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Evaluation of tree crown detection with various spatial resolutions of aerial images

DIPLOMA THESIS

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Abstract

Name: Vojtěch Miklas

Topic of diploma thesis: Evaluation of tree crown detection with various spatial resolutions of aerial images

Abstract: This work reviewed various tree detection and delineation algorithms and developed another one for ESRI ArcGIS Desktop software. This algorithm which employs the principles of local maxima filtering and region growing technique was enhanced by successfully applying NDVI index. Consequently, this algorithm was tested on 11 sample plots. These plots were located in the forest stand 187 C 10a (according to Forest Management Plan 2013 – 2022) in the forest section Proklest which belongs to the forest district Habrůvka in The Training Forest Enterprise Masaryk Forest Křtiny. The results were consequently, evaluated using these 6 different spatial resolutions: 10 cm, 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. This evaluation was based on the comparison with manually vectorised 1,560 tree crowns. Spatial resolution of 40 cm provided the most accurate results for tree counting. At a standard deviation of 7.8 %, the accuracy reached 98 % of the reference layer. In the case of tree crown delineation, the most accurate results were provided for the spatial resolution of 80 cm. The accuracy reached 103 % with standard deviation of 9.6 %.

Key words: tree crown delineation, spatial resolution, ArcGIS, inventory, aerial image, resampling, remote sensing

Abstrakt

Jméno: Vojtěch Miklas

Název diplomové práce: Vyhodnocení detekce korun stromů z leteckých snímků o různém rozlišení

Abstrakt: V této práci byl proveden přehled rozmanitých algoritmů určených k detekci a vymezení korun stromů a na základě literární rešerše byl vytvořen vlastní algoritmus v prostředí ESRI ArcGIS Desktop. Tento algoritmus, využívající principů filtrace lokálních maxim a metody spojování oblastí, byl rozšířen o úspěšnou aplikaci NDVI indexu. Následně byl algoritmus testován na 11 zkusných plochách. Tyto plochy se nacházely v lesním porostu 187 C 10a (podle lesního hospodářského plánu 2013 – 2022), na lesnickém úseku Proklest, který spadá pod Školní lesní podnik Masarykův les Křtiny. Dále bylo provedeno vyhodnocení výsledků pro 6 různých rozlišení: 10 cm, 20 cm, 40 cm, 60 cm, 80 cm a 100 cm. Toto vyhodnocení bylo založeno na porovnání s manuálně vektorizovanými korunami 1560 stromů. V případě jednoduchého sčítání stromů založeného na extrakci lokálního maxima bylo dosaženo nejlepších výsledků u rozlišení 40 cm. Tady přesnost dosáhla 98 % v porovnání s referenční vrstvou při směrodatné odchylce 7,8 %. V případě vymezení koruny stromu bylo dosaženo nejlepších výsledků u rozlišení 80 cm. V tomto případě přesnost dosáhla 103 % v porovnání s referenční vrstvou při směrodatné odchylce 9,6 %.

Klíčová slova: vymezení koruny stromu, prostorové rozlišení, ArcGIS, inventarizace, letecký snímek, převzorkování, dálkový průzkum země

List of Abbreviations

TIDA – Tree Identification and Delineation Algorithm

ITC – Individual Tree Crown

TM – Thematic Mapper

UAV – Unmanned Aerial Vehicle

VTOL – Vertical Take-Off and Landing

NIR – Near Infra-Red

MATLAB – Matrix Laboratory

RGB – Red, Green, Blue

PAR – Photosynthetically Active Radiation

NDVI – Normalized Difference Vegetation Index

RVI – Ratio Vegetation Index

GRVI – Green Ratio Vegetation Index

GIS – Geographic Information Systems

PLA – Plot-Level Accuracy

Table of Contents

List of tables, graphs and pictures

1 Introduction

Before aerial photography was used for forest management purposes, information was generally obtained by means of field surveys, identifying and measuring forest types and stands. This is still by far the most accurate and detailed way of measurement, although the lack of geographical positioning systems did not allow accurate location of the forests classified. The method is, however very elaborate, time consuming and expensive, and it is nowadays used predominantly for research purposes and for intensive sustainable production purposes. The traditional aerial photograph resulting from different film types was and still is an important remote sensing tool. Knowledge of photogrammetry and photography is essential for its proper use. For many decades the use of aerial photographic data has been accepted by many forest institutions as a tool in various forest activities, such as planning, mapping, inventory, harvesting, area determination, road lay-out, and registration of declined and dead trees etc. (Hussin and Bijker, 2000)

