CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

DIPLOMA THESIS ASSIGNMENT

MSc. Nikola Tričković

Forestry Engineering

Forestry, Water and Landscape Management

Thesis title

Predicting forest growth using modern remote sensing methods.

Objectives of thesis

Objective of the work is to describe and test methods for growth estimation using repeated airborne laser scans, describe the accuracy and precision of evaluated methods.

Methodology

The work area will be National Park of Bohemian Switzerland. The work will follow these steps:

- arrange data from laser scans for the national park from 2005 and from 2019. Perform correction, alignment and necessary filtering. Describe individual steps and procedures.

- acquire ground truth from forest management plan and propose appropriate ground truth network of plots and acquire data on them. Describe and explain this sampling.

- estimate the growth from repeated laser scans using methods of e(1) estimation of volume in each scan and (2) estimation in the differences.

- Evaluate the accuracies using both methods, describe advantages and disadvantages prepare recommendations for future studies and practice.

The proposed extent of the thesis

60 pages

Keywords

Remote sensing, laser scan, growth and increment

Recommended information sources

Hernandez PA, Franke L, Herzog K, Pacheco V., 2007: Predicting species distributions in poorly-studied landscapes. Springer Science and Business Media B.V. 2008. Biodivers Conserv (2008) 17:1353–1366.

Hernández-Stefanoni JL, Gallardo-Cruz JA, Meave JA, Manuel Dupuy J., 2011: Combining geostatistical models and remotely sensed data to improve tropical tree richness mapping. Ecological Indicators. Volume 11, Issue 5, September 2011, Pages 1046–1056.

Hsu, C.W., Chang, C.C. and Lin, C.J., 2010: A Practical Guide to Support Vector Classification (Taipei: Department of Computer Science, National Taiwan University).

Mcrobert R, Tomppo E, Finley A, Heillinen J., 2007: Estimating aerial means and variances of forest attributes using the k-nearest neighbors technique and satellite imagery. Remote Sensing of Environment, 111, pp. 466–480.

Mohammadi J., Shataee Sh., Yaghmaee F. and Mahiny A.S. 2010: Modeling Forest Stand Volume and Tree Density Using Landsat ETM+ Data. International Journal of Remote Sensing, Vol. 31, No. 11, 10, 2959–2975.

Noordermeer, L.; Økseter, R.; Ørka, H.O.; Gobakken, T.; Næsset, E.; Bollandsås, O.M. Classifications of Forest Change by Using Bitemporal Airborne Laser Scanner Data. Remote Sens. 2019, 11, 2145.

Surový, P.; Kuželka, K. Acquisition of Forest Attributes for Decision Support at the Forest Enterprise Level Using Remote-Sensing Techniques—A Review. Forests 2019, 10, 273.

Expected date of thesis defence

2020/21 SS – FFWS

The Diploma Thesis Supervisor

Ing. Peter Surový, PhD.

Supervising department

Department of Forest Management

Advisor of thesis

Ing. Zlatica Melichová

Electronic approval: 28. 2. 2020

Ing. Peter Surový, PhD.

Head of department

Electronic approval: 14. 3. 2020

prof. Ing. Róbert Marušák, PhD.

Dean

Prague on 10. 04. 2022

Czech University of Life Sciences

Faculty of Forestry and Wood Sciences

Master Thesis

Predicting Forest Growth using Modern Remote Sensing Methods

Candidate: Nikola Tričković
Supervisor: Peter Surový

Prague, 2022

Contents

Abstract

21. Century is the Century of new, modern technologies and forestry sector is doing its best to adapt to it. Using Remote sensing technologies has seen exponential growth in the forestry sciences and practice as well. In this thesis remote sensing is used as evaluation of bi-temporal laser scans of the forested area as a mean for predicting forest growth. The area of National Park Bohemian Switzerland has been chosen and tree and stand parameters were measured on the field as a validation data. Correlations between trees height and increment had been established, growth was modeled and its accuracy calculated. Presented results in this thesis suggest that this method is acceptable for forest growth predictions and can be used in the future.

Keywords: Remote sensing, laser scan, forest growth, increment, ALS, LiDAR

Introduction

Remote sensing is becoming more important in forestry management as the technology is becoming cheaper and easily accessible. Using these technologies can be of a great help to forest managers. Traditional forest management practices are time consuming and at quite amount require hard work.

Remote sensing in forest management has been the topic of many projects and research papers over the past quarter century across the globe. Publications over the past years increased significantly and that, according to Tang&Shao (2015), can be seen while searching by key words such as "forest" or "remote sensing". Same authors note that the number of papers published in 1960s is one; in 1970s it's four; in 1980s it's twenty four and impressive number of 2930 in only four years, between 2010 and 2014.

Remote sensing in forestry is used trough different systems and forms of mapping and taking high resolution footages (imagery). These footages could be obtained by satellites, airplanes or, in the recent years popular, unmanned aerial vehicles (UAV).

It's worth mentioning that weather we are talking about aerial photographs made by airplanes during both world wars, or satellites being launched within Space race during cold war madness,

or even drones in 21. Century modern warfare, remote sensing has always been connected with high-end technologies and as such it has almost always been used and tested in military field at first hand. Only after did the life sciences got the chance to try it for its own purpose. So, the question which arises here is: Is the focus of the human race in 21. Century really in trying to save the World from the mess that nobody else but humans themself created?

The aim of this work was to estimate the possibility and accuracy of using bi-temporal laser scaning methods in predicting growth of the forest stands. Chosen area of interest was National Park Bohemian Switzerland, in the north of Czech Republic. Two laser scans, from 2005 and 2019 were used. Also, practical part of the work included field measurements from the forests of National Park.

Literature review

1. Introduction to remote sensing

Remote sensing in forest management has been the topic of many projects and research papers over the past quarter century across the globe. Remote sensing found its place in forestry as well and it's on the rise. This can be clearly seen in the number of publications trough time. According to Tang & Shao (2015), increase in publications with ISI-index journals is seen while searching the keywords "forest" and "remote sensing". They note that there was one article published in the 1960s, four in 190s, 24 in the 1980s, 536 in the 1990s, 2519 in the 2000s and 2930 in the 2010–2014 short period.

2. Earth scanning technologies

In the first half of the previous century properties of the forests could be analyzed by remote sensing only on a local scale using aerial photography. Fifty years ago, in 1972 a satellite designed to collect multispectral remote sensing data was launched. It was a part of the Earth Resources Technology Satellite (ERTS) programme (later known as Landsat). Forestry had a great benefit of this satellite because the satellite scanner was specially designed to monitor Earth's natural resources. Information provided by this satellite, concerning forestry can be

obtained in different levels – spatial extent of forest cover, forest type and in the end, biological properties of forests (Boyd & Donson, 2005).

Even in the beginning of the twenty first century scientists thought that satellites are suitable only for larger scale mapping. They saw that for smaller scales something more useful will be invented in the years to come. This happened to be unmanned aerial vehicles (UAV), or simply, drones.

Application of drones in civil activities is increasing over the past decade especially. As technology is becoming cheaper and developing rapidly in the modern world, drones are not an exception. Their shape and size can vary, and by that alone drones are becoming popular in different scientific fields such as agriculture, forestry, meteorology, natural disasters management, traffic, but also in everyday life of common people (travel documentaries, music concerts and festivals) etc.

The benefits of drone remote sensing include low material and operational costs, flexible control of spatial and temporal resolution, high-intensity data collection, and the absence of risk to crews (Tang & Shao, 2015).
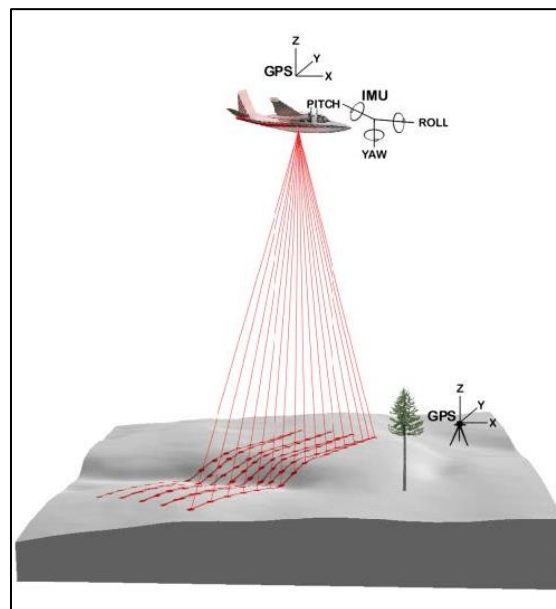
In literature, drones could be found by different names such as unmanned aerial systems (UAS), unmanned aircrafts (UA), unmanned aerial vehicles (UAV), remotely piloted aircrafts (RPA). There are various classifications of drones. For example classification by size: large, medium, small and mini, and micro and nano (Anderson and Gaston, 2013; Tang & Shao, 2015). Or, classification by usage: target and decoy, reconnaissance, combat, research and development, and civil and commercial (www.theuav.com). Also, there are differences in takeoff and landing, and in that sense there are drones with vertical and horizontal takeoff and landing. Horizontal is typical for fixed-wing, while vertical is typical for rotary-wing drones. A lot more classifications could be found in literature, but what is important is that all these classifications are made in purpose of describing the drone characteristics and make choosing the right one for the job easier.

Aircrafts and drones can carry a variety of sensing instruments, including visible light, near infrared (NIR), shortwave infrared (SWIR), thermal infrared (TIR), Radar, and LiDAR sensors (Tang & Shao, 2015).

2.1. LiDAR

The name LiDAR is derived from light detection and ranging, and it defines the remote sensing technique which in difference to radar uses laser light for deriving results. Work mechanism of LiDAR is based on measuring travel time of laser beam between the sensor and target. The light from laser reflects of the target surfaces and returns to the measuring instrument. This travel time is converted into distance or range from the instrument to the target (object) (Dubayah & Drake, 2000). Sensor is calculating coordinates (x, y and z) according to returned signal from the ground or ground objects, creating the 3D point clouds (Koma et al, 2021)

Picture 1 Airborne laser scanning scheme; Source - https://www.researchgate.net/profile/Robert-Mcgaughey-2/publication/283413311/figure/fig1/AS:614211524771840@1523450847130/Schematic-of-an-airborne-laser-scanning-system.png

LiDAR is typically functioning on a wavelength around 1064 nm which is in the infrared part of the electromagnetic spectrum. Almost all objects on the earth surface have a good reflectance at infrared wavelengths so their return signal is of sufficient intensity and can be detected. But, on

the other hand, water bodies and dark surfaces such as dump soil have very low reflectance so it's not easy to catch a reflected signal from them (Harding, 2004; Bang, 2010).
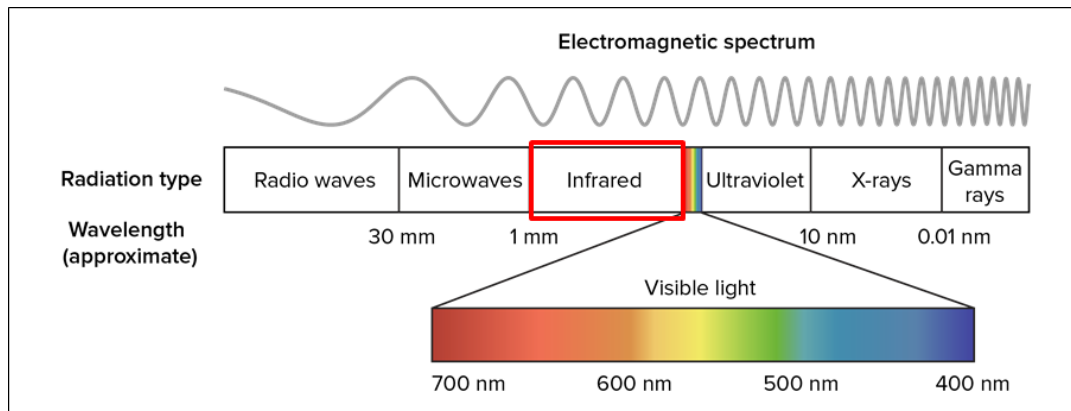
Picture 2 Scheme of the electromagnetic spectrum; Source - https://www.pngfind.com/pngs/m/74-742812_minnesota-how-do-electromagnetic-waves-travel-images-wavelengths.png

As described by Habib et al. (2010), LiDAR system consists of two parts. These parts are ranging and scanning unit, and position orientation unit (POS). Further, POS has and integrated differential global positioning system (DGPS) and internal measurement unit (IMU). Duty of laser scanning unit is to measure distances from the sensor to the object on the ground or the ground itself, while the duty of the integrated GPS/IMU is to collect information about position and altitude. Combination of the data measured by these two components is the point cloud with its coordinates.

LiDAR can record returned light energy based on two systems:

a) Discrete return system - it records only peak points of the waveform curve. These points are called returns, and discrete system can record 1–4 returns from one laser pulse.

b) Full Waveform system - records a distribution of returned light energy. This is more complex system and it can record more information than discrete system

2.2. Airborne laser scanning (ALS)

Technology of laser scanning could be classified as static or dynamic. Static scanning implies scanner to be in secured position while acquiring data. What is achieved with this scanning

8

method is high precision and relatively high point density. On the other hand, dynamic scanning implies that scanner is applied to some moving vehicle. In this case, additional position systems are needed (INS and GPS). Dynamic scanning could be done from different vehicles, weather manned (car, airplane) or unmanned (drone) (Van Genechten et al, 2008). Additionally, interesting mark from the authors of the book "Theory and practice on Terrestrial Laser Scanning" (Van Genechten et al, 2008) must be mentioned and it says that "All static laser scanning can be seen as terrestrial laser scanning, however not all terrestrial laser scanning can be categorized as being static laser scanning".

According to Mikita et al (2013), airborne laser scanning can be used for different forestry practices such as:

- creation of digital model of canopy surface

- tree identification

- measurement of tree parameters.

Using ALS makes foresters lives easier, works could be done in less time and with more efficiency. For example, laser is sending beams to the target and they can reflect from different layers of vegetation. First pulses return are reflected from the highest vegetation layer, second returns (and following ones) from the middle vegetation layer, and the last return is from the earth ground. Comparing first and last return some forest characteristics could be identified – forest border, individual trees or canopy surface, tree height or canopy density (Mikita et al 2013).

