. Methods for detecting LAI can be divided into two categories – direct and indirect. Direct methods generally apply destructive methods to estimate the total number of leaves on the tree and their area, whereas indirect methods use some aspects of the radiation regime inside the forest stand, and LAI is subsequently derived from the distribution of light under the canopy [11].

Direct measurement of solar radiation and detection of the canopy characteristics is unrealistic in vast territories due to the number of measurements needed to create a proper distribution model [23]. The so-called indirect methods have a much greater use for modelling at the level of large forest units, in particular the airborne laser scanning (ALS) which serves to collect highly accurate 3D data to create digital models also for areas permanently covered with forests. The system of ALS or generally LiDAR (Light Detection and Ranging) is an innovative, progressive method of remote sensing. This method enables mass collection of highly accurate elevation and topographic data to the earth's surface and of objects that are located on it (vegetation, buildings) [16].

ALS has found its use in various applications, such as 3D models of cities and buildings, delineation of above-ground power lines and aerial parts of the pipelines, and surveys of building and field barriers to flying, search for extensive archaeological objects, analyses of vegetation cover, mapping of water bodies, etc. [9]. With the development of the use of modern technologies in forestry, this method of data collection found its place here as well. Based on the multiplication of returns in a forest, it is possible to estimate some parameters of forest stands or individual trees, for example, to define individual tree crowns, to detect the number of trees in the stand, the width of the crown and its deployment, canopy width, estimates of the volume of wood and biomass, or even tree species [e.g. 8, 13, 20]. Due to the easy availability of ALS data, these were then used for mapping of canopy characteristics, such as canopy cover, canopy closure, canopy gap fraction or LAI [e.g. 17, 12, 18].

Korhonen et al. [12] verified that the use of ALS data is a very good alternative for obtaining reliable information on canopy for large wooded areas. However, to validate the results and for the empirical estimation of the variables of interest, there is a continuing need for use of data from terrestrial measurements. A widespread alternative among the terrestrial methods for calculating LAI is digital hemispherical photography [5].

Hemispherical photography allows characterizing the canopy utilizing vertically oriented images taken by a camera with a wide-angle lens, the so-called fish eye. It provides a permanent record, which makes it a valuable source of information about the position, size, density and distribution of gaps in the canopy. This method is advantageous over others in terms of speed, low cost and easy availability. Despite its indisputable advantages, the manual acquisition and subsequent processing form a potential source of errors [11].

At locations of terrestrial measurements by means of hemispherical photography, a close correlation of LAI with penetration indices derived from the ALS data was demonstrated [17].

Lefsky et al. [15] used data from the SLICER scanner (Scanning LiDAR Imager of Canopies by Echo Recovery) and tested the ability to estimate LAI for 5 different types of coniferous forests of the temperate zone. They obtained indices from ALS data analysis and derived models to estimate the characteristics of vegetation structure. The highest degree of correlation 0.81 was demonstrated for LAI and 0.92 for estimation of the aboveground biomass.

Species composition of the vegetation must be taken into account as well, when it shows significant differences in the parameters of the canopy derived from hemispherical images, which results in varying degrees of correlation between variables. Correspondence between LAI derived from the ALS data and LAI determined from hemispherical photography is unusually higher in deciduous forests than in coniferous ones in the work by Riaño et al. [26]. As a reason for this finding, the factor of dense clusters in the tight canopy of coniferous forests is reported. Nevertheless, as well as Morsdorf et al. [17], he agrees with the statement that the ALS data can provide a much better horizontal sampling of the canopy than field research methods, such as hemispherical photography.

Indirect measurements of the leaf area index using hemispherical photography are based on the transmission of solar radiation through the vegetation. It can thus be assumed that the same is true for the penetration of LiDAR laser beams through the vegetation canopy. Based on this premise, the Laser Penetration Index (LPI) can be easily calculated.

$$LPIij = mGij / (mGij + mVij) \tag{1}$$

where:

mGij represents the number of laser beam returns per unit area of the ground and

mVij represents the number of returns per unit area of vegetation.

Subscripts i and j refer to the respective grid cell column and row. A significant linear correlation between LAI obtained from ground measurements using hemispherical photographs and LPI allows the use of ALS data for LAI surface modelling [1].