Image interpretation is conduction of several kinds of tasks, many of which may be completed together in an integrated process. Nonetheless, for purposes of clarification, it is important to distinguish between these separate functions. *Classification* is the assignment of objects, features, or areas to classes based on their appearance on the imagery. Often a distinction is made between three levels of confidence and precision. *Detection* is the determination of the presence or absence of feature. *Recognition* implies a higher level of knowledge about a feature or object, such that the object can be assigned an identity in a general class or category. *Identification* in context of image interpretation means that the identity of an object or feature can be specified with enough confidence and detail to place it in a very specific class. *Enumeration* is the task of listing or counting discrete items visible on an image. The ability to conduct such enumeration depends on an ability to accurately identify and classify items as discussed above. *Mensuration* is the process of measurement of objects in terms of length, area, volume or height. *Delineation* is process of delineating, or outlining regions as they are observed on remotely sensed images. It depends on ability to separate distinct areal units that are characterized by specific tones and textures to identify edges or boundaries between separate areas. (Campbell and Wynne, 2011)

Considering the facts mentioned above, the interpretation of forest stands aerial images can be perceived on different levels. Detection of trees in forest can be simply generalized to decision between forested and non-forested area. But this interpretation does not provide any information about individual tress. Next step of forest stands is recognition of individual trees. This process is associated with allocation of crown area. Finally, the identification can be explained as the detailed classification of recognized tree crowns for instance according to tree species. In this case of forest interpretation the delineation process is definition of borders around individual tree crowns and consequently transformation of the newly created features into geometrically analysable form. In case of enumeration of forest stands from aerial imagery, the desired outputs of analysis is number of trees on specified area. Mensuration of forest stand consist of various data. Aerial imagery can provide information about tree crown areas, stand density, and canopy closure.

Nowadays, there are several methods of forestry inventory. However every method is suitable for different conditions, provides various quality of reports and least but not last are also typical with various cost per area unit.

According to Suárez et al. (2005), manual interpretations of aerial photography supported by field surveys have frequently formed the basis for wider scale forest inventories. However, digital photos can also be analysed to produce information about forest stand characteristics like stocking densities, standing volume, or mortality rate.

However, there are two main problems with manual stand delineation. Firstly, the delineation of homogeneous vegetation units is not based on explicit measurement procedures, and as such, the information is not objective and therefore not necessarily repeatable. (Harari-Kremer, 1999 *in* Culvenor, 2002)

Automated approach to image classification

The fundamentals of visual image interpretation were developed for interpretation of aerial photograph, and have been suitably adapted for remote sensing image interpretation. With the availability of remote sensing images in digital form and high speed computing facilities, digital image analysis provides an automated approach to the image interpretation. (Chandra and Ghosh, 2007)

2 The current state of the topic

Most practical forest management decisions are made at the stand scale, where a stand typically represents a discrete area of forest with similar species and structural composition. Aerial photography is often used for the delineation of forest stand boundaries (Leckie et al., 1998 *in* Culvenor, 2002), a task that is often performed manually.

The optimum spatial resolution vary between forest types and individual algorithms, they typically require that the ground resolution cell of the sensor be considerably smaller than the size of the tree crown objects in the scene. Perhaps, the most fundamental assumption of crown delineation algorithms is that the centre of a crown appears radiometrically brighter than the edge of the crown. (Culvenor, 2002)

The spatial resolutions of images available from multispectral airborne sensors, digitized aerial photographs and upcoming earth observation satellites caused simply a change in the digital image analysis paradigm for forestry. With the increased level of details, individual tree crowns are now visible. The forest stand based approaches relying on pixel-based classifications at low spatial resolutions (10-100 m per ground pixel) and area-based texture segmentations at medium resolutions (1-10 m per ground pixel) get increasingly inappropriate. At high resolutions (10-100 cm per ground pixel), it is better to deal directly with the essential structural element of the forest stands: the individual tree crown. (Gougeon, 1998)