Scanning itself depends on the device type, but also terrain topography or speed and path the vehicle is producing. Different devices can be used for scanning such as oscillating mirror, rotating polygon, nutating mirror (palmer scanner), and fiber scanner (Wehr and Lohr, 1999; Brenner, 2006; Shan and Toth, 2009; Bang, 2010).
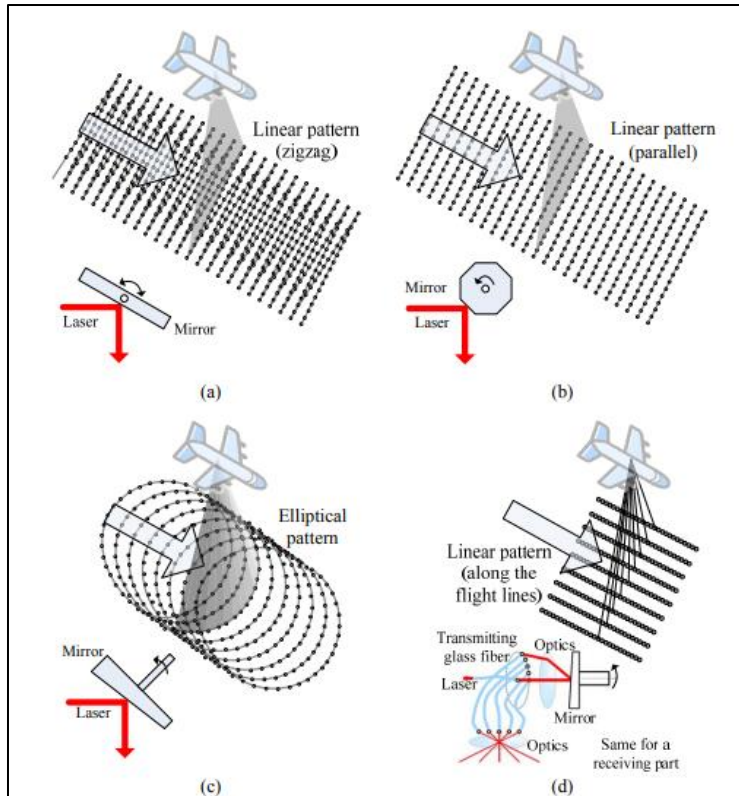
Picture 3 Scanning devices and patterns; Source - Bang, Ki In. (2010)

LiDAR systems for forestry applications can be classified based on the following characteristics:

(1) Whether they record the range to the first return and/or last return or fully digitize the return signal;

(2) Whether they are small footprint (typically on the order of a few centimeters) or large footprint systems (tens of meters);

(3) Based on their sampling rate/scanning pattern.

LiDAR technologies provided base for development of digital surface models (DSM) which are now along with digital terrain models (DTM) widely used in deriving canopy height models (CHM). LiDAR is todays used in different fields of life sciences, and for forestry, it is important in management of forest inventories, assessment of forest biomass, monitoring fire hazards etc. (Szostak, 2020).

3. Remote sensing in forestry practices

Remote sensing started to be popular tool in forest management only a couple of decades ago. As the technology itself is developing rapidly, it's becoming more available in different fields of science, including forestry. Airborne laser scanners and LiDAR are being used in forest inventories as well as in monitoring of different parameters such as forest height, canopy cover, biomass, disturbances etc. (Arumäe et al, 2020).

Scientists working in forestry all around the globe are doing different studies using ALS as well as other remote sensing techniques in order to prove it useful, time saving and cost efficient.

Forest managers use data from remote sensing in combination with field measurement data for producing forest inventories. Aerial images are being used since the 1940s for deriving data important in forest inventories. Later, during 1970s global forest cover statistics has been developed because of occurrence of optical satellite images. These images were indeed low-cost, with low spatial resolution and were susceptible to interference of clouds. In the beginning only two dimensional information could be derived from these images, but in the later years it was possible to have three dimensions from satellite imagery by using digital photogrammetry (Hansen et al, 2015).

For example, biomass is one of the parameters in which foresters are often interested and in order to model it they need good quality terrain data as reference surface. These data can be acquired by the ALS and SAR (synthetic aperture radio detection and ranging) technologies. Both systems work on the principle of emitting pulses of electromagnetic radiation. Differences between these two systems are that ALS is airborne while SAR is satellite based. That being said, ALS probably has a small advantages like producing high resolution data and heights of both terrain and objects on it. On the other hand however, SAR has lover resolution and can produce only terrain heights, but it's cheaper and can cover bigger areas (Hansen et al, 2015).

Hansen et al. (2015) note that the forest parameters are usually modeled using methods like regression analysis, nearest neighbors, neutral networks or ensemble learning, all this following the area based approach, firstly tested by Næsset (1997).

Arumäe et al. (2020) did a study on repeated ALS measurements in north of Estonia. They established 15x15 km test site and did scanning during leaf-on and leaf-off seasons. There was thinning included in their stands before, between and after two scanning's. Their study indicated that the thinnings which were performed between two scanning's were detected and that there were clear differences in ALS point clouds between first and last ALS measurement.

In 2016, Guerra-Hernández et al did a study with aim to develop ALS-based models to estimate stem, crown and aboveground biomass. They state that ALS systems were successfully used for this purpose in different types of forests (Atlantic, Boreal, Temperate, Mediterranean, Alpine). They used low density ALS data in three types of Mediterranean forests. The study used two approaches in modeling:

      1. Linear models with different variable selection methods

         - Stepwise Selection (SS)

         - Clustering/Exhaustive search (CE)

         - and Genetic Algorithm (GA)

      2. Published Models (PM) applicable to diverse types of forest

They say that their results show more accurate biomass estimations for pure stands of *Pinus pinea* (Stone pine) than for mixed stands or stands of *Quercus pyrenaica* (Pyrenean oak). They note that the research provides some information about the biomass in the Mediterranean forests and should be continued and discussed in the future.

 "Being airborne, ALS has the advantage of providing high resolution data and heights of both the terrain and the canopy surface. Satellite-based SAR has, in comparison, lower spatial resolution, and it can only provide heights of the canopy surface" (Hansen et al, 2015). Data from these sensors have been of great help for the estimation of forest ecosystems biomass. Hansen et al. also state that when compared to other sensors, ALS gives the best results of root mean square error (RMSE) for modeling biomass, and additionally, RMSE varies with forest type. Hansen et al performed their study with the aim to estimate biomass in rainforest in Tanzania. Their results showed that remote sensing data should be used for increasing the

12

precision of biomass estimates as well as that the efficiency of using remote sensing increased with the plot size.

At the other part of the World, in Wisconsin, Hawbaker et al (2009) used low-density LiDar data to estimate forest biomass and structure at the study area of 53,600 ha. As the result, they got 65 to 88% of the variability in DBH, basal area, tree height, and biomass. They noted that models using random sample had larger prediction errors than those with stratified sample which gives stratified sample a greater range of variability. In the end, they conclude that LiDAR data combined with field data can give a good assessment of forest biomass and structure which, according to them is crucial information for biodiversity science.

Remote sensing can also be used in the urban areas. Holopainen et al. (2013) evaluated the accuracy and efficiency of airborne (ALS), terrestrial (TLS) and mobile laser-scanning (MLS) methods that can be utilized in urban tree mapping and monitoring. For their study area, they chose one park in Finlands Helsinki, where they mapped and measured 438 urban trees. They used several methods for tree detection but the ones which showed best results were TLSauto and MLSmanual with the 73,29% and 79,22% of detected trees respectively. They also note that the location accuracies (RMSE) varied between 0.44 m and 1.57 m. Their conclusion is that TLS and ALS can be used for the mapping of trees in urban environment, and that these environments are a suitable ground for testing the laser scanning methods which could later be transferred and applied into forestry practices. They also say that according to previous studies visibility was the problem for ALS, TLS and MLS in tree detection. In that sense, scanning made from the ground can be obstructed by shrubs, and scanning made from the air by canopy closure.

One of the recent studies from the last year aimed to compare ALS datasets to the field measurements dataset. Koma et al. (2021) focused on vegetation height, biomass and Leaf Area Index (LAI) parameters from three lakes in Hungary (Balaton, Ferto and Tisza). Their results showed big differences among ALS recordings, and according to Koma et al. (2021) were affected by differences in spatial resolution, temporal offset and seasonality between field and ALS data acquisition. In conclusion, authors gave recommendation for ecologists to better handle the data and to make standardization for acquiring the field and ALS data for wetland habitats.

Another recent study, this time from Finland aimed to produce a nationwide model for predicting the stand age by merging data from National Forest Inventory (NFI) and airborne laser scanning (ALS). The authors, Maltamo et al. (2020), note that for boreal forests stand age is rarely predicted unlike in plantation forests. "The result of nationwide model for the stand age of managed forests yielded a root mean square error (RMSE) of about 14 years". They say that the result could be better by adding more forest structure characteristics to the equation, but that it is not always available in practice. In the end, they conclude that prediction of stand age with their proposed approach is challenging but possible.

Mikita et al. (2013) tried to use ALS for the purposes of terrain modeling and for determination of some forest parameters such as height, diameter at breast height (DBH) and volume. They choose the area of 1,5 ha for which they described topography and heights and position of all trees using total station. They evaluated the accuracy of airborne laser scanner data in order to create digital elevation model (DEM). They used different data sources and scanners with different density per m2. After that, they compared tree heights from ALS with the surveyed ones, and also did calculations of DBH and volume based on the regressions. Data accuracy for DEM and height was satisfactory, but for DBH and tree volume of individual trees was not. Discussing their results, authors of this study state that ALS is, de facto, good for mapping of vegetation and terrain, and in forest practices it will have a use for determining average height of forests, tree species etc.

About quarter century ago Næsset (1997) did one of the first testing's of laser scanner technology in forestry field. The study aim was to check if laser scanning could replace traditional techniques such as field and photogrammetric measurements of forest stand parameters. Indication was that the accuracy of laser scanning data could be the same as the accuracy when using traditional inventory methods. As it was only the inception of this kind of research the results were not impressive, but however were very important for future studies. This study was done in a few forest stands and the control of laser scanning system was not yet perfected. So the author implies further improvements and calibration of scanning systems for the forestry practices.

Næsset (2002) did a study with aim to estimate the accuracy of six forest stand characteristics (mean tree height, dominant heights, mean stem diameter, stem number, stand basal area, stand volume) determined by laser scanning, using regression analysis. These characteristics were assessed over 144 plots of different young and mature stands and different canopy height and density. The results showed higher precision than when using conventional methods for all parameters except stem number. But, the author states that attention should be paid to ensuring the stabile laser footprint size, which is not easy in steep terrains and big topographic variations.

In southeast Norway, on the area of 852,6 ha Næsset (2013) did a case study with multi-temporal LiDAR scanning data. The aim of the study was to see how changes in biomass and other forest management parameters could be evaluated trough repeated measurements with LiDAR scanning. Discussing the results, the author says that they "indicate a significant gain in precision of areal estimates of deforestation, forest degradation, and untouched areas by adding LiDAR data to the estimation". Additionally, results for the category of forest degradation showed the biggest improvement in precision, but the sample sizes could be a challenge for the evaluation of change. (Næsset, 2013).

I the other part of Scandinavia, in Sweden, Nilsson (1996) used airborne LiDAR in order to estimate forest stand volume and height of trees. For the purpose of estimating the *Pinus sylvestris* (Scots pine) stand, laser scanner was attached to a helicopter and was operated in different scanning densities and had three separate measuring times (June, October, December). In cooperation with the Swedish Defense institutions research started in 1991. and the aim was the estimation of tree heights and stand volume using LiDAR. Also, it was interesting to test how different scanning densities affect height estimates. The results showed that the difference between laser data is less than one meter for mean tree height and that that the laser is usable for estimation of mean height. The author took a guess that in the future LiDAR techniques will be used in the National Forest Inventories because of their flight below the clouds in difference of satellites. Also, there was a thought that combination of satellites and LiDAR data could be useful when describing and monitoring changes in biodiversity (Nilsson, 1996).

According to Noordermeer et al. (2019), forest changes over time and space should be integral part of forest monitoring for various reasons, one of them being their impact on other ecosystem

functions. One of the ways of doing that was presented in the Noordermeer et al. (2019) study, where the bi-temporal ALS data were evaluated in order to classify changes in height, aboveground biomass, disturbances and other forestry activities. Authors used data from 5858 plots and four ALS-based inventories spanning from 11 to 15 years, from southeastern Norway. They discuss that in their results there is clearly visible change of forest structure and thus can be classified with certainty at plot level. The changes in dominant height (Hdom) and aboveground biomass (AVB) are expected to have accuracy of over 90% while forest disturbances and activities have accuracies of 89% and 88% respectively. They conclude that using bitemporal ALS data will increase in the future as part of the local forest inventories practice, and that is something they are encouraged by.

Maltamo et al. (2009) did a thorough study on using ALS data of high resolution for prediction of tree characteristics (crown height, height of the lowest dead branch, sawlog portion of tree volume) as well as basic tree attributes (height, crown height and diameter of the tree). The study was performed in the Koli National Park in Eastern Finland, on 14 defined plots of *Pinus sylvestris* (Scots pine) stands. Authors decided to use models based on both tree level and area based ALS. "A non-parametric k-MSN method and a parametric set of models constructed simultaneously by the Seemingly Unrelated Regression (SUR) approach were compared and appraised on the basis of mean prediction error and RMSE estimates". (Maltamo et al, 2009). Results report high accuracy for both tree characteristic and attribute categories, with especially interesting, and by the words of authors, very promising high accuracy for DBH. The conclusion again cast a positive impression that forest inventories will benefit of ALS and these kind of management.

It's already mentioned a few times previously that LiDAR could be used to provide information about forest characteristics. Scientists across the Globe are using these kinds of data for their own research ideas, and for example, Racine et al. (2014) used it to test the competence of LiDAR data to estimate the age of a forest stand. Some 158 plots were evaluated; all consisting of boreal forest stands in Quebec, eastern Canada. They used data derived from LiDAR and their results point out that age could be estimated well (R^2=0.83, root mean square error [RMSE] 19%) with a predicted error of less than 10 years. They conclude that their methodology showed good results of predicting the stand mean age by combining vegetation structure and site

indicators. They singled out forest parameters which contributed to the age estimation of which forest structure was of bigger importance and elevation for example was of lesser importance.