LPI values are ranging from 0 to 1. Values close to 0 show the presence of dense vegetation while values close to one characterize an open canopy and earth surface [18].

The aim of this work is therefore statistical verification of usability of the ALS data for evaluation of the leaf area index in forest stands of different tree species composition in the Czech Republic.

2 MATERIALS AND METHODS

2.1 ALS Data

ALS was performed in September 2012 by discrete return scanner Leica ALS50-II from flight altitude of 1400 m with average density of 4.6 points per square meter.

Data were acquired for the territory lying near the village called Hostětín located at the foot of the border ridge of the White Carpathians. Field measurements were carried out on the estates of forest owners under 50 ha in the district of Uherský Brod. Forest management schemes No. 601804 Brumov effective from 2008 to 2017 are developed for these stands.

2.2 Field Measurements

Hemispherical photographs were taken in the stands with the following characteristics:

- Stand types – beech (22 areas), pine (14 areas), spruce (5 areas), other deciduous (3 areas);
- Age structure – 45 to 104 years.

Forty-five hemispherical photographs were acquired by Nikon Coolpix 4500 camera with a fisheye converter lens FC-E8. The photos were taken in August 2013 in the stands with various species composition and varying age and spatial structure. Photos were taken under low light condition. The camera was mounted at the height of 130 cm from the soil surface, levelled and oriented so that the north was located on the top edge of the hemispherical image. Position of the camera was precisely measured using GNSS assembly consisting of a GPS/Glonass Trimble Pathfinder ProXRT receiver, dual frequency Trimble Zephyr 2 antenna and Trimble Nomad 900G controller using post-processing RINEX correction.