Tuček et al. (2011) studied the influence of spatial resolution to the automated individual tree crowns detection from aerial images with high spatial resolution. This comparison used previously tested approach detecting local maxima from image modified by Gaussian filter. Delineation was carried out by region growing based on distance from seed pixels. For this comparison, various spatial resolutions were used: 0.4 m, 0.6 m, 0.8 m, 1 m, 1.2 m and 1.6m. Measured stands were represented by various species. In most cases (5 sample plots from 7) were the best results provided by the size of pixel 0.6 m. Average tree counting accuracy for this resolution was 94.3 %. The result for the size of pixel 0.4 m was 126.5 % and 78.8 % for the size of pixel 0.8 m.

2.1 Algorithms of individual tree crown detection and delineation

Many methods were developed based on the assumption that tree crowns have a conical shape such that they appear as a circular shape in two-dimensional imagery, with the treetops having the strongest reflectance within the crown area. The characteristics of this reflectance pattern were substantially used in tree detection and delineation methods. The irregular-shaped crowns commonly seen with deciduous species make the reflectance pattern more difficult to recognize. (Ke and Quackenbush, 2011)

Culvenor (2002) divided algorithms developed for the automated delineation of tree crowns into two categories: In the first group, there are algorithms that focus on local minima and radiometric valleys as a means of 'isolating' tree crowns, such as the valley-following algorithm developed by Gougeon (1998), and the minimum-texture algorithm by Warner et al. (1998). In the second group, there are algorithms that place more emphasis on the local radiometric shape of illuminated tree peaks for locating tree crowns and fitting boundaries, (e.g. Pollock, 1996).

2.1.1 Tree crown detection algorithms

2.1.1.1 Local maxima filtering

The local maxima was defined in earlier works as moving windows of predefined size (Gougeon and Moore, 1988).

Local maximum filtering algorithm was developed based on the assumption, that images of forested area are typical with increasing brightness (reflectance of trees) from shaded area towards the tree peaks. Treetops can be easily detected once maximum brightness values were detected locally. The main principle of this method is scanning through this predefined window across the whole image and identification of centroid pixels as a probable tree location if it had the highest digital number within the window. The size of the window is determined by the user based on the relationship between the image resolution and tree-crown size. The fixed-window local maxima filtering method worked well for imagery with a near-nadir view of forest with uniform tree-crown size. However, for forests with varying crown sizes, large windows caused omission errors when small tree crowns were missed, while small windows caused increasing commission errors, since large tree crowns could be counted several times. This proposed the necessity to detect local maxima using variable window sizes commensurate to the tree crowns being detected. (Ke and Quackenbush, 2011)

This algorithm of tree crown detection algorithm was also used by Wang et al. (2004), Culvenor (2002), as well as Pouliot et al. (2005).

2.1.1.2 Image binarization

Image binarization aims at converting a grey-level image into a black-and-white image where white pixels represent objects of interest and black pixels represent background. The contrast between the brightness of the tree crowns compared to the shaded area around them can be utilized to separate the tree crown area from the darker background. Dralle and Rudemo (1996) in Ke (2011) analysed image histograms and used the histogram mode as a threshold; pixels above the modal level were counted as individual tree stems. It should be noted that the contrast between tree crowns and the background varies among trees in the image, which may lead to only partial success of a single threshold when applied to an entire image. In addition, the performance of one global threshold tends to be different between images due to different view angle and illumination. (Ke and Quackenbush, 2011)

2.1.1.3 Scale analysis

The proportion between resolution of image and the tree crown which is supposed to be detected seemed to be big issue in many previous studies. For images, where tree crown sizes are typical with the higher variance and the image resolution is invariant, it is difficult to detect all crowns simultaneously – small tree crowns, relative to image resolution, are sometimes not successfully detected while large crowns are sometimes identified as multiple tree crowns. Scale problems are common to a variety of tree crown detection methods, and require appropriate considerations to improve the results. On the other hand, there is possibility to apply scale directly for identified tree crowns. In case that tree crown size is relatively large in comparison to the ground pixel size, the scale analysis usually involves smoothing of the image. (Ke and Quackenbush, 2011)