Tompalski et al (2016) in their study propose a new "approach to utilizing airborne laser scanning (ALS)-derived forest stand attributes to determine future growth and yield of six attributes at a sub-stand (25 m grid cell) level of detail: dominant height (HMAX), Lorey's height (HL), quadratic mean diameter (QMD), basal area (BA), whole stem volume (V), and trees per hectare (TPH)". They designed the model to find the best yield curve and to assign the attributes to the age of 80 years. Growth models are used in forestry to see what the stand would look like in the certain age in the future. These models are basically set of equations which can predict the forest growth with different assigned conditions. There are, in general, three groups of growth models:

- whole stand models

- size-class models

- single-tree models

Authors are noting that their results show larger estimates for stand attributes when compared to traditional yield projection methods, for both stand level and plot level. Differences between these two approaches results were connected to the data of stand-level age and site index, derived from the forest inventories. They conclude that sustainable forest management would have lots of benefits by improving of growth and yield modeling such as a long-term harvesting planning as well as better selection of harvest stands or stands for silvicultural works (Tompalski et al, 2016).

Tompalski continued with the same approach in another study only with slightly different data. The study was based on the data from ALS and DAP (Digital Aerial Photogrametry), obtained on two occasions (2008 and 2015) in the same forest stand. Prediction of height, basal area, total volume and stem density was done with area-based approach for both measuring times. Authors made two scenarios and for both they assigned yield curves. The first scenario implied estimation of parameters only from first scanning time and the second scenario combined both times. These yield curves were than compared to yield curves from the growth simulator. The

result showed a little bit higher accuracy for the second scenario but difference between the two scenarios was not major. Tompalski et al. (2018) state that the contributions of this kind of approach are seen in the accuracy change analysis of yield curves depending on the used ABA outputs (single or multiple) and also assessment of main triggers of the yield curve matching error. Approach described in this study could be of significant benefit to forest planners in the sense of more details in yield projections.

Another study by Tompalski et al. (2019) was done for the mixed boreal forest in Alberta, Canada. This time, bi-temporal and multi-sensor scans of low density were used to quantify changes in forest structure. Subjects of observation of changes were height, volume and basal area of the stand. Based on the results, authors state that this approach should be used with caution when there is a slow forest growth and high mortality levels. They conclude that the estimations of growth for basal area and volume were inaccurate and that the overall accuracy of predictive models is lower when there is high level of mortality in the plot and therefore it's necessary to minimize it in order to get high accuracy predictions. In the end, by the words of this study authors, more research is needed for this approach in the future, especially in unmanaged boreal forests.

Counting trees using ALS is also one of the topics Tompalski was interested in. Until that point, using ALS for tree counting led to underestimation of tree numbers. The errors which could happen were that some objects, such as branch for example, which is only a part of the tree is detected to be a tree, or one tree could be detected as many trees. On the other hand, existing tree sometimes could not be detected. In this study authors test different approaches in order to see what the best method for tree counting is. They report that the most accurate results they got using the OBIA method and while the using of ALS is possible it needs some improving. For better results with using the ALS, better resolution and point density is very important so that the model could describe the canopy better (Tompalski et al, 2009).

Study area

1. About the park

As mentioned in the Introduction, area chosen for execution of the thesis aims and ideas was National Park Bohemian Switzerland. The park is located in the Northern Czech Republic, on the border with Germany, behind which it continues under the name of National Park Saxon Switzerland.

Geologically dominant formations are sandstones with sporadic occurrence of claystones and limestones. Rock formations in the area within but also beyond the park imply the presence of a large water body in the geological past. These rocks form very interesting shapes and thus the park, besides scientific, has also great touristic potential. Almost all streams flow into Elba river which then flows to the North sea. The biggest river on the Czech side of the park is river Kamenice. National Park Bohemian Switzerland has the area of $80km^2$ and around 95% of forest cover. It is the youngest of four Czech Republic's national parks, established in the year 2000.
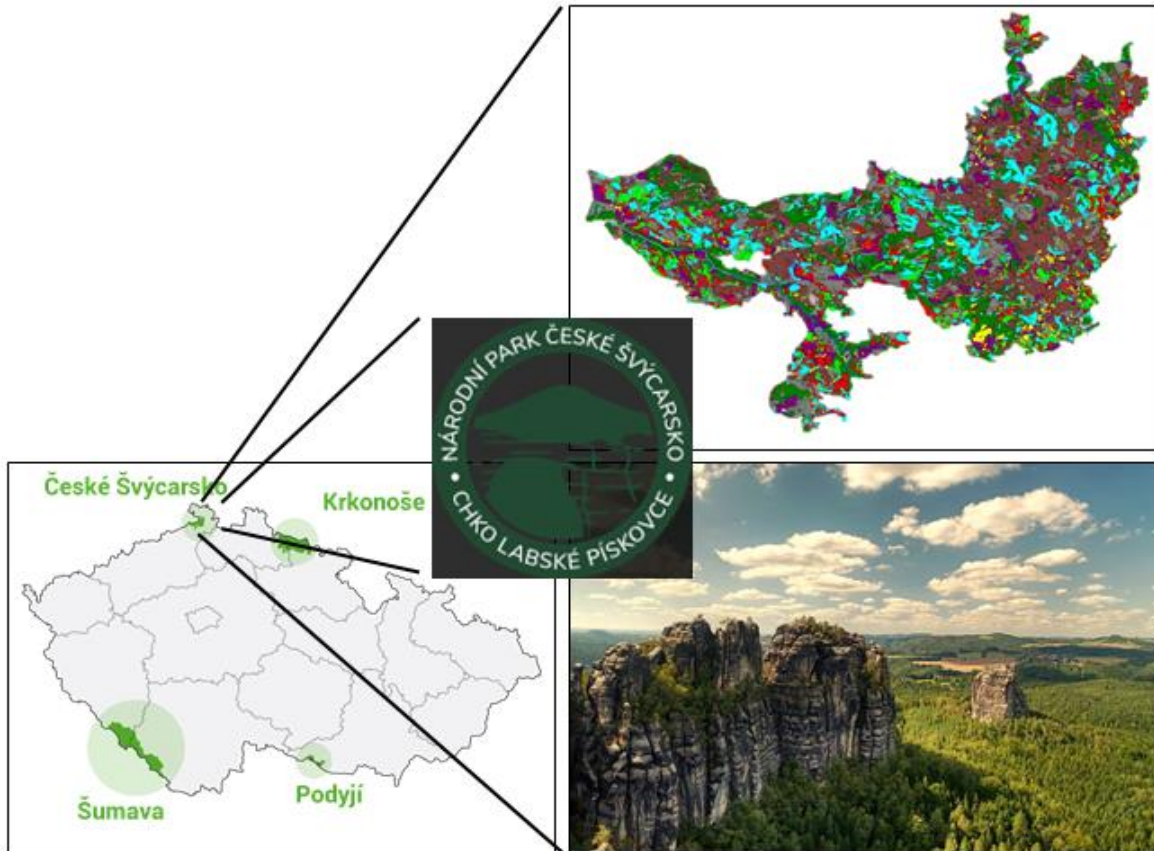
Picture 4 Location of the National Park Bohemian Switzerland with forest map and landscape display;
Sources - https://www.npcs.cz/lesy, https://cdn.i0.cz/graphics/public-data/e1/05/305aa9f020f8f45d0f4194cc24efe105/desktop-np-cr._6_.png,
https://upload.wikimedia.org/wikipedia/commons/thumb/3/38/Schrammsteine_LC0185.jpg/1200px-Schrammsteine_LC0185.jpg

2. Geology

Landscape of Bohemian Switzerland National Park is controlled by numerous geological structures such as volcanic domes, faults and erosion landforms. These structures also largely impact all life forms that lives in this area. Considering plants and trees, geology of this area makes a lot of refuge places where only the most resistant species can survive.

Large part of Bohemian Switzerland National Park is built of quartz sandstone, sedimentary rock that is formed by litification of sand that contains more than 95% of quartz. This rock represent very good base for various landforms and structures. Those sandstones are relatively young compared to the oldest rocks that are present in this area.

The oldest rocks: Area, of which the Bohemian Switzerland National Park is, began to form in late Proterozoic 700 million years ago. Those rocks from Proterozoic are composed of quartz, orthoclase and sodium plagioclase which sorts them into granite group. Granites mostly lie beneath younger sandstones and limestones. They are only present at the northeastern border of the national park.

Sandstones: Rocks that cover the most part of the national park are formed around 90 million years ago in upper Cretaceous when dinosaurs roamed the earth. At that time, Bohemian Switzerland was flooded by the shallow Cretaceous sea. This sea represented good environment for deposition of quartz sandstones. Sedimentation lasted only 3 million years. Similar rocks such as conglomerates and siltstones can be found in this area, which is connected to the constant sinking of the sea bed.

Volcanic activity: Tertiary period lasted from 65 to 2 million years ago. That time was marked with intense volcanic activity in Bohemian Switzerland. Interesting volcanic forms have been preserved such as typical hexagonal basalt columns. This kind of geological structures are created when magma shrinks and cracks during the cooling process. One of the dominant peaks in national park Růžovský vrch is formed by volcanic activity.

Geomorphology: After the Cretaceous sea started to retreat, sandstones were exposed to weathering and erosion which led to the creation of the different kinds of structures such as gorges, canyons, towers, windows, etc. Strong river erosion occurred in early Quaternary, after the interglaciation, which created big height difference. The base is composed of the Elba canyon, in the middle part are present plateus and the upper part contains table mountains and sandstone peaks. The most of the peaks in the national parks are between 450 to 480 meters above sea level. The highest peak in the national park is basalt peak Růžovský with 619 meters above sea level. And the lowest point is Elbe canyon with 110 meters above sea level.

3. Forestry

Dominant species in almost 60% of forest cover is *Picea abies* (Norway spruce). Natural forest composition was gradually changed from beach to spruce stands over the past century. Tree species composition in forest stands is presented in the graph 1.
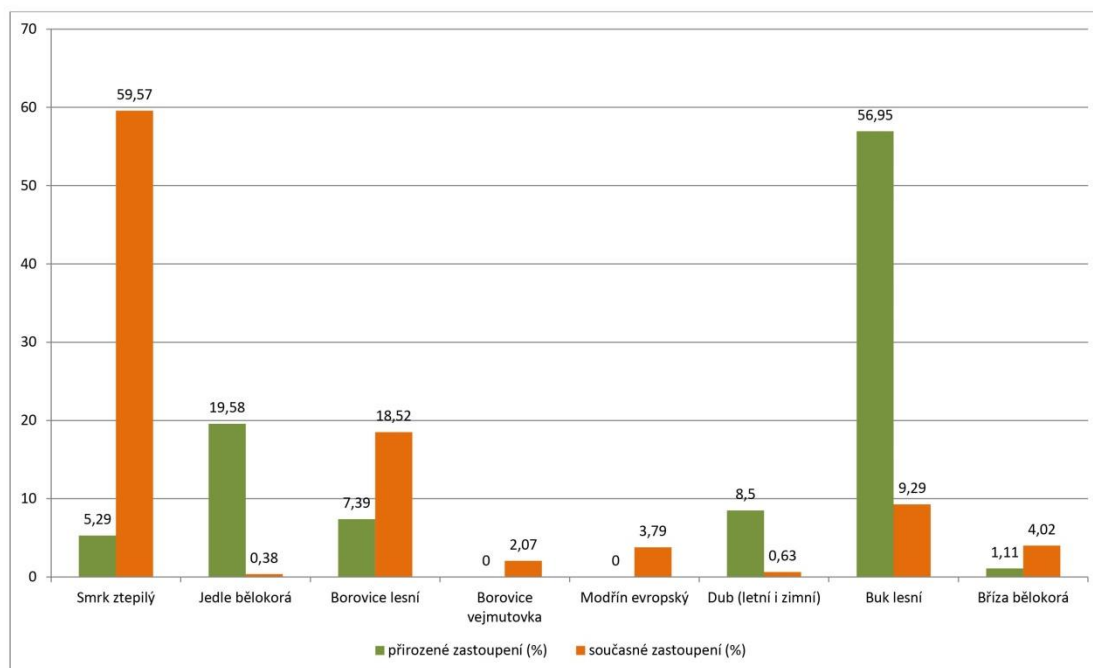
Forests are the biggest habitat type in the Bohemian Switzerland National Park, with the cover of over 95% of its area. However, the species and age composition of the local forests has undergone significant changes during its history, which were related to their economic use (examination of the original and current species composition of forests in the Czech Switzerland National Park).

The remains of the original forests have been preserved today, especially on inaccessible rock peaks in the form of so-called relict pines and in deeply cut gorges, where the original form (ecotype) of Norway spruce still grows. Remains of deciduous forests have been preserved in some places, especially beech forests, but also more thermophilic oak groves and floodplain forests bound to watercourses. In most areas, however, the original mixed forests have been replaced by monocultures of coniferous trees, especially Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*).

Flooding forests

The willow meadows have been sporadically preserved along the Elbe river. Along with the predominant willows, such as White willow (*Salix alba*), Brittle willow (*S. fragilis*) and Basket willow (*S. viminalis*), there can also be found black poplar (*Populus nigra*).

The rarest communities include valley ash-alder meadows and spruce-alder stands. Extensive floodplain floodplain forests with typical species of the herbaceous layer are *Stellaria holostea*, *Pulmonaria obscura*, *Corydalis cava* or *Anemone nemorosa* only in the southern part of the area, on the border with Central Bohemian Highlands. Along the Kamenice River, alder stands could be found, with indicator plants species such as *Primula elatior*, *Chaerophyllum hirsutum*, *Leucojum vernum* and *Aruncus vulgaris*. Remains of so-called swamp alders with elongated sedge (*Carex elongata*) have been preserved in the vicinity of the Olešský pond in the Protected Area Labské pískovce.