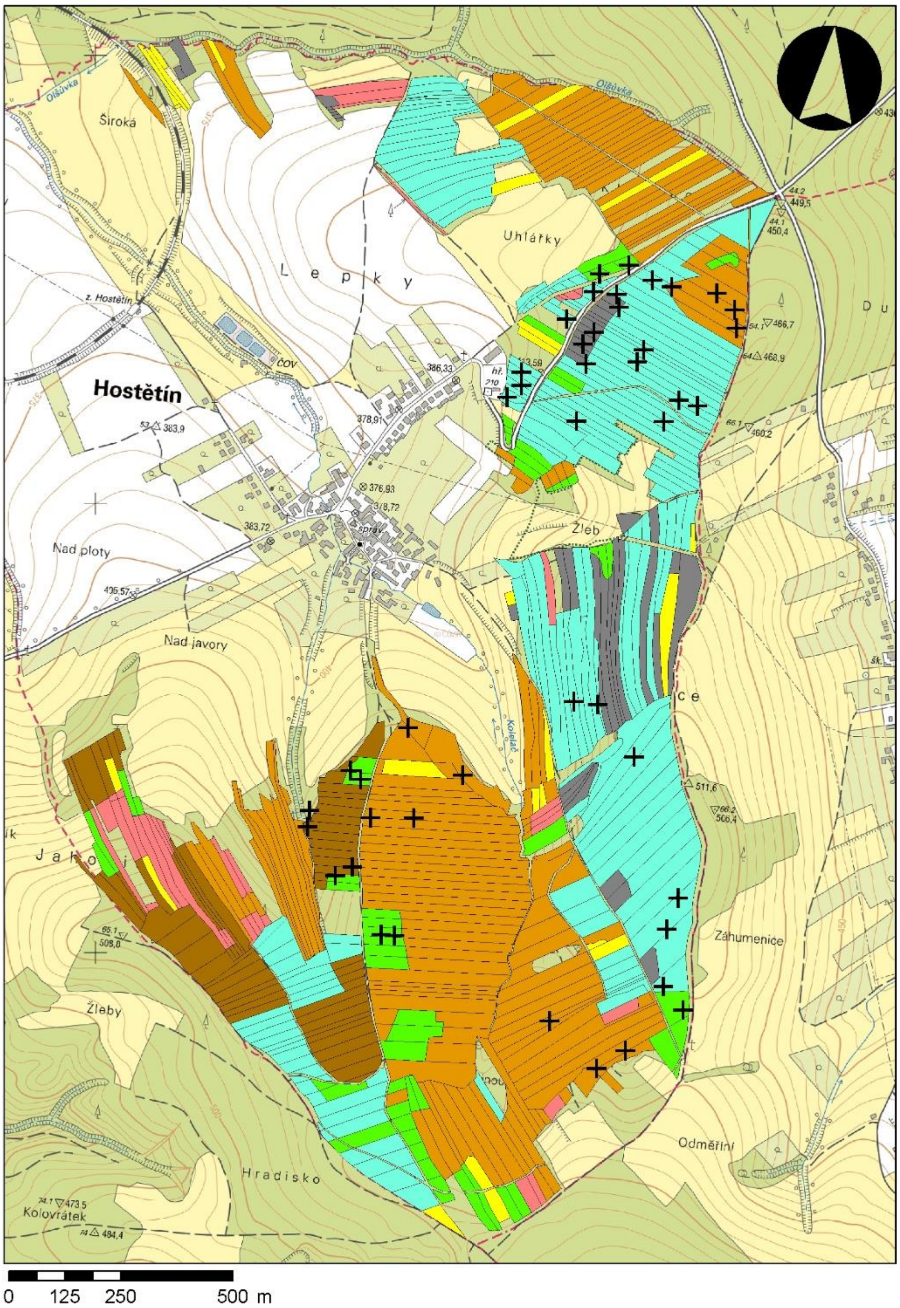

Fig. 1 Stand map of the study area and localizations of hemispherical photographs (black crosses)

2.3 Analysis of hemispherical images

Hemispherical images were analyzed using a combination of freeware software of Gap Light Analyzer + SideLook and in commercial WinScanopy software. In the SideLook program, individual images were converted to black and white based on the blue channel in accordance with Frazer et al. [7]. In the Gap Light Analyzer, the area of the photo itself was determined based on the image with the highest contrast and firmly fixed for the other images. Using the threshold values determined from the SideLook software, images were converted to black and white and LAI was calculated with differently limited zenith angles (LAI 4 Ring = 0° - 60°, LAI 5 Ring = 0° - 75°) [6]. Furthermore, images were evaluated in the WinScanopy software with the difference that the threshold was detected automatically and LAI 3 Ring was counted (zenith angle 0° - 45°) using LAI-2000. At the same time, the leaf area index was also determined using LAI-2000G by entering specific values of the angle.

2.4 ALS Data Processing

The point cloud from the first airborne laser scanning return, the point cloud classified by ASPRS as high vegetation and the point cloud returning from the ground were entered into the ESRI ArcMap program. Filtering and classification of these points was performed earlier in the TerraScan software for Bentley MicroStation. Using the ArcMap software tools, grids having different pixel sizes were created depicting a number of ALS points per a specific area. Next, a point shapefile with the position of hemispherical images was connected, whereas number of the first return points and of points reaching the ground for different pixel sized were extracted into its attribute table. Subsequently, LPI was calculated according to the abovementioned formula.

Determination of the optimal method of calculating LAI and LPI for the purpose of regression analysis was performed by calculating the correlation matrices. A correlation matrix always contained one way of calculating LAI and all the methods of calculating LPI. LAI was the most accurately estimated in the WinScanopy software with the angle (FOV = Field of View) limited to 30° and the LPI calculation in the grid with a pixel size of 15 m. To create a digital surface model using this method, all points of the first return were applied, instead of points classified as Class 5 – High Vegetation in accordance to ASPRS.

3 RESULTS

To calculate the LAI, 4 regression models were created in total with various coefficients of determination. The first of them was entered by independent variables of LPI, age and type of composition, however, on the basis of parameters estimate, statistical insignificance of the variable of age was found (probability p-value of t-test is greater than the significance level of $\alpha = 0.05$, therefore, we accept the null hypothesis that the age parameter is zero), therefore, further processing was conducted without this variable. A regression model with two independent variables – LPI and type of composition – was thus created. On the basis of t-tests performed, these parameters were evaluated as statistically significant. Furthermore, a model with one independent variable was created, not considering tree species composition of the vegetation (Fig. 2). Subsequently, two more models were created with one independent variable (LPI) separately for coniferous (Fig. 3) and for deciduous trees (Fig. 4). Statistical characteristics of each regression model are shown in the table below (Tab 1). An important part of the regression analysis comprises of the study of the regression triplet, i.e. assessing the quality of data, quality of the model and quality of the estimation method (least squares method). Based on the tests performed, no negative conclusions were drawn that would affect the credibility of the regression models.