The purpose of smoothing is to round off the contour of each individual tree crown and merge different contour parts that are close to each other. Furthermore, the smoothing identifies those edge contours that obviously belong to the same circular tree crown. As crowns are of different sizes and shapes, smoothing must be at different scales. (Brandtberg and Walter, 1998)

2.1.1.4 Template matching

This object recognition image-processing technique is applied by searching for a match between artificially defined model of object, supposed to be detected and various regions within the image. This 'model' is usually called template. (Gonzalez and Woods, 2007 in Ke and Quackenbush, 2011) The main principle of this method is evaluation of matching between the template and the object assumed to be located. One of methods for the template definition could be manual picking of representative objects from the original image containing various objects. The matching is defined as correlation between these two features. The higher correlation implies the occurrence of the searched object. (Ke and Quackenbush, 2011)

Pollock (1996) defined the templates for the matching analysis by generalising the geometric and radiometric characteristics of the tree crowns and defining the three-dimensional models. The automatic recognition of individual trees in aerial images of forests based on a synthetic tree crown image model. This method was not based only on general conception of tree crown exposed from nadir but also operated with triangular-like shape of tree crowns exposed from various angles.

2.1.2 Tree crown delineation algorithms

2.1.2.1 Valley-following algorithm

This tree crown delineation algorithm was firstly published by Gougeon (1998). It was used for the inventory of mature coniferous forests in Canada. The mature forest stands were characterized by moderate density and presence of the shaded area between tree crowns. Gougeon (1998) interpreted the image of forest stand as three dimensional mountain-like model where tree peaks are located above the shaded gaps between them which can be interpreted as network of valleys. Instead of searching for the local maxima (tree peaks) his methodology was based on localizing of local minima as valley bottoms. Consequent valley network was created by following adjacent pixels located between the pixels with higher values. However the problem with branches extending from one tree crown to another one represented the barrier which caused interruptions of this following. Afterwards Gougeon (1998) developed five-level rule based algorithm where the first rule was aimed to clockwise displacement of the tree crowns – this algorithm successfully avoids extended branches.

This delineation algorithm for individual tree crown delineation was also used by Leckie et al. (2003).

2.1.2.2 Region growing algorithm

This algorithm is based on sophisticated image segmentation based on assumption that this image is divided to various regions. Main principle is allocation of seed pixels which represent such regions. Region growing means examining all neighbouring pixels as a part of the region and automatically expand the region to that pixel. This operation is performed for all seed pixels simultaneously. When a significant boundary is found, these pixels are labelled as belonging to the region specific to the seed pixel. This approach is usually applied simultaneously with image segmentation defining the background which is stopping barrier for ongoing growth (Gonzalez and Woods, 2007 in Ke and Quackenbush, 2011).

According to Wang et al. (2004) a treetop is located at or near the centre of the tree crown when it is viewed from a near-nadir perspective.

Culvenor (2002) presumed this fact and used local maxima representing tree tops as seed pixels for region growing delineation of tree crowns.

This tree crown delineating algorithm was also used by Pouliot et al. (2005).

2.1.2.3 Watershed segmentation algorithm

Watershed segmentation is based on assumption that image of forested area from near to nadir view can be interpreted as topographic surface, where the digital value for every pixel is considered as the elevation of the point. This assumption is the same as in the case of local maximum filtering or valley-following algorithms. By inverting the whole image the local maxima become local minima and vice versa. After this overturn, the image is virtually flooded. The local minima are being flooded as first. Watershed lines are being defined as borders of (Gonzalez and Woods 2007 in Ke and Quackenbush, 2011).

Wang et al. (2004) also used this algorithm for delineation of individual tree crowns.

2.1.2.4 Hill climbing algorithm

In this mathematical optimization algorithm, the tree crown area is defined by location of maximum value for an objective function. The basic idea is to always towards a state which improves the current one (Huang and Shibasaki, 1995 in Ke, 2009).