Oak-Hornbeam forests

The oak-hornbeam stands in the area are connected only with warmer locations on nutrient-rich soils on the southern edge of the area, which biogeographically already belongs to the Bohemian Central Mountains, in the belt running from Libouchec through Děčín to Česká Kamenice. In some places, there are also so-called black oak stands with typical species *Melampyrum nemorosum*), *Hepatica nobilis*, *Asarum europaeum, Corydalis cava*. Hornbeam (*Carpinus betulus*) and the Winter oak (*Quercus petraea*) are main species found in the tree layer.

Acid Oak forests

Acid, oak stands were widespread in the area in warmer locations, like the Růžovská plateau, in the Elbe canyon.. The tree layer consisted mainly of Sessile oak (*Quercus petraea*), Pedunculate oak (*Quercus robur*) and Scots pine (*Pinus sylvestris*). Today, however, these habitats are completely dominated by cultivated pine forests, but their herbaceous and mossy layer largely corresponds to the original communities. Species which could be found in the bottom layer of these forests are Cowberry (*Vaccinium vitis-idaea*), Blueberry (*Vaccinium myrtillus*), Common Heather (*Calluna vulgaris*), Common Cow-wheat (*Melampyrum pratense*), White Wood-rush (*Luzula luzuloides*), Purple Moor-grass (*Molinia arundinacea*). In the middle forest layer species like Alder buckthorn (*Frangula alnus*) could be found.

Karst forests

The Elbe canyon is dominated by karst forests with a significant representation of Small-leaved Lime (*Tilia cordata*), Hornbeam (*Carpinus betulus*), and Field Maple (*Acer campestre*). The peaks of volcanic origin (eg Růžovský vrch) are inhabitet by sub-mountain karst forests, consisting mainly of Sycamore maple (*Acer pseudoplatanus*), Scots elm (*Ulmus glabra*) and Ash (*Fraxinus excelsior*). Very rare are the so-called gorge and slope forests with a dominant species like *Arunucus vulgaris* and *Lunaria rediviva*.

Beech forests

Beech forests occupy only a very small area of the total area, but they significantly increase the biodiversity of the area. The richest are the stands bound to the basalt rocks (eg on Růžovský vrch, Mlýny or Suchý vrch) with typical species of herbs *Dentaria enneaphyllos*, *Dentaria bulbifera*, *Galium odororemum*, *Lathyrus vernus Galeobdolon luteum*, *Anemone nemorosa* and *A. ranunculoides*. At the turn of spring and summer, many species of grasses bloom here, especially *Melica uniflora*, *Festuca altissima* and *Hordelymus europaeus*. In some places the protected species of *Lilium martagon* could be seen. Less rich beech forests are the ones with the dominant grass *Festuca altissima*, which can be found only in the Elbe canyon.

Acid Beech forests

In the past, acid beech forests were transformed into spruce monocultures in most areas and have been preserved only to a very limited extent, eg scattered throughout the Jetřichovice municipality, around Bělá, in the so-called Libouchecké beech forests, in the Elbe canyon. These forests have underdeveloped ground layer with only few species like *Luzula luzuloides* or *Avenella flexuosa*, or *Calamagrostis arundinacea*. Beach (*Fagus sylvatica*) is dominant species in the top layer but there are also, Maple (*Acer pseudoplatanus)*, Norway Spruce (*Picea abies*) and, with rare occurrence White Fir (*Abies alba*) which can be found in the gorges. Interesting is that these beeches here occure naturally at unusually low altitudes around 300 m above sea level, which is related to the overall Suboceanic character of the whole area and the phenomenon called climate inversion. The beeches in the Elbe canyon are the lowest beeches stands in the Czech Republic (below 150 m above sea level)!

Relict Pine forests

Relict Pine forests on sandstones are a characteristic type of forest communities in Bohemian Switzerland, although they are not very present on the large area. These forests are very poor in species. The tree layer is dominated by Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pendula*), along with Rowan (*Sorbus aucuparia*). There are two basic types of relict pines which can be distinguished in the area: dry pines are bound mainly to sunny localities oriented to the south, while so-called wet pines, on the other hand, occur in shaded localities. The ground layer of dry pines consists mainly of *Calluna vulgaris*, *Vaccinium myrtillus*, *V. vitis-idaea* and *Avenella flexuosa*. The occurrence of lichens of the genus Cladonia sp. is typical for these stands. Characteristic plants of wet pine are *Ledum palustre* and rarely *Empetrum nigrum*. Relict forests on the Czech side occur mainly in the Bohemian Switzerland National Park and several smaller places around the park.

Norway spruce (*Picea abies*) naturally occurred in Bohemian Switzerland only in inverse gorges, either as an admixture of so-called acid beeches, or in deeply cut gorges, where it formed small-area waterlogged spruces. To this day, the remains of these spruces have been preserved mainly in the Bohemian Switzerland National Park. Characteristic plants of these stands are *Trientalis europaea*, *Lycopodium annotinum*, *Huperzia selago* and *Streptopus amplexifolius*.

<u>Artificially made forests</u>

Most of the forests growing in the Bohemian Switzerland today are the cultural forests, or forests made by man, or artificially made forests, whose tree and age composition is very much dkfferent from original old-growth forests. Cultural forests can be found on sandy and dusty clays. Natural forests on the other hand were mostly found their place on different substrates of volcanic and metamoprhic origin. Thus, it can be said that cultural forests were established in habitats whose natural species diversity was mostly low, while localities with rich natural vegetation were largely preserved.

Plants typical of the so-called acid beeches predominate in cultivated spruces. However, large-scale spruce cultivation has probably contributed to the widespreading of some species associated with natural spruces, such as *Blechnum spicant* or *Calamagrostis villosa*. Surprisingly, these otherwise species-poor stands also host some important species, especially

along forest roads, such as the sub-Atlantic species *Hypericum pulchrum*, *Rubus lusaticus* and the *R. geminatus* - critically endangered species of Czech flora.

In cultivated pine forests, mainly typical species of pine-oak forests are present. Along with pines of cultural origin, in the past, foreign species of Weymouth pine (*Pinus strobus*) were also used in the area, which today represent the source of an almost nationwide invasion.

Cultures of other non-native tree species, such as deciduous larch (*Larix decidua*) or red oak (*Quercus rubra*), do not occur in a large area. In some places, other non-native tree species were planted in the forests, such as Douglas-fir (*Pseudotsuga menziesii*), horse chestnut *(Aesculus hippocastanum)* or chestnut (*Castanea sativa*).

4. Hydrology

The main river of Bohemian Switzerland National Park is Elba. Other important flows are, on the Czech side river Kamenice and its inflows, in Saxon rivers Biela and Lachsbach with inflows Sebnitz and Polenz. Elba watershed covers most of the park, so almost all water from is flowing toward North sea. Near Děčín, Elba forms a deep canyon as a result of constant river erosion processes and tectonic charactericstics of the area. Kamenice is the biggest and the most important river on the Czech side. It's spring is under the mountain Jedlová, in the upper parts it flows through Lužicke mountains, then trough CHKO Labské pískovce and near the small village of Srbska Kamenice, it enters the area of National Park. In this part,Kamenice river forms three gorges and later inflows to Elba river in the municipality of Hřensko. Tributaries of the river Kamenice are small mountain streams with clear, cold water and as such are ideal for salmonide fishes. The largest water reservoir in the area, Olešský rybník, is located on the younger Cretaceous rock formations (siltstones) and thus belongs biogeographically to the Bohemian Central Mountains. The Olešský rybník nature reserve is an important habitat for many endangered species of plants and animals, especially birds. Smaller reservoirs are located in the left bank near Ostrov (Ostrovský rybník - interesting with peat areas in its vicinity) and in Maxičky. In terms of species diversity, however, the Královomlýnský pond and the nearby water reservoir are really important as the only places in the Czech Republic where the species *Luronium natans* (floating water-plantain) occurs. On the right side of the Elbe there are smaller reservoirs between Nová Oleška and Srbská Kamenice, in Jetřichovice (Pavlínka), in Dlouhý Dol

and Kopec. The Bohemian Switzerland National Park itself is practically without larger areas of stagnant water, but only few smaller forest fisheries and ponds. Bohemian Switzerland is an area of outstanding importance in terms of the formation and circulation of groundwater. This is because of sandstones, which create the majority of lands, where they reach big depths and are highy permeable.

5. Wildlife

Forest habitats completely prevail in the territory of Bohemian Switzerland. In places of natural forest, valuable and characteristic rock habitats for the local landscape could be found. Diverse meadow communities are typical of the protected landscape areas surrounding the Czech and Saxon Switzerland national parks. Streams and other aquatic habitats are negligible in size, but they fundamentally increase the otherwise relatively poor species diversity of the whole area. The flow of the river Elbe is especially important from this point of view. Specific habitats arise in the landscape affected by human activities. Many valuable habitats are threatened by the spread of non-native plant and animal species.

In a relatively small area, there are both thermophile and drought-loving species, as well as mountain, foothill, northern or alpine species, or Atlantic and sub-Atlantic species (ie species associated with humid climates with relatively smaller differences between summer and winter, which have a center of distribution in Western Europe).

In general, the species representation of higher plants is, as in other sandstone areas, relatively poor. On the contrary, the community of mosses is rich.

About 300 species of bryophytes were found in the Czech Switzerland National Park, of which 71 are included in the Red List of Rare Bryophytes of the Czech Republic. In the environment of sandstone rock towns, mosses find ideal conditions for growth, especially in deep shady gorges, but they could also be found in forests, on wet and peaty soils, in the vicinity of watercourses, on rocky outcrops, in rock crevices, etc.

The community of higher plants in Bohemian Switzerland National Park is characterized by a high proportion of sub-Atlantic species (eg Chrysosplenium oppositifolium, *Galium saxatile, Potentilla anglica, or Blechnum spichant*). The occurrence of foothill and mountain species at

low altitudes in deeply cut gorges is also interesting. Thermophilic species, on the other hand, occur on sunny basalt hills, in the Elbe canyon and in the southernmost part of the protected area Labské pískovce. The spread of non-native species is a major problem, especially in the vicinity of watercourses and human settlements.

The territory of the Bohemian Switzerland National Park (and the neighboring Saxon Switzerland National Park) is very forested and rocky and relatively little disturbed by human activities. The protected areas surrounding both national parks are characterized by an agricultural landscape with scattered buildings. All this allows the occurrence of many species of animals, with often very different environmental requirements, in a relatively small area. Species diversity is significantly increased by species associated with their occurrence on watercourses and their surroundings, ponds or peat bogs. The Elbe corridor, in turn, serves as an important migration route and wintering ground for many bird species.

In addition to completely new species discovered in this area, there are also species limited by their distribution only to this area. Many species considered extinct or very rare in the Czech Republic were also found here. There are also a number of protected species, including highly and critically endangered ones.

In Bohemian Switzerland, there are both mountain and thermophile species of invertebrates, or species associated with specific conditions, such as incinerators. The best researched group of invertebrates is insects, especially some beetle families.

More than 330 vertebrate species have been described in the territory of the Bohemian Switzerland National Park and the neighboring protected area Labské pískovce. Among them, there are both common and highly or critically endangered species. The most species-rich groups of vertebrates are fish and birds.

Materials and methods

1. Laser scanning

Laser scanning of the whole park was done in 2005 and 2019. The laser data for National Park Bohemian Switzerland from 2005 were in the binary data format 3d3 (format from Toposys) and have a structure according to the type of scanner used. Therefore, for further processing, data in these formats were converted to text format using TopoSys Converter V.2.2.0. Because of large amount of data, it was necessary to divide the territory into smaller parts and convert it. Data from 2019 were acquired by Czech University of Life Sciences Prague in April 2019.A four-channel, medium-format camera with erasure compensation and parallel laser scanning Leica ALS60 was used for imaging. The longitudinal overlap of the images was 80%, the transverse overlap of the images was 80% and the average resolution of the images at ground level was 10 cm. Regarding aerial laser scanning, the point density was 3 b/m2, the scanning image angle was a maximum of 50° and the transverse overlap of the individual scanning series was 30%.
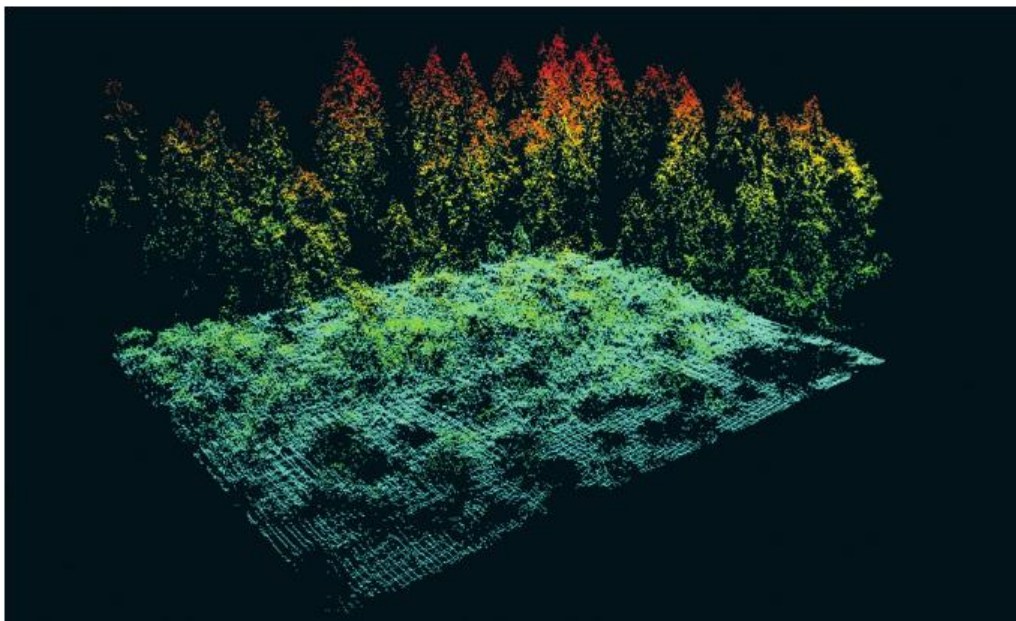
Picture 5 Example of height measurement using ALS; Source - https://www.researchgate.net/profile/Erik-Naesset/publication/248969913/figure/fig1/AS:298269474344971@1448124392656/Height-measurements-from-an-airborne-laser-scanning-ALS-data-set-of-a-spruce-forest.png

Table 1 Scanner information (2005)

Company	Toposys Topographische Systemdaten GmbH, Biberach
Number of flights	16
Time range of flights	14.04.2005 - 01.05.2005
Mean flight heights above ground	1200 m
Resolution of the heights of the laser measurement points	0.01 m
Number of data stripes	281 plus across-stripes
Pixel size of the ortho imagery (L1_DAT)	0.50 m
Dimension of the ortho image tiles (L1_DAT)	2000 x 2000 m2
Number of tiles (L1_DAT)	238
Primary spatial reference system	ETRS-TM 33, ellipsoidal heights
Sensor type	FALCON II
Specification of the laser unit	
Range	1600 m
Scan width	14.3°
Effective measurement rate	83000 per second
Laser wavelength	1560 nm
Data recording	Dirst Echo; Last Echo and Intensity

Table 2 Scanner information (2019)

System	ALS60
FOV	50°
Flight altitude	2600 - 3070 m
Flight speed	100 - 150 kn
Scan rate	33.7 Hz
Pulse rate	93900 Hz
INS	IMU POS-AV 510
GNSS	NovAtel MILLENIUM at 0.1 Hz

Picture 6 Types of scanner used - 2005 (left) and 2019 (right);

LiDAR data were collected as a LiDAR point cloud. Point clouds are stored in the most cases in .las and sometimes in .laz formats. All LiDAR data points had coordinates, X and Y which determine the location of the point, and Z which determines the elevation. And most data points will also have Intensity value which represents the amount of light energy which sensor recorded. LiDAR point cloud data were also classified. This means that each point contained information about the object from which the light was reflected. So, there could be different classes like ground or vegetation etc.