Tab. 1 Statistical characteristics of regression models

	model 1	model 2	model 3	model 4
Multiple correlation coefficient R:	0.867791292	0.845354927	0.899514223	0.865797
Coefficient of determination R^2:	0.753061727	0.714624952	0.809125837	0.749604
Predicted correlation coefficient Rp:	0.510048496	0.470583133	0.561539265	0.511894
Mean quadratic error of prediction MEP:	0.105909848	0.116354043	0.114690429	0.085616
Akaike information criterion:	-101.6130942	-97.10313002	-39.88265038	-65.8134

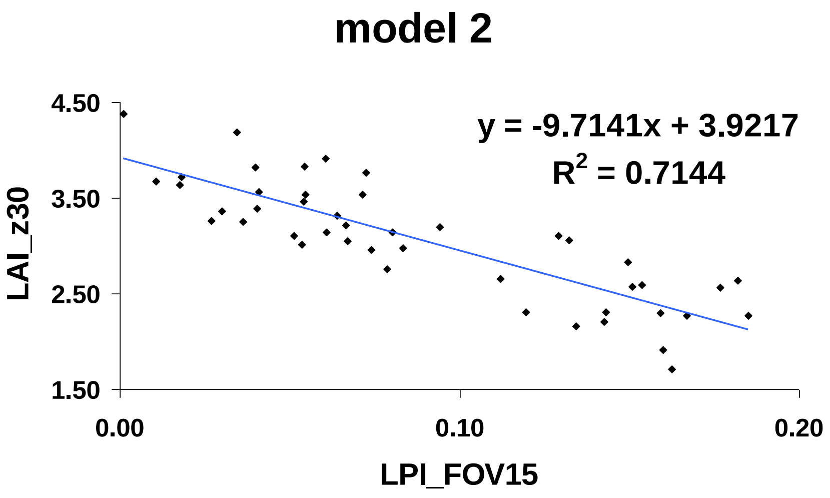

Fig. 2 Graph of the regression curve, the regression model with one independent variable

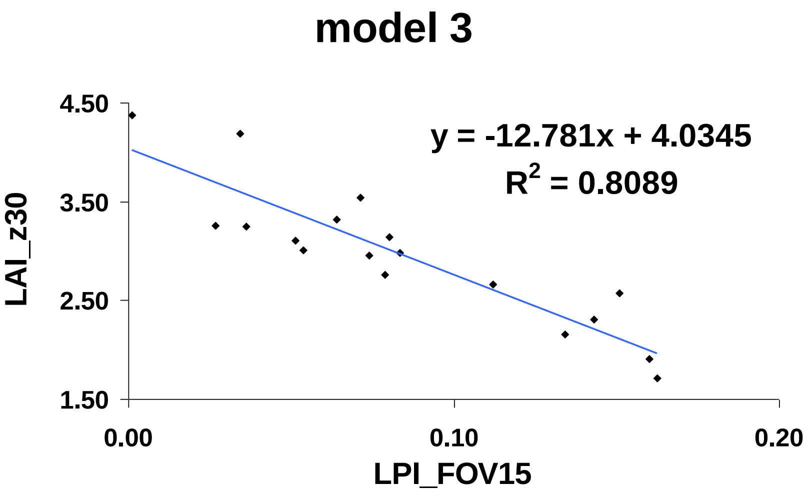

Fig. 3 Graph of the regression curve, the regression model for coniferous forests