Ke (2009) successfully applied the hill-climbing algorithm to classify the pixels within crown clusters according to the tree tops. The main principle of this algorithm is identification of every single pixel's relation to appropriate tree crown. This task was practically carried out by the moving pixel allowed to move only one step (defined as one pixel distance) from the current position. Performing this algorithm the moving pixel climbs 'up the hill' until it reaches the tree top. (Ke, 2009)

2.2 Suitable image resources

Gougeon and Leckie (2006) compared individual tree delineation from IKONOS satellite images with spatial resolution from 1 m per pixel to 4 m per pixel with previous study using similar signature types and methodology (Gougeon 1998), but with 36 cm per pixel multispectral airborne data. Results for that study indicated an overall accuracy of 74 percent for five coniferous species.

According to Gougeon (2009) images from aerial sensors bring many additional challenges to an ITC analysis: The first problem is its large view angle ±20°. These view angles show increasingly leaning trees as one gets away from the image centre (nadir), making crown delineation difficult and increasing the probability of trees being completely hidden. The second problem are the effects of solar illumination which are quite different from one side of the image to the other, as the trees on one side are generally seen as front lit, while on the other side, mostly backlit. The third complication is need to normalize between images taken and flight lines of planes taking those pictures.

However, according to Pollock (1996) it is possible to define the individual tree crown detection model adjusted for the processing of the tree crowns projected in various angles. (See in the chapter 2.1.1.4.)

Based on literature research, the following types of resource data for individual tree crown delineation were used:

2.2.1 Aerial photography

There are many types of aerial photography in contemporary use, however their specifications are quite similar. The camera which expose images is located at the bottom of the plane and vertically pointed to the ground. Then the plane is flying parallel strips in a cardinal directions. For successful completion of image mosaic, it is necessary to overlap stripes in parallel direction. This overlapping is usually represented by 60 % of the image width. This procedure also provides opportunity to use exposed data for stereoscopic interpretation of data and photographic triangulation. Images taken in consecutive direction are usually overlapped by 30 %. To be successful with taking of images, it is necessary to avoid tilt of plane higher than 3 degrees. So, precision cameras and highly trained crew are necessary. (Spurr, 2015)

2.2.2 Unmanned Aerial Vehicle (UAV) aerial photography

The main advantage of UAV is its ability to reach various areas without increased risk of plane accidents. This ability is enhanced by the fact, that UAV can reach places hardly reachable by conventional manned planes and can also fly in lower altitudes. Typical sample of such extreme use can be in case of various natural disasters, e.g. volcanic activity, earthquakes, floods etc. Another advantage is derived from the fact that UAV usually fly under the clouds, so the cloudy weather does not harm the quality of exposed images. In addition, the cost of UAV use is much lower, not only because of lighter construction and insignificant amount of energy consumed, but also due to lower expenses for highly trained pilots. This economical aspect has influence especially on small-scale projects which can be sometimes unrealisable because of the price of typical solution. Thus the UAV can replace manned aircrafts in such cases. In case of rotary wing UAVs, the VTOL (vertical take-off and landing) mean no need of runway and also enhanced use of this solution in cramped areas. However, UAVs suffer also from disadvantages. Payload limitations mean that lower quality of sensors must be used compared to manned aircraft solution. As a consequence, significantly smaller area is usually exposed in individual exposure and higher number of images must be taken in the same conditions compared to classic solution. And the last known disadvantages are caused by light platform and low-power engines. The stability of the platform is usually lower compared to manned aerial vehicle. Low power leads to decreased service ceiling of the plane. (Eisenbeiß, 2009)

2.2.3 Satellite images

Satellite sensors has some advantages compared to aerial photography. They are sensing the earth surface 365 days per year. In addition, there are very short re-visit times for the same place (usually around 4 days). However there are also some disadvantages. The imaging time is fixed and can't be adjusted according to cloud conditions or any other needs. The image resolution is fixed and most of the time significantly lower than in case of aerial imagery. The typical off-nadir viewing angle of up to 25° is problematic in image matching. The cloud cover completely cover the view and cause inability to take desired image. The cost of the imagery is quite high compared to aerial imagery (especially in case of UAVs). (Gruen, 2012)