2. Processing LiDAR data

Rasterization and filtering of LiDAR data was done through the open library PDAL.

During last years, open source libraries became really important tool for processing point cloud datasets. One of them is Point Data Abstraction Library or simply PDAL. Large point cloud datasets, which can consist of millions of points, require some tool which can process and analyze it. This library is capable to read, write and filter point clouds as well as transform them. "PDAL is a C++ library with a JSON-based processing pipeline domain-specific language, Python, Java, Julia, and MATLAB support, and a convenient command line application." (Butler et al. 2021) This kind of approach enables scientists from various fields to use PDAL for their causes. It had been released in 2015, but among the US Army research institutions and since it's being updated on the half year basis (Butler et al. 2021).

2.1. Filtering

Accurate display of the Earth surface is always a challenge and a lot of research has been devoted to it. LiDAR lasers have multiple returns which represent ground terrain and other objects on the ground. In order to process LiDAR data, filtering must be done. This means that ground points should be separated from other points such as vegetation, buildings, and other bodies. When the filtering is done properly, then models such as DTM, DSM etc. could be created. Different methods could be done to filter the data, including morphological filtering, TIN models, surface interpolation etc. (Ming et al. 2013). Filtering of point clouds could also be done in GIS software's one of them being ArcGIS.

PDAL library has two filters ready to use – progressive morphological filter (PMF) and simple morphological filter (SMRF). "PMF generates an initial elevation grid from the point cloud by selecting the points with minimum elevation in each cell. If the cell contains no points, the nearest neighbor interpolation is used to derive the elevation. Subsequently, the morphological operation of opening (erosion followed by dilation) is used to filter the grid surface. This operation is repeated iteratively (each time with a different window size and a different height threshold)." (Moudrý et al. 2020)

"SMRF differs from PMF by using ''painting technique" to interpolate empty cells in initial elevation grid, it only allows a linearly increasing window size up to a specified maximum (Window size), and the change of the elevation difference threshold for classifying the points as non-ground is controlled by a single parameter (Slope) which simplifies exploratory analysis". (Moudrý et al. 2020)

In their study, Moudrý et al. (2020) tested six filtering algorithms and among them were both SMRF and PMF. All of them showed good results, but the authors note that their performance was affected by slope and vegetation. They also mark that filters work better in forest covered terrains than in steppes and single out SMRF as promising for the forest areas.

2.2. Rasterization

How does it work? – "PDAL's distinguishing design choice is to model the processing of point cloud data using the concept of a pipeline, or a directed graph. Point cloud data is read from a set

of input sources using format-specific readers, the data is passed through various filters that transform data or create metadata, and the data is then written to an output stream using format-specific writers." (Butler et al. 2021).

Point clouds for PDAL processing are mandatory to have XYZ coordinates, but other, optional, data could be there too. In the future, PDAL will stay open source tool and will try to connect with other open source formats such as QGIS, an open source GIS software. (Butler et al. 2021).

Point clouds from laser scanning were converted to raster using PDAL. This could be done by different methods. One of the methods is called gridding. This method means that there is a grid placed over the LiDAR data which divides it into cells. Each of these cells has the same spatial dimension. The resolution (1x1 m for example) can be chosen. For each cell that has a LiDAR point inside, the value will be created. Naturally, some cells will be empty because of LiDAR density, and for them the value will be "no data".

There is also a method of interpolation. This method is creating values also for the cells without the LiDAR point. It uses mathematical operations to find values for these cells based on the existing values. This method can be useful for the areas for which there is no data, but these data often come with less accuracy.

3. Canopy height model

Canopy height model (CHM) was created for the whole area of National Park Bohemian Switzerland, based on the laser scans from 2005 and 2019. Derived raster formats from the lasers needed for creating the CHM are Digital Elevation Model (DEM) and Digital Surface Model (DSM). DEM represents the ground elevation and DSM represents elevation of top points of trees, buildings and other objects. Difference between these two raster's is CHM (DSM – DEM = CHM) and its values represent the height of the trees (or other objects), or in other words, it is the distance from the top of the object to the ground.
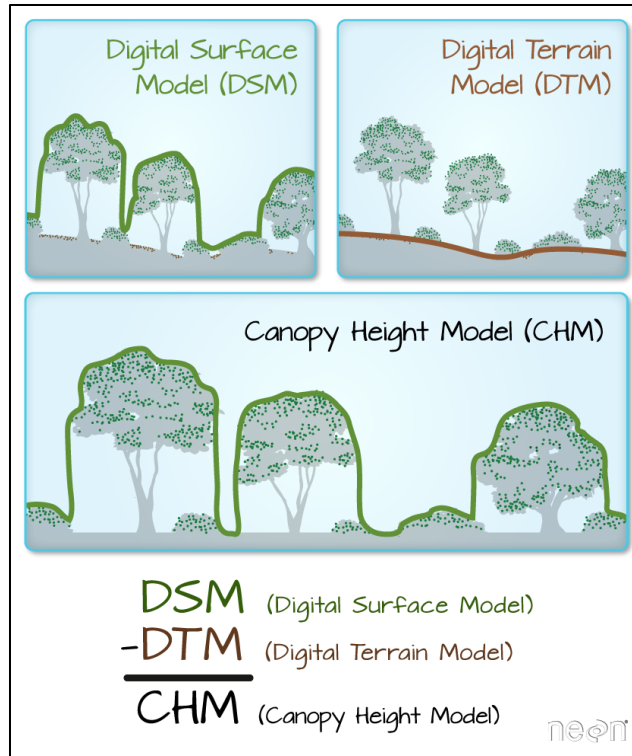
Picture 7 Example of canopy height model derivation, difference between DSM and DTM rasters makes as a result raster for CHM; Source - https://i.stack.imgur.com/1l3EA.png

4. Field data acquisition and processing

Field measurements for the acquisition of validation data in the Bohemian Switzerland National Park took place in the months of September to November in 2020 and in the months of June to October in 2020. Parameters that were measured included tree height, crown height, diameter at breast height (DBH) and increment (measured later based on the drilling of trees on the field).

An inventory hexagon network has been created in the entire area of the Bohemian Switzerland National Park. This network was created based on previous processing of laser data based on stand heights and their standard deviations in the ArcGIS program by stratified selection. A 10-ares circular sample plot was created in each hexagon. The centers of the areas were located by GPS and refined by orthophoto map. The orthophoto map from aerial photography showed the forest stand according to the intensity of the infrared light reflection. Such a display allows a visual assessment of the difference between deciduous and coniferous trees and what kind of tree it is.

The height of the tree was measured on each area, either with a Vertex Laser GEO laser altimeter using a laser in stands with good visibility or with ultrasound in dense stands.

The diameter was measured with the Haglöf caliper or the circumferential band if the diameter exceeded the length of the scale on the caliper. To limit the occurrence of errors, the long arm always points to the center of the sample plot when measuring the diameter.

Three to four trees were selected on each area, and were drilled by the increment borer to determine increment. The bores were glued to the boards with pre-prepared grooves. Each bore had a tree number, name of the plot, and a tree number. Boards with bores were later scanned with the 2400dpi scanner and images were imported to the ArcMap software for further increment measurement.

Picture 8 Increment bores

The orthophoto map of the park together with the hexagons was uploaded to the ArcGIS Collector Application. Sample plots and measured tree quantities were also marked on this application.

Validation data measured on areas throughout the Bohemian Switzerland National Park served to verify the accuracy of the Digital Surface Model and the Canopy height model.
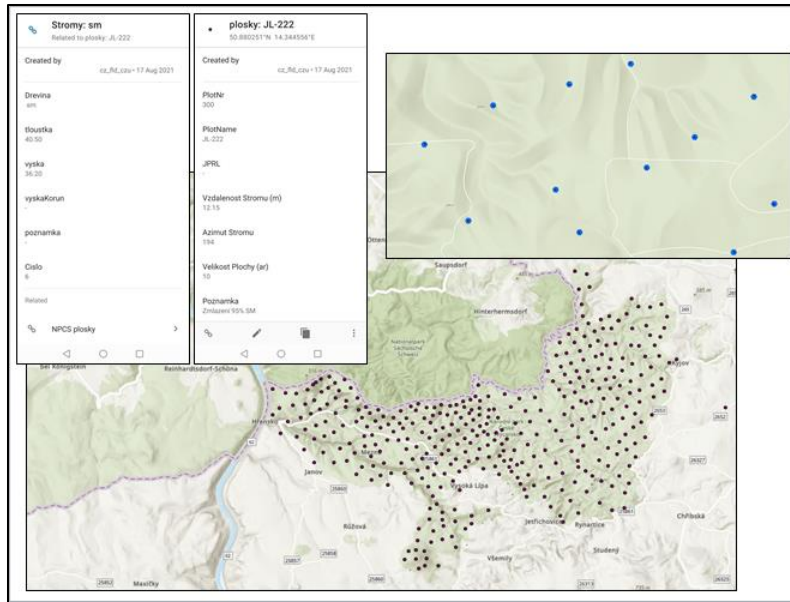
Picture 9 Established field plots

5. Area based approach

Estimation of the growth from laser scans is done using the Area-based approach.

Data about forests could be modeled using two approaches: Individual tree detection (ITD) and the Area-based approach (ABA) (Yu et al. 2010; Surovy & Kuželka, 2019). Forest parameters usually modeled using area based approach are – top height, dominant height, mean height, lorey's mean height, quadratic mean diameter, basal area, gross total volume, aboveground biomass etc. (White et al. 2017).

Individual tree approach is based on detecting the tree tops and the extent of tree crowns. This method can have errors, or difficulties, if the stands have really dense canopies with different height peaks close one to another. The Area-based approach is different and aims at the whole stand (or other areal unit). This approach usually has two steps:

- Obtaining data for the entire area of interest from ALS. Then, plots for field measurement data are formed, and desired characteristics are measured. In the end of this step, both ALS and field data are combined and processed through regression models.

- In the second step, wall to wall ALS data are calculated and applied to the area of interest which results with the estimation of particular forest attribute.
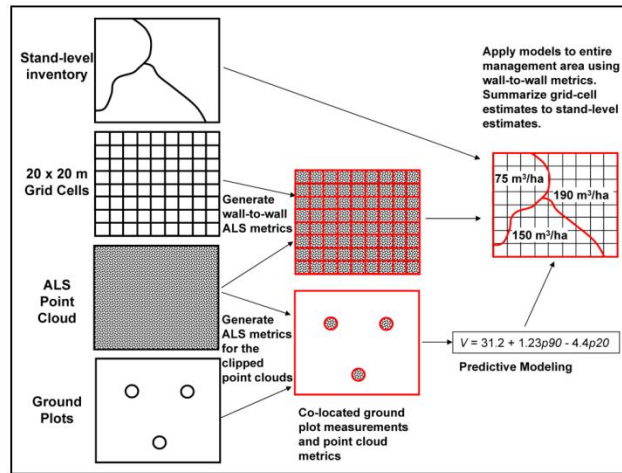
Picture 10 Scheme of the area-based approach; Source - https://www.mdpi.com/forests/forests-04-00518/article_deploy/html/images/forests-04-00518-g001.png

Yu et al. (2010) compared ABA and ITD, based on the same data, and did the evaluation of both methods capability to predict forest parameters at the plot level. The area based approach use the canopy height to estimate plot parameters such as mean height, mean DBH and volume. Individual tree-based approach, however, focuses on detection of individual trees, describing their height, or even crown shape, and calculate parameters such as stem diameter or stem volume etc.

Both methods gave a similar accuracy results considering mean diameter but for mean height and volume ITD was better. In general, both methods gave good results in estimating all forest parameters. Point density of laser data was lower than usual and for better results, better density is always a plus. Considering individual tree-based method, it is necessary to form plots with simpler structure so the trees could be detected with higher precision. Area-based approach is generally cheaper and more efficient in that way, because lower data density is acceptable (Yu et al. 2010).

5.1. Zonal Statistics as table

This function derives values from a raster for established plots or areas from the different dataset, and presents the results in a table. If all areas from the input have the same value then one zone is established and that is the case for each different value. Area doesn't have to be one whole, it can be separated into plots.

"If the Input Zone Raster or Features has overlapping features, the zonal analysis will be performed for each individual feature. If the Input Zone Raster or Features is a point feature, it is possible to have more than one point contained within any particular cell of the value input raster. For such cells, the zone value is determined by the point with the lowest ObjectID field (for example, OID or FID). When specifying the Input Zone Raster or Features, the default zone field will be the first available integer or text field. If no other valid fields exist, the ObjectID field (for example, OID or FID) will be the default". https://pro.arcgis.com/en/pro-app/2.8/tool-reference/raster-analysis/zonal-statistics-as-table.htm

Input raster can be of different type, it could be integer or point. If the raster is the type floating-point, deriving parameters of max, min and var is not possible. The output of this function will always be a table consisting of fields with statistical parameters. Zones in the table are described trough the number of rows.