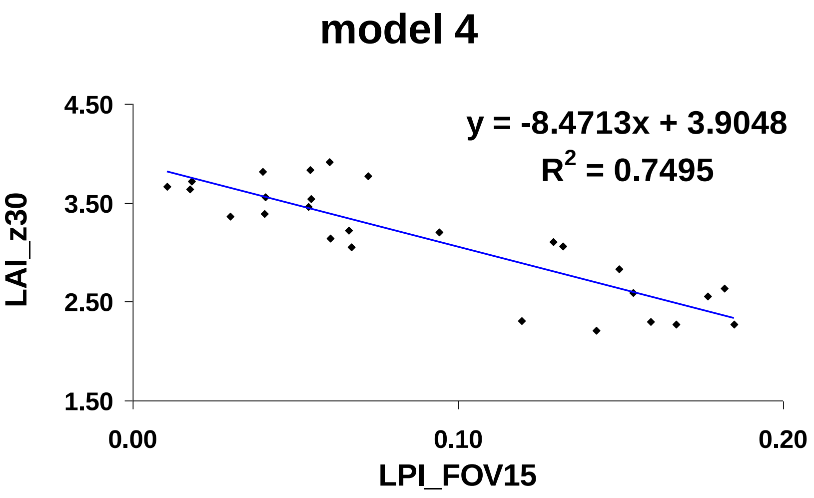

Fig. 4 Graph of the regression curve, the regression model for deciduous forests

4 DISCUSSION

Based on all analyses, it was found that successful and the most accurate calculation of leaf area index requires application of as fine grid as possible. However, there should be the minimum amount of empty pixels. The smallest suitable pixel size in this case was 15 m x 15 m. In the analysis of hemispherical images, it was necessary to reduce the angle of the area used for the calculation of the leaf area index as much as possible, particularly down to 30°. Locally reduced value of LAI given by a gap or thinning vegetation fails to be reflected when averaging the image of a too large area, nevertheless, laser penetrates this gap or thinning vegetation without any problems and it will be indicated by the higher LPI value for the given area. Musselmann et al. [18] argues likewise.

Four regression models were created with different coefficients of determination (0.71 to 0.81). It can be said that the most appropriate model is, paradoxically, the regression model with the smallest regression rabat (regression model with one unknown variable), as subjectivity of deciding the sorting of images into groups by composition is the most limited therein. Tree species composition, however, proved to be an important parameter, thus it would be useful to take more measurements with graded degree of composition in future research. For the most precise estimate of LAI in mixed vegetation, it is optimal, either on the basis of vegetation indices, or based on the shape of LiDAR point cloud, to divide mixed stands into the smallest possible fragments by tree species and apply regression model specific to the trees in the particular segment. Ground verification of these models is then necessary to perform only in monocultures.

Barilotti et al. [1] developed a regression model for the calculation of LAI with the coefficient of determination at 0.89. However, he only performed measurements in 25 transects, out of which six transects were in deciduous forests. Fifteen transects had an area of 400 m 2, which is comparable with the angle of view 42° in an hemispheric image (zenith angle of 0° - 21°). Two transects had an area of 1,000 m 2 and three transects an area of 10,000 m 2. Theoretically, it is possible to state that if Barilotti et al. [1] performed 45 measurements as in this work, regression rabat would drop. At the same time, however, he reports that with low number of points the determination coefficient decreases as well, but is still relatively high (0.61). For the field measurements he did not use the method of computer analysis of hemispherical images, but measurement by means of Licor LAI-2000 Plant Canopy Analyzer. In his work he also does not mention performing the regression triplet analysis, so it can be assumed that the regression models developed in this work are more suitable, despite the generally lower coefficients of determination.

Musselmann et al. [18] developed a regression model with the coefficient of determination of 0.64. He performed 24 LAI measurements using analysis of hemispherical photographs. He reports that it is preferable to realize multiple flights with the scanner above the stand. Musselmann et al. [18] used LPI calculation by means of raster filtering. He reached the abovementioned coefficient of determination after application of a circular filter with a radius of 35 m, but does not consider limiting the zenith angle used for LAI calculation, since he conducted the evaluation in the Gap Light Analyzer which lacks this option. A specific area of the hemispheric image can only be defined manually to limit the zenith angle.

Kwak et al. [14] developed equations of interdependence between LAI and LPI for the three tree species. The coefficient of determination of 0.73 was reached in Larix leptolepis Sieb. et Zucc, and the coefficient of determination of 0.81 was reached in Quercus spp. Sieb. et Zucc and Pinus koraiensis Sieb. et Zucc. He also applied the so-called Laser Intercept Index (LII) which can be calculated according to the formula:

$$LII = \frac{N_{(high+mid)}}{N_{all}} = 1 - \frac{N_{gnd} + N_{low}}{N_{all}} \qquad (2)$$

where N(high+mid) is the sum of returns from high and medium vegetation, Ngnd is number of the points in the terrain, Nlow is number of returns from high vegetation, and Nall is the sum of all the returns in the area. By means of this index Kwak et al. [14] reached relatively high coefficients of determination (0.85 to 0.88). This index is not losing the original information on the number of all the transformation points into the grid and at the same time allows for normalization of distorted local variation of the number of points. Kwak et al. [14] did not use the analysis of hemispherical photographs to measure LAI, nevertheless, he applied the AccuPAR-80 Linear PAR/LAI Ceptometer, which can of course give different results.