WorldView – WorldView-2 satellite was launched on October 8, 2009. The data provided by its sensor has spatial resolution of 46 cm. This satellite is able to collect nearly 2 million of km^2 alone. It revisit any place on earth in 1.1 days. This satellite works in two exclusive modes – Panchromatic and Multispectral. Sensor bands of this satellite are divided into two groups: First is represented by 4 standard bands Red, Blue, Green and Nera Infra - Red. In addition to this 4 bands, four new colours were added: The red edge, Coastal, Yellow and NIR2. (SATELLITE IMAGING CORPORATION, 2014)

GeoEye – This satellite sensor was launched on September 6, 2008 from Vandenberg Air Force Base, California, USA. The spatial resolution of this satellite sensor is 0.46 m. It works in two separated modes – panchromatic mode and multispectral mode. The ground pixel size of 46 cm is provided only in panchromatic mode, resolution for multispectral images is 184 cm. Spectral bands are:

Panchromatic:	450 - 800 nm
Blue:	450 - 510 nm
Green:	510 - 580 nm
Red:	655 - 690 nm
Near Infra - Red:	780 - 920 nm

(SATELLITE IMAGING CORPORATION, 2014)

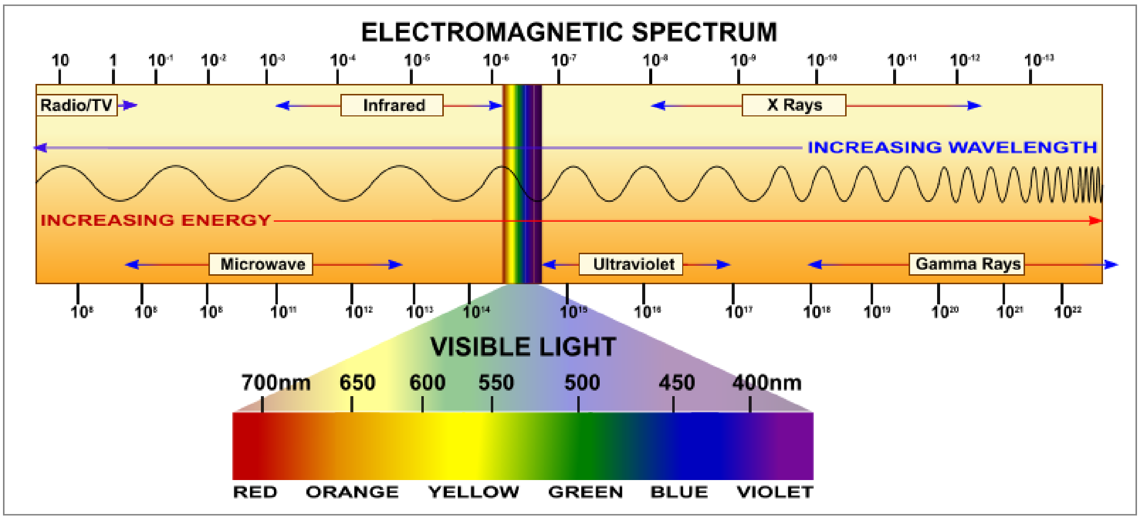
Ikonos – This satellite was launched as the first commercially available high resolution satellite sensor on September 24, 1999 from Vandenberg Air Force Base, California, USA. This satellite can be reprogrammed to take stereoscopic data image for the production of digital surface models with spatial accuracy of 5 m. Its spatial resolution is different for panchromatic mode = 0.82 m per ground pixel, and for the multispectral mode = 3.2 m per ground pixel. This satellite sensor is capable of taking 5 different spectral bands: Panchromatic, Blue, Green, Red and Near Infra – Red. (SATELLITE IMAGING CORPORATION, 2014)

QuickBird – This satellite was successfully launched on October 18, 2001 from Vandenberg Air Force Base, California, USA. The spatial resolution of this satellite is 0.65 m. This satellite provides 5 spectral bands:

Panchromatic:	450-900 nm
Blue:	450-520 nm
Green:	520-600 nm
Red:	630-690 nm
Near Infra - Red:	760-900 nm

(SATELLITE IMAGING CORPORATION, 2014)