Detailed description of the function zonal statistics as a table could be found on the ArcGIS pro website, under raster analysis toolbox summary.
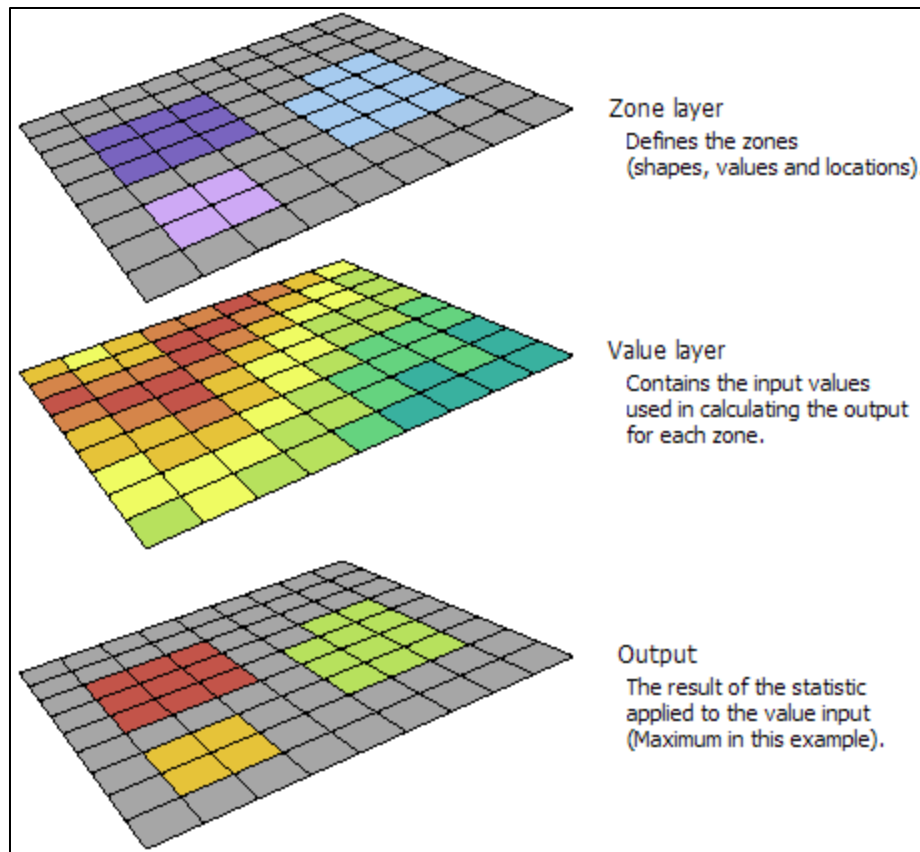
Picture 11 Schematic overview of the Zonal statistics as table function; Source -
https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/GUID-407BA24C-A633-43A8-
8D11-7A6FE3EF3609-web.png

5.2. Stepwise regression

Method of stepwise regression was invented around sixty years ago because of need to determine which variable can be meaningfully used in multiple regression models. This model is created to efficiently choose the variable which is the most appropriate to explain parameter relations.

Smith (2018) notes that the principle of choosing the right variable is to use the same dataset and do the same calculations over and over again, with discarding or selecting certain parameters. In the beginning, each variable should be evaluated usually by t-value. There are basically two ways of doing stepwise regression – forward and backward. When doing stepwise regression by forward selection variables are calculated by adding one statistically most significant variable, than check the result, then repeat the process until there are no more statistically significant variables. On the other hand, stepwise regression by backward-elimination in the beginning includes all possible variables and as such is diametrically opposite of forward selection. The

variables are discarded one by one based on the least statistical significance. The end of the process occurs when all of the variables left are statistically significant. According to Smith (2018) backward elimination can be difficult to perform in the case of a large number of variables and basically impossible if the number of variables exceeds the number of observations. There is also a method of combined forward selection and backward elimination and it's called bi-directional stepwise procedure.

In short, statistical significance is the considered trait of the variable which the model of stepwise regression tends to determine. This model is really useful and popular when working with large datasets because it relatively easy trims the possible variables to a small number. (Smith, 2018).

6. Linear regression model

As the validation, data were measured on the field, the next goal was to create a model which will check the relation between scanned data and predict the increment based on the scans. In other words, based on the height (CHM) it should be possible to predict the increment. For that purpose, linear regression model was used and R^2 and p-value were calculated. R studio statistical software was used for calculating these values.

First step in linear regression is to use least-squares to fit a line to the data. Than calculate R^2 and in the end p-value for R^2.

Least squares is done by drawing the line between the data and measuring the distance from the line to the data (residual), then squaring each distance and summing them up. Then, it's necessary to do more iteration while rotating the line and in the end find the least sum of squares. This value will be the one to fit to the data. Least squares estimated two parameters: y-axis intercept and a slope. If the slope is not 0, guessing, in this case increment, is possible. How good this guess will be is determined by the R^2 value. R^2 has the value between 0 and 1, or in other words 0–100%. If the R^2 is closer to 1 that means the relationship between the data is bigger. But, in order for R^2 to be statistically significant the p-value must be calculated as well. If the p-value is small the relationship between the data is more reliable.

Results

1. Results of laser scanning

Laser scanning was done in 2005 and 2019. Rasterization of these scans was needed because LiDAR stores data as point clouds and we need data in different format in order to read them. Point clouds already have those data stored so the PDAL (Point Data Abstraction Library) was used to make a raster for further GIS processing. Digital terrain models and digital surface models were derived and are presented in the picture 10.
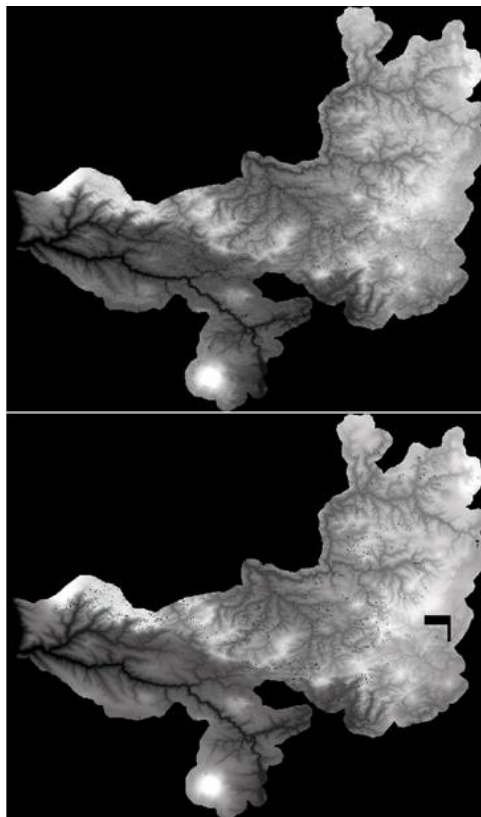
Picture 12 DSM (up) and DTM (down) scanned in 2019

Results of the Canopy height model were derived and processed into ArcGis software. Map of heights change was made and is presented in the Picture 11. Height change is presented on the map by colors. Red shades represent decrease in height (probably due to harvesting or some disturbances like windbreaks etc.), while green shades represent increase in height.
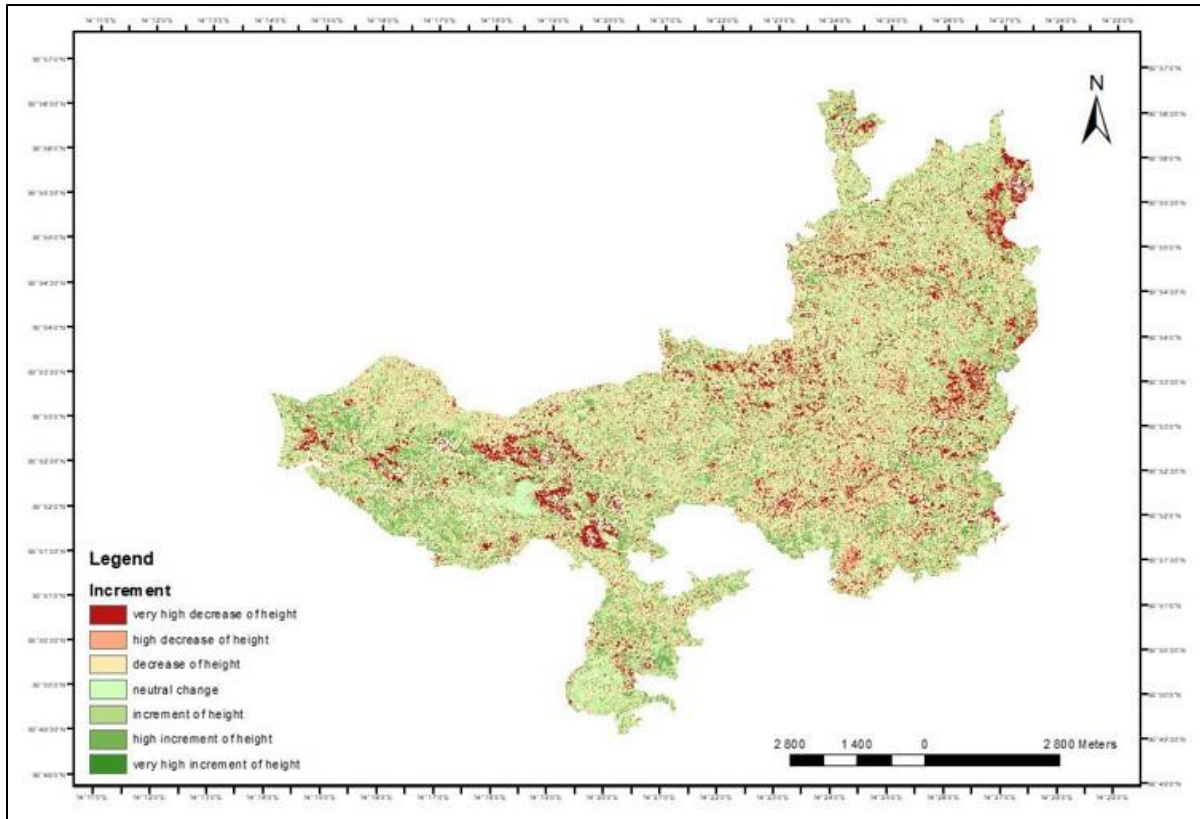
Picture 13 Height change (height difference)

2. Field measurements results

Results of field measurements were sorted into excel tables and processed through further modeling. Total increment for every stand was measured. The period 2005–2020 was used to measure the increment of every tree, and then summed up as total increment. Plots included for further processing and modeling were selected according to standard deviation of mean stand increment. All stands with the standard deviation of mean increment ≤5 were selected. Data from the field were sorted into 48 spruce forest stands which are shown in the Table 4.

Table 3 Data from some of the plots

Plot	2020	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006	2005	Tree_sp	Total increment (mm)	DBH (cm)	Height (m)	Crown height (m)
BF-253	1.045	0.817	0.670	1.956	1.511	1.631	1.579	1.765	1.284	1.084	0.817	1.084	2.006	1.862	1.124	1.020	sm	21.252	24	16.7	9.5
BF-253	0.567	0.768	0.640	0.330	1.006	0.769	0.603	1.012	0.882	0.897	0.951	0.659	1.134	1.701	1.410	0.882	sm	14.210	30	21.5	11.7
BF-253	1.684	1.208	1.711	1.712	1.458	1.173	1.206	1.268	1.903	1.236	1.934	1.838	1.533	0.418	1.328	1.781	sm	23.392	37	23.7	12.9
BU-224	0.452	0.501	0.716	1.211	1.213	1.472	1.449	1.377	2.825	1.757	1.139	0.855	1.021	1.258	1.662	2.516	sm	21.420	32	15.5	0.0
BU-224	0.980	1.371	1.513	1.475	1.929	1.763	1.305	1.486	1.581	1.484	1.212	2.813	1.923	1.531	1.995	1.978	sm	26.339	29	30.7	24.1
BU-224	1.480	1.303	1.629	2.207	1.985	2.286	2.024	1.795	2.030	2.732	2.043	1.308	1.523	1.779	0.447	1.363	sm	27.933	36	31.2	23.3
DN-233	2.395	1.716	2.552	3.179	3.436	2.423	3.619	3.015	2.950	2.276	1.927	2.227	1.787	3.063	3.271	3.300	sm	43.137	16	16.9	1.4
DN-233	0.644	0.418	0.594	0.644	0.821	1.550	1.321	3.439	3.735	5.900	2.103	3.023	2.459	3.522	3.559	3.508	sm	37.239	24	17.3	2.9
DN-233	1.419	1.020	2.764	0.893	1.176	1.938	1.798	3.001	2.944	2.310	3.158	4.302	4.497	1.523	3.805	2.691	sm	39.239	27	22.2	8.8

3. Area based approach results

In GIS increment trough height change was analyzed. On the bi-temporal raster changes of heights between two scanning's were shown. Buffers of 17,84 meters radius were made to the plots. ArcGis function Zonal statistics as a table was used to extract data from a map, and the result was a Table 5 with important statistical values for every plot – count, area, min, max, range, mean, std, sum, median, pct90. Further, data from this table were analyzed in R studio.