Zhao and Popescu [31] made a comparison of LAI calculation based on data from airborne laser scanning and data from the ESA GLOBCARBON project that display information about LAI derived from satellite measurements from 1999 to 2002 [21]. By means of the LPM index (Laser Penetration Metrics – alternative to LPI) 84 per cent of the variability of data could be explained by the regression model. They tried to calculate LAI also using the index HRM (Height-Related Metrics), but the LPM index proved to be more reliable. Compared with multispectral images from the MODIS satellite, LiDAR seems to be a better source of data, but currently it is still impossible to develop a model of LAI from airborne laser scanning without reference ground measurements. When mapping leaf area index using LiDAR, in future studies it is necessary to ensure greater accuracy in-situ measurements of LAI and thereby calibrate the LiDAR models which again may serve to make calculations based on satellite multispectral images more accurate.

Possible errors in the measurement of LAI could be caused by the Nikon Coolpix 4500 camera, which was placed in the market already in 2002. This leads to easier the blowouts, which are white areas in the image that do not contain artwork and it cannot be obtained in any post-processing adjusting of the exposure using the histogram in any of the photo editing software. The hemispherical crown density images have a huge dynamic range, thus using preferably a full-frame digital SLR camera would be more appropriate. Some solution could also be a deliberate underexposure by several exposure levels [29, 32], with modern cameras also modification of the layout of the brightness values in accordance to histogram [2]. Overall, the results of LAI measurements by this method can be underestimated, in particularly in coniferous forests. Some authors refer to LAI determined by optical methods as "effective leaf area index" (LAIe – effective LAI) [3, 4]. This index can be then converted to LAI using the formula of LAIe=β*LAIe, where β is the correction factor different for different species of trees. Gower and Norman (1991) set out the factors 1.60 and 1.49 for spruce and larch respectively. This correction factor is not used for beech. Misinterpretation of results is highly probable, as leaf area index in the range from 1.71 to 4.38 has been achieved, but in forests LAI valuesnormally amount to about 6-7 and in spruce coppice over 20 [25]. As put by Van Leeuwen et al. [28], effective LAI is better than real LAI for the purposes of radiation modelling based on Beer-Lambert law.

The discovered dependencies are valid either in scale of individual research areas or at the regional level. Some models are affected by the seasonality of the vegetation (trees foliage) and some apply only to specific types of vegetation [24]. Regression models published herein achieve a similar regression rabat, as models by other authors. Any other work dealing with the calculation of radiation or LAI from LiDAR has never been published in the Czech Republic.

5 CONCLUSION

Four different regression models were created to calculate the leaf area index based on airborne laser scanning data. Calculation of models was preceded by LAI field measurements using hemispherical images. A total of 45 hemispherical photographs were acquired and processed in the Gap Light Analyzer + SideLook and WinScanopy softwares. The highest correlation with the airborne laser scanning data is ensured by the zenith angle limited to 30°. For this reason, it is preferable to use the commercial software called WinScanopy that allows setting the angle limit by entering a specific value.

LiDAR penetration index (LPI) studying the penetration of the laser beam through the forest canopy was selected as a reference value for the calculation of LAI. Optimal correlation with LAI for 30° angle was provided by LPI grid with pixel size of 15 m. Regression models of LAI dependence on LPI were calculated in QC Expert software. The first model with the determination coefficient of 0.75 is entered by two independent variables: LPI and tree species. The second model with the determination coefficient of 0.71 and one independent variable does not consider tree species composition of the stand, it has the lowest potential errors caused by the incorrect classification of tree species composition and it is probably the most suitable for the given application, since the area of interest is uneven in terms of tree species composition. Next, sub-models were developed for coniferous and deciduous forests with regression rabat of 81 per cent and 75 per cent respectively.

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RESUMÉ

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