2.2.4 Spectral bands and possible use of vegetation indices

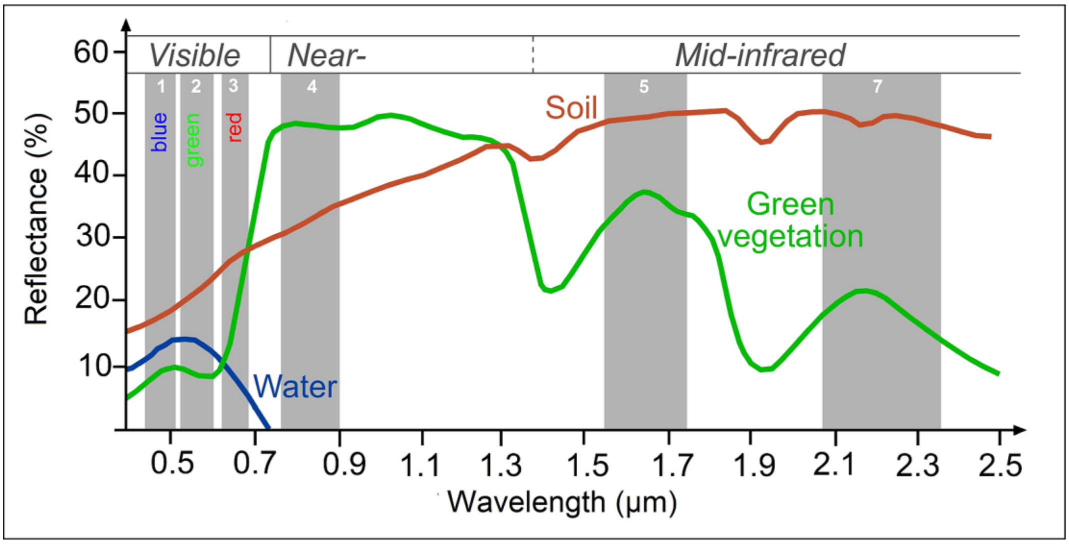


Picture No.1: Complex graph describing the position of visible light and infrared light compared to in electromagnetic spectrum according to its wavelength. Mikkola, (2013)

For individual tree crown delineation are usually used multispectral images containing at least four spectral bands. Red, green and blue parts of spectral elements and also Near Infra – Red band. Combination of the red, green and blue band (RGB image –

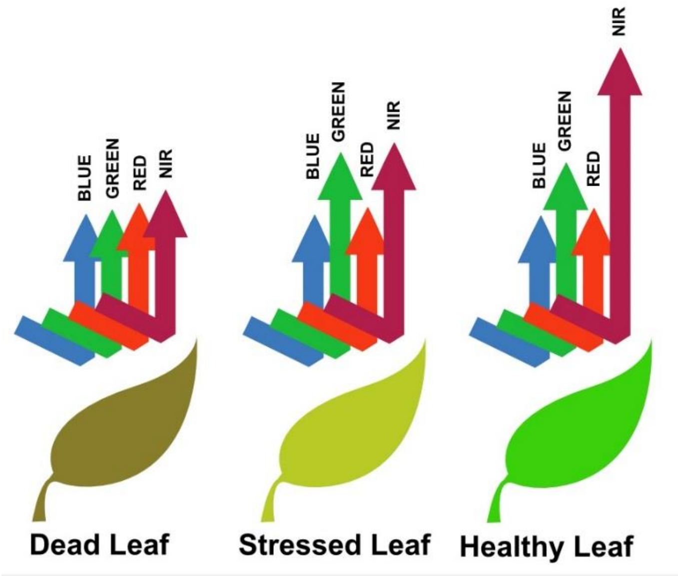
also called visible spectrum) lead to the true colour view. While Near Infra – Red or its combination with visible spectrum provides so called false colour view. (Desert Highlands Paranormal Research, 2013)

The Photosynthetically Active Radiation (PAR) or Visible Red (630 nm to 690 nm) is a chlorophyll absorption band important for vegetation classification. Live green plants absorb solar radiation in the PAR spectral region, which they use as a source of energy in the process of photosynthesis (Gates, 1980).