Table 4 Plot characteristics

PlotName	DBH (cm)	Height (m)	Crown height (m)	Increment (mm)	BUFF_DIST
SJ-269	49.7	35.9	0	26.599	17.84
QF-250	41.5	31.3	0	24.464	17.84
PV-246	21.7	11.6	0	15.933	17.84
QH-204	32.4	21.4	0	24.166	17.84
SE-218	36.7	32.2	0	15.906	17.84
RT-227	43.9	33	0	17.740	17.84
V-231	64	34.7	22.8	33.236	17.84
PF-199	45	35.4	19.2	20.905	17.84
OB-197	27.4	27.8	0	18.045	17.84
BF-253	24	16.7	9.5	21.252	17.84
OA-231	30.3	26	0	12.575	17.84
DN-233	16	16.9	1.4	43.137	17.84
ET-278	32.6	20.7	0	24.294	17.84
BU-224	32	15.5	0	21.420	17.84
EH-263	34.4	31	0	15.603	17.84
FI-291	18.3	16.8	7.3	17.673	17.84
FI-275	25	21.1	0	16.281	17.84
FT-285	16	13.4	2.7	39.842	17.84
GH-281	29.8	18.4	0	37.396	17.84
GZ-279	39.4	32.4	0	22.098	17.84
EE-226	39.5	33.5	0	30.514	17.84
FB-240	38.7	32.6	0	22.613	17.84
FW-243	35.4	30.5	0	25.356	17.84
FH-250	41.9	29.7	0	47.246	17.84
GD-233	56	33.7	0	31.575	17.84
GT-268	35	26	0	25.355	17.84
EL-221	22.8	26.5	0	13.201	17.84
HQ-273	19	15.6	10.7	16.774	17.84
FF-209	38	28.4	14.7	11.978	17.84
EF-213	15.3	16.3	12.5	5.713	17.84
EB-199	29	19.1	11.2	29.480	17.84
HR-200	16	12.3	8.5	27.913	17.84
GV-201	28.1	23	0	26.929	17.84
HZ-217	34.5	26.3	0	23.248	17.84
JN-281	27.2	24	0	25.180	17.84
JY-245	33.8	25.3	0	14.389	17.84
JL-222	36.7	34.2	0	26.625	17.84
IA-234	19.1	12.8	6.5	26.520	17.84
IK-194	19.4	22.3	17.1	9.009	17.84
MR-216	33.7	34	0	45.039	17.84
KE-255	47.4	28.8	0	19.209	17.84
NJ-288	26.4	24.2	0	45.322	17.84
MH-256	38.5	36	0	13.187	17.84
LO-257	49.2	31.9	0	14.395	17.84
KX-202	46.8	29.9	0	28.704	17.84
KW-193	18.3	15.4	0	15.912	17.84
JE-318	23	22.9	16.3	14.021	17.84
KL-334	15	14.1	11	6.804	17.84

Table 5 Results of the Zonal statistics as a table function

PlotName	ZONE_CODE	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	MEDIAN	PCT90
SJ-269	1	1006	1006	-34.22100	7.79901	42.02001	-2.07144	7.85766	-2083.86405	0.23400	3.19900
QF-250	2	995	995	-34.65500	26.23499	60.88999	-7.49150	12.17610	-7454.04570	-1.74500	3.04101
PV-246	3	992	992	-20.02299	5.08800	25.11099	-3.16885	4.42906	-3143.49517	-2.14749	1.26601
QH-204	4	995	995	-22.37599	17.00299	39.37898	-2.97826	6.37271	-2963.36749	-0.84601	2.35340
SE-218	5	994	994	-38.88300	15.56601	54.44900	-21.00142	14.46987	-20875.40885	-28.31650	1.57761
RT-227	6	993	993	-30.64301	12.36700	43.01001	-2.75626	9.34197	-2736.96484	0.36200	3.93321
V-231	7	989	989	-31.80400	22.84500	54.64900	-0.80622	6.93353	-797.34711	0.23601	5.56979
PF-199	8	983	983	-37.57099	7.16899	44.73998	-7.37893	12.48618	-7253.48391	-1.58100	2.65979
OB-197	9	994	994	-28.51599	6.18501	34.70100	-3.16773	8.74094	-3148.72744	0.29399	3.10199
BF-253	10	995	995	-32.74601	28.29499	61.04100	-1.38163	6.78400	-1374.72542	-0.89499	5.95039
OA-231	11	993	993	-30.38000	12.66001	43.04001	-1.31652	6.73989	-1307.30105	-0.21999	5.21001
DN-233	12	992	992	-11.81000	15.87000	27.67999	4.90189	4.19681	4862.67245	5.54450	9.61799
ET-278	13	991	991	-25.13701	8.85300	33.99001	-1.23808	4.63116	-1226.93674	-0.22701	3.46301
BU-224	14	991	991	-29.22500	11.15500	40.38000	0.47387	6.16943	469.60557	1.88501	5.05500
EH-263	15	992	992	-33.28699	7.52400	40.81099	-3.52858	7.88086	-3500.35427	-0.83701	2.01101
FI-291	16	998	998	-21.80600	11.29399	33.09999	-0.61753	3.62683	-616.29440	-0.01151	2.68329
FI-275	17	1003	1003	-32.75200	8.86701	41.61901	-2.25585	7.45799	-2262.62145	-0.33301	3.66500
FT-285	18	998	998	-23.53200	16.58799	40.12000	0.67027	4.89658	668.93388	1.56800	5.16700
GH-281	19	1002	1002	-21.38801	22.14199	43.53000	4.99585	4.25453	5005.83958	5.85201	8.48201
GZ-279	20	993	993	-30.37301	9.10700	39.48002	0.08125	4.34673	80.68359	0.83699	3.59501
EE-226	21	989	989	-34.03301	21.62701	55.66002	-12.82873	13.86852	-12687.61748	-6.32401	2.60701
FB-240	22	993	993	-31.97899	10.21001	42.18900	-1.05431	7.99147	-1046.92715	0.98001	4.97600
FW-243	23	992	992	-31.81399	11.96600	43.78000	-6.94655	12.19806	-6890.98109	-1.50349	3.85211
FH-250	24	992	992	-30.38900	9.09100	39.48000	-1.76200	6.99707	-1747.89993	-0.16399	4.09900
GD-233	25	989	989	-39.90299	14.06701	53.96999	-18.72380	14.06287	-18517.83692	-25.94399	1.45001
GT-268	26	997	997	-37.27200	11.12800	48.40000	-3.59116	10.27486	-3580.38248	-0.05100	3.48840
EL-221	27	988	988	-30.40999	15.87899	46.28898	-3.05032	10.29632	-3013.71384	0.91450	5.09869
HQ-273	28	993	993	-38.63900	33.26101	71.90001	-1.58552	8.43816	-1574.41739	0.14100	5.47701
FF-209	29	995	995	-30.33801	30.33201	60.67002	-3.65516	8.98424	-3636.88617	-0.75701	4.42799
EF-213	30	996	996	-20.93701	10.92299	31.86000	2.98951	2.83354	2977.55050	3.22299	5.92799
EB-199	31	987	987	-25.92300	13.24703	39.17003	-1.52093	4.66935	-1501.15513	-0.46299	3.01102
HR-200	32	996	996	-32.22900	12.18101	44.41000	-1.89573	5.65558	-1888.14407	-0.69451	3.64500
GV-201	33	994	994	-29.28699	5.40399	34.69098	-4.72613	7.85486	-4697.77084	-1.38100	1.41099
HZ-217	34	992	992	-34.20000	14.60099	48.80099	-1.45792	9.48564	-1446.25471	1.51500	5.57999
JN-281	35	997	997	-32.40799	12.38200	44.78999	-3.15590	7.48125	-3146.43442	-0.58799	3.55901
JY-245	36	994	994	-22.47901	9.43099	31.90999	-0.05163	3.29997	-51.31615	0.27099	3.28100
JL-222	37	989	989	-37.14101	9.38900	46.53000	-8.60847	10.87628	-8513.77515	-4.73100	2.09920
IA-234	38	999	999	-28.65400	18.18601	46.84001	-0.33342	5.66299	-333.08581	0.05600	6.04001
IK-194	39	995	995	-32.35598	9.67399	42.02998	-1.99985	6.25228	-1989.84934	-0.52599	2.80401
MR-216	40	994	994	-27.79401	21.73600	49.53001	-2.79711	7.37759	-2780.32360	-0.31401	3.60600
KE-255	41	998	998	-26.69301	16.70700	43.40001	-1.54988	4.72964	-1546.77492	-0.45800	2.71000
NJ-288	42	994	994	-36.00699	21.08301	57.09001	-1.85049	13.04877	-1839.38774	2.17301	8.89100
MH-256	43	994	994	-37.17900	25.03099	62.20999	-2.77638	8.88145	-2759.71925	-0.29349	4.21199
LO-257	44	990	990	-36.73201	28.24799	64.98000	-3.23660	9.14702	-3204.23537	-0.31300	2.95709
KX-202	45	989	989	-30.76299	17.80699	48.56997	-2.46105	6.19174	-2433.97343	-1.16299	2.74620
KW-193	46	981	981	-19.67901	7.62099	27.30000	-1.17320	4.98431	-1150.90445	0.21001	3.52999
JE-318	47	998	998	-29.07401	8.45600	37.53001	-1.81283	4.61241	-1809.20274	-0.59400	1.86200
KL-334	48	993	993	-26.28299	11.67700	37.95999	-0.03335	3.91998	-33.11940	0.72700	3.00701

After that R software was used to derive statistical values, using area based approach. The method of stepwise regression was applied and showed the important variables. The results are presented in the form of graphs. On the graph 2 the frequencies of the mean stand increment for the spruce stands are shown. It is visible that the most frequent increment, based on the 48 plots is 15–30 cm.

Graph 2 Increment frequencies
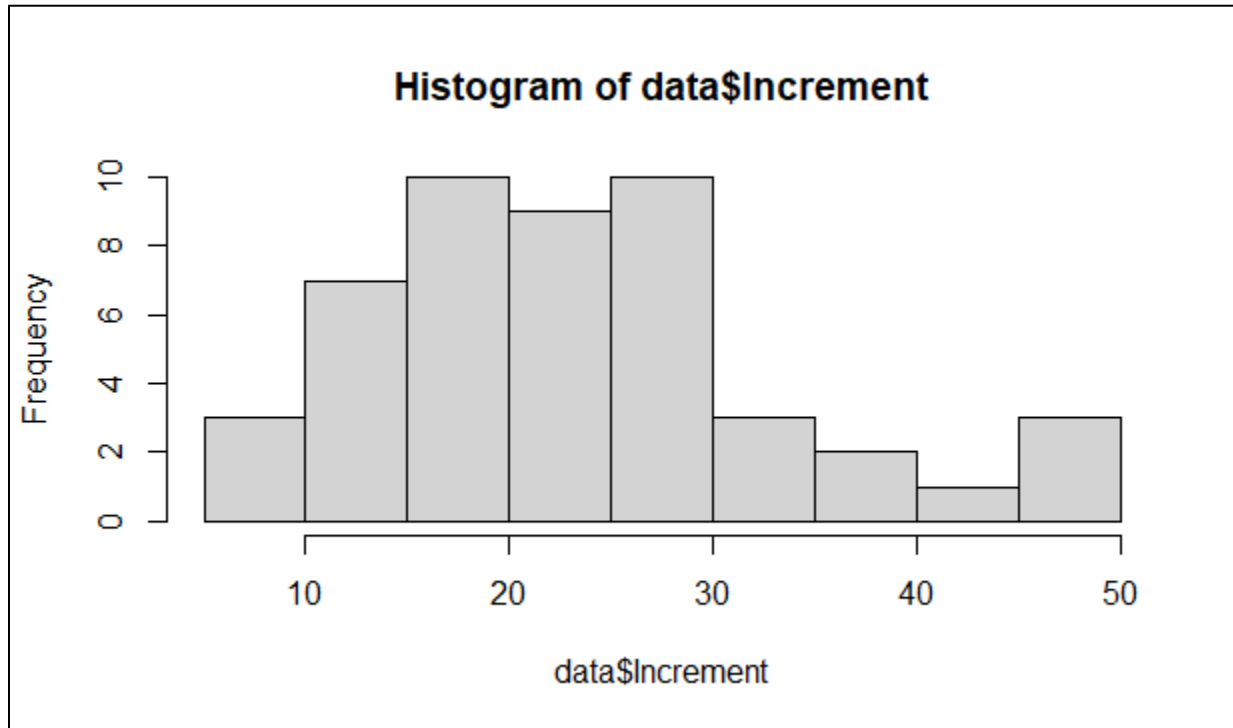
Stepwise regression model was used to find the best fit variable according to increment. The data were sorted into excel table and run through the R studio. Stepwise regression with forward selection was used. Results of the model show that the increment is best fitted according to PCT90 and MEAN parameters, while min, max, range, std, sum and median were discarded.

```
> all <- lm(Increment~MIN+MAX+RANGE+MEAN+STD+SUM+MEDIAN+PCT90, data=data)
> #perform forward stepwise regression
> forward <- step(intercept_only, direction='forward', scope=formula(all), trace=0)
> forward$anova
     Step Df Deviance Resid. Df Resid. Dev      AIC
1         NA       NA        47   4678.916 221.8218
2 + PCT90 -1 626.3565        46   4052.560 216.9233
3  + MEAN -1 216.5413        45   3836.018 216.2875
> forward$coefficients
(Intercept)        PCT90        MEAN
  10.544180     2.794356   -0.560658
```

Figure 1 Stepwise regression model results visible in R studio

Based on the stepwise regression results increment was plotted according to pct90 and the result can be seen in graph 3. R studio function ggplot2 was used for presenting this result. On the graph, blue line represents the regression line; grey area around the regression line represents the confidence band; red dotted lines represent the prediction band.

PCT90 represents or the 90th percentile represents the value for which 90% of the data points are smaller. In order to calculate the pct90 value, the dataset must be arranged by values and the top 10% should be removed. The highest value left is the value 90th percentile. Practically, percentiles are showing how the value is performing in the group of values.

Graph 3 Increment according to PCT90
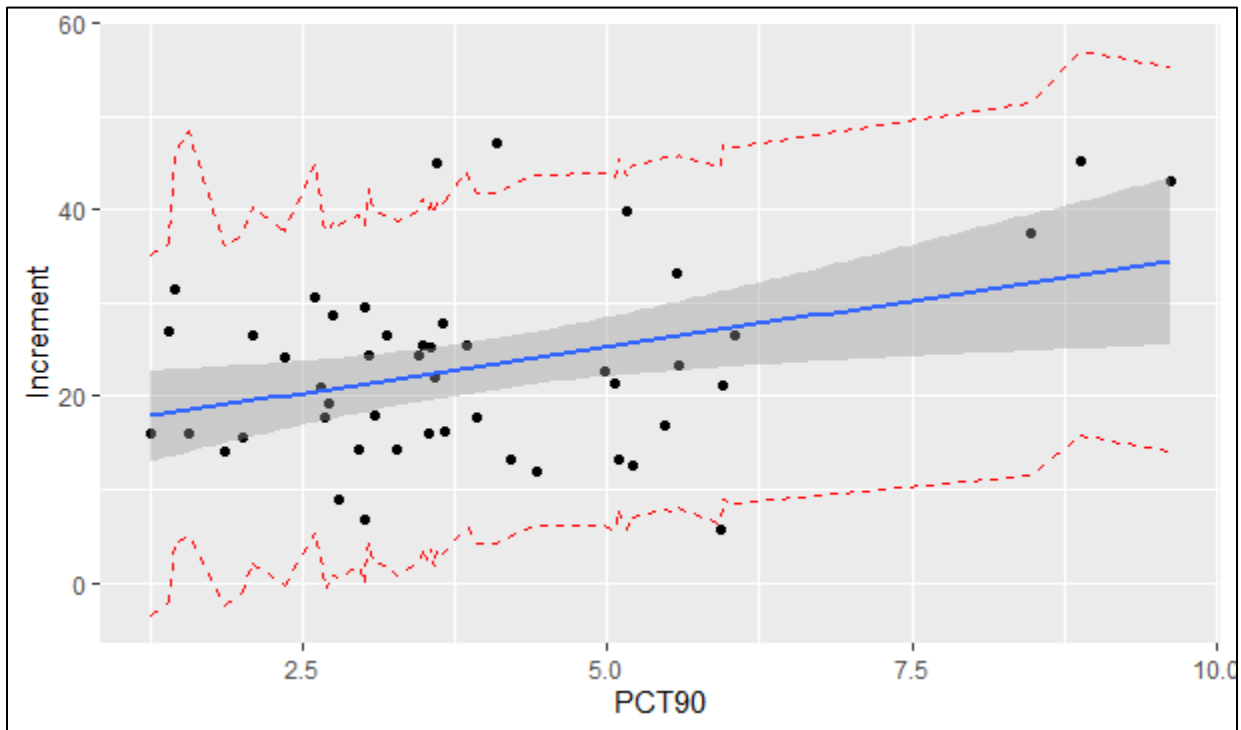
4. Results of linear regression

Linear regression model was established for increment based on height change, and produced results are R-squared value and p-value. R-squared value is 0,1437, which is rather small and indicates that in the future more data should be used for analysis. The result of p-value is 0,01146 which proves statistical significance. Model was set up in R studio and the results could be seen in the Figure 2.

```
> model <- lm(Increment ~  PCT90 + MEAN, data = data)
> summary(model)

Call:
lm(formula = Increment ~ PCT90 + MEAN, data = data)

Residuals:
    Min       1Q    Median       3Q      Max
-19.7198  -5.4567  -0.3202   5.9517  24.2598

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  10.5442     4.3793   2.408  0.02021 *
PCT90         2.7944     0.8913   3.135  0.00302 **
MEAN         -0.5607     0.3518  -1.594  0.11798
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 9.233 on 45 degrees of freedom
Multiple R-squared:  0.1801,    Adjusted R-squared:  0.1437
F-statistic: 4.944 on 2 and 45 DF,  p-value: 0.01146
```

Figure 2 Results derived using linear regression trough R software

Discussion

Bi-temporal laser data, constructed over CHM model clearly show the differences in height of the forest between two years (2005–2019) and are presented on a map (Picture 10). Red parts on the map show decrease in increment which can be explained by planned cuts from the forest management plans. Green parts present the increase of height, on which this thesis relies on for the future growth predictions.

Field measurements were done as a validation of the model. Although data were obtained for all of the established plots, in order to get a representative sample these data were filtered to 48 plots of spruce stands and only increment and trees height data from these plots went into further modeling.

The zonal statistics as a table function was used in ArcGIS in order to obtain statistically significant values. CHM data were with this function merged into the table with established plots. For each plot, statistical data were measured using zonal statistics.

Stepwise regression model found the best statistical variables to fit according to increment of each stand, and those are pct90 and mean. Results of stepwise regression model are presented as Graph 3, and indicate that the prediction of growth is possible using bi-temporal laser scans.

The results of linear regression prove that the model is working, but the R-squared value is too low so no extrapolation to the broader area is recommended. On the other hand the parameters and overall models proved to be significant and the framework of this study can serve for future research and studies.

Conclusion

Remote sensing systems are being used in all developed countries today for forest management practices. As in the Czech Republic it is relatively new technique, this research aimed at producing results of reliability and to justify its broader use for forest inventories. Some breakthrough technologies were used and valuable data were obtained for the future research of the forest changes in the Bohemian Switzerland National Park. Field data for the whole park were obtained which can also be used in future research projects. Results of the thesis showed that these kind of techniques can and will be used by forest inventories, but more research is needed, especially on broader area.

Acknowledgements

By this acknowledgement, I, author of this thesis want to thank my supervisors Peter Surový and Zlatica Melichová who guided me through the process of writing and data processing. Also, I want to thank my family and friends for constant support and advices on how to deal with all the difficulties I've had during the writing of this thesis. In the end, I want to thank my brother Aleksandar for his help with samples processing and geological characteristics description.

Literature

1. Anderson, Karen & Gaston, Kevin. (2013): Lightweight unmanned aerial vehicles will revolutionize spatial ecology, Frontiers in Ecology and the Environment, 11, 138-146, 10.2307/23470549.

2. Ayman, Habib & Bang, Ki In & Kersting, Ana & Chow, Jacky. (2010): Alternative Methodologies for LiDAR System Calibration. Remote Sensing. 2. 10.3390/rs2030874.

3. Bang, Ki In. (2010): Alternative Methodologies for LiDAR System Calibration, PhD thesis

4. Boyd DS., Danson FM., (2005): Satellite remote sensing of forest resources: three decades of research development. Progress in Physical Geography: Earth and Environment.;29(1):1-26. doi:10.1191/0309133305pp432ra

5. Erik Næsset, (1997): Estimating timber volume of forest stands using airborne laser scanner data, Remote Sensing of Environment, Volume 61, Issue 2, Pages 246-253

6. Erik Næsset, (2002): Predicting forest stand characteristics with airborne scanning laser using a practical two-stage procedure and field data, Remote Sensing of Environment 80, 88 – 99

7. Erik Næsset, Ole Martin Bollandsås, Terje Gobakken, Timothy G. Gregoire, Göran Ståhl (2013): Model-assisted estimation of change in forest biomass over an 11 year period in a sample survey supported by airborne LiDAR: A case study with post-stratification to provide "activity data", Remote Sensing of Environment, Volume 128, 21 January, Pages 299-314

8. Estimation of Tree Heights and Stand Volume Using an Airborne Lidar System, Mats Nilsson (1996): Remote Sensing of Environment, Volume 56, Issue 1, Pages 1-7

9. Etienne B. Racine, Nicholas C. Coops, Benoît St-Onge, Jean Bégin, (2014): Estimating Forest Stand Age from LiDAR-Derived Predictors and Nearest Neighbor Imputation,

Forest Science, Volume 60, Issue 1, Pages 128–136, https://doi.org/10.5849/forsci.12-088

10. Hansen, E.H.; Gobakken, T.; Solberg, S.; Kangas, A.; Ene, L.; Mauya, E.; Næsset, E., (2015): Relative Efficiency of ALS and InSAR for Biomass Estimation in a Tanzanian Rainforest. Remote Sens., 7, 9865-9885. https://doi.org/10.3390/rs70809865

11. Hawbaker, T. J., Keuler, N. S., Lesak, A. A., Gobakken, T., Contrucci, K., and Radeloff, V. C. (2009): Improved estimates of forest vegetation structure and biomass with a LiDAR-optimized sampling design, J. Geophys. Res., 114, G00E04, doi:10.1029/2008JG000870.

12. Howard Butler, Bradley Chambers, Preston Hartzell, Craig Glennie, (2021): PDAL: An open source library for the processing and analysis of point clouds, Computers & Geosciences, Volume 148, 104680, ISSN 0098-3004, https://doi.org/10.1016/j.cageo.2020.104680.

13. Juan Guerra-Hernández, Eric Bastos Görgens, Jorge García-Gutiérrez, Luiz Carlos Estraviz Rodriguez, Margarida Tomé & Eduardo González-Ferreiro (2016): Comparison of ALS based models for estimating aboveground biomass in three types of Mediterranean forest, European Journal of Remote Sensing, 49:1, 185-204, DOI: 10.5721/EuJRS20164911

14. Maltamo, M., Kinnunen, H., Kangas, A. et al. (2020): Predicting stand age in managed forests using National Forest Inventory field data and airborne laser scanning. For. Ecosyst. 7, 44, https://doi.org/10.1186/s40663-020-00254-z

15. Maltamo, M., Peuhkurinen, J., Malinen, J., Vauhkonen, J., Packalén, P. & Tokola, T. (2009): Predicting tree attributes and quality characteristics of Scots pine using airborne laser scanning data. Silva Fennica 43(3): 507–521

16. Markus Holopainen, Ville Kankare, Mikko Vastaranta, Xinlian Liang, Yi Lin, Matti Vaaja, Xiaowei Yu, Juha Hyyppä , Hannu Hyyppä, Harri Kaartinen, Antero Kukko , Topi Tanhuanpää, Petteri Alho, (2013): Tree mapping using airborne, terrestrial and mobile

laser scanning – A case study in a heterogeneous urban forest, Urban Forestry and Urban Greening, Volume 12, Issue 4, Pages 546-553

17. Mikita, T., Klimánek, M., & Cibulka, M. (2013): Evaluation of airborne laser scanning data for tree parameters and terrain modelling in forest environment. Acta Univ. Agric. Silvic. Mendel. Brun., 61(5), 1339-1347.

18. Noordermeer, L.; Økseter, R.; Ørka, H.O.; Gobakken, T.; Næsset, E.; Bollandsås, O.M. Classifications of Forest Change by Using Bi-temporal Airborne Laser Scanner Data. (2019): Remote Sens., 11, 2145, https://doi.org/10.3390/rs11182145

19. Ralph O. Dubayah and Jason B. Drake, (2000): Lidar Remote Sensing for Forestry Applications, Journal of Forestry

20. Smith, G., (2018): Step away from stepwise. J Big Data, 5, 32. https://doi.org/10.1186/s40537-018-0143-6

21. Surový, Peter, Kuželka, Karel, (2019): Aplikace dálkového průzkumu Země v lesnictví, Česká zemědělská univerzita

22. Szostak, M. (2020): Automated Land Cover Change Detection and Forest Succession Monitoring Using LiDAR Point Clouds and GIS Analyses. Geosciences, 10, 321. https://doi.org/10.3390/geosciences10080321

23. Tang, L., Shao, G., (2015): Drone remote sensing for forestry research and practices. J. For. Res. 26, 791–797. https://doi.org/10.1007/s11676-015-0088-y

24. Tauri Arumäe, Mait Lang & Diana Laarmann (2020): Thinning- and tree growth-caused changes in canopy cover and stand height and their estimation using low-density bi-temporal airborne LiDAR measurements – a case study in hemi-boreal forests, European Journal of Remote Sensing, 53:1, 113-123, DOI: 10.1080/22797254.2020.1734969

25. Tompalski, P.; Coops, N.C.; Marshall, P.L.; White, J.C.; Wulder, M.A.; Bailey, T. (2018): Combining Multi-Date Airborne Laser Scanning and Digital Aerial

Photogrammetric Data for Forest Growth and Yield Modelling. Remote Sens., 10, 347. https://doi.org/10.3390/rs10020347

26. Tompalski, P.; Coops, N.C.; White, J.C.; Wulder, M.A. (2016): Enhancing Forest Growth and Yield Predictions with Airborne Laser Scanning Data: Increasing Spatial Detail and Optimizing Yield Curve Selection through Template Matching, Forests, 7, 255. https://doi.org/10.3390/f7110255

27. Tompalski, P.; Rakofsky, J.; Coops, N.C.; White, J.C.; Graham, A.N.V.; Rosychuk, K. (2019): Challenges of Multi-Temporal and Multi-Sensor Forest Growth Analyses in a Highly Disturbed Boreal Mixedwood Forests. Remote Sens. 11, 2102. https://doi.org/10.3390/rs11182102

28. Tompalski, Piotr & Wezyk, Piotr & Kok, Roeland & Kukawski, Mateusz. (2009): Determining the Number of Trees Using Airborne Laser Scanning and True Orthoimagery. Annals of Geomatics. 8. 133-141.

29. Van Genechten, Björn. (2008): Theory and Practice on Terrestrial Laser Scanning: Training Material Based on Practical Applications. 4th ed., Universidad Politecnica De Valencia Editorial; Valencia, Spain

30. Vítězslav Moudrý, Petr Klápště, Michal Fogl, Kateřina Gdulová, Vojtěch Barták, Rudolf Urban, (2020): Assessment of LiDAR ground filtering algorithms for determining ground surface of non-natural terrain overgrown with forest and steppe vegetation, Measurement, Volume 150, 107047, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2019.107047.

31. White, Joanne & Tompalski, Piotr & Vastaranta, Mikko & Wulder, Michael & Saarinen, Ninni & Stepper, Christoph & Coops, Nicholas. (2017): A model development and application guide for generating an enhanced forest inventory using airborne laser scanning data and an area-based approach. 10.13140/RG.2.2.26770.96964.

32. Yang Ming, Chujiang Chen, (2013): A Robust Filtering Algorithm of LiDAR Data for DTM Extraction, Atlantis Press, Proceedings of the 2nd International Conference On Systems Engineering and Modeling (ICSEM 2013)

33. Yu, X. & Hyyppä, Juha & Holopainen, Markus & Vastaranta, Mikko. (2010): Comparison of Area-Based and Individual Tree-Based Methods for Predicting Plot-Level Forest Attributes. Remote Sensing. 2. 10.3390/rs2061481.

34. Zsófia Koma, András Zlinszky, László Bekő, Péter Burai, Arie C. Seijmonsbergen, W. Daniel Kissling, (2021): Quantifying 3D vegetation structure in wetlands using differently measured airborne laser scanning data, Ecological Indicators, Volume 127, 107752, ISSN 1470-160X, https://doi.org/10.1016/j.ecolind.2021.107752.

35. https://pro.arcgis.com/en/pro-app/2.8/tool-reference/raster-analysis/zonal-statistics-as-table.htm