Picture No.2: Graph showing the reflectance of water, soil and vegetation in different wavelengths and Landsat TM channels. (Science Education through Earth Observation for High Schools, *2015*)

The graph above shows the difference of reflectance in case of various materials. It is obvious, that in case of various spectral bands the amount of reflected light is different. This principle is elementary for image classification and also opens an opportunity to apply some mathematical equation to the data which can lead to highlighting of the searched class in image.



Picture No.3: The disproportion in reflectance in the case of green vegetation. Healthy green leaves reflect higher amount of near Infra – Red and green light than stressed and dead material. (Agribotix, 2014)

2.2.4.1 NDVI – Normalized Difference Vegetation Index

NDVI is the most widely used vegetation index. It is calculated as ratio between difference between NIR and RED band and sum of these two bands. This equation leads to the linear index where healthy vegetation has higher values than the background. However this index is also sensitive to the soil background, atmospheric aerosols and vegetation covered with moisture. Areas of little or no vegetation have positive or negative values near zero. NDVI index is more sensitive in areas with sparse vegetation cover than RVI.

$$NDVI = (NIR - RED) / (NIR + RED)$$

(Rouse et al., 1973 in Raster & Image Processing, 2015)

2.2.4.2 RVI – Ratio Vegetation Index

This vegetation index is simple ratio between NIR spectral band and red spectral band. It shows the high contrast between vegetation and non-vegetation in examined image. This index is non-linear and thus sensitive in areas with intensive vegetation cover but less sensitive in areas with sparse vegetation cover.

$$RVI = NIR / RED$$

(Birth et al., 1968 in Raster & Image Processing, 2015)

2.2.4.3 GRVI – Green Ratio Vegetation Index

This index is derived from RVI, however the red band is replaced with green band. Considering the fact that reflectance of the green spectrum depends less on health state of vegetation, this index is typical with lower variance and lower sensitivity in dense vegetation covers. This index could be used for detection of living vegetation under condition that health condition is secondary priority.

$$GRVI = NIR / GREEN$$

(Sripada et al., 2006 in Raster & Image Processing, 2015)

2.3 Suitable software environments

2.3.1 ESRI ArcGis

ESRI ArcGis software is representing three synergic views to GIS systems. The geodatabase view based on ide that a GIS should be a spatial database containing datasets that represent geographic information as GIS data model (e.g. raster data, topological data, various features, networks, etc.). Another view of GIS is The Geovisualization view based on relationships between various map layers. This approach is supported by analyses, queries and various editing tools. The last view is The Geoprocessing view assuming that GIS is a set of information transformation tools able to derive new datasets from existing datasets. These three views are represented by various toolboxes, intelligent map views and by the catalog. (ESRI, 2014)

Tuček et al. (2011) successfully used this software for Gaussian filtering of image, definition of local maxima values – supposed tree peaks, extraction of local maxima by raster algebra operations and extraction of peaks by reclassification.

Wang (2010) used ArcInfo software only as a support software for extraction of successfully delineated tree crowns.

2.3.2 Idrisi

The IDRISI GIS Analysis tools are in development for almost thirty years, the IDRISI GIS tool set offers over 300 different analytical tools, primarily oriented to examination of raster data. This software is also suitable for the manipulation with geospatial datasets. Additional tools are added to meet the needs of the day-to-day GIS professional as well as advanced procedures for complex modelling and analysis. (Clark Labs, 2015)

Šumbera and Židek (2003) used software IDRISI32 for supervised classification of aerial image to differentiate various tree species in forested areas. Modules Maximum basic probability (MAXSET), Supervised hard classification (MAXLIKE) and Supervised soft classification (BYCLASS were used for this purpose. They used IDRISI software as well as for allocation (delineation) of tree crowns based on seed pixels and consequent post-processing of allocated pixels by transformation to polygons. COST-GROW and COST-PUSH modules were applied for this operations.

Tuček at. Al (2011) applied the same region growing technique in IDRISI software for analysis of spatial resolution influence on individual tree detection.

2.3.3 eCognition

eCognition software has wide spread of use, however especially in forestry industry it provides the ability to carry out large-scale rapid and precious tasks in forestry. Automated classification of fusion and analysis is available as well as identification of tree species, quantification of forest variables (canopy, biomass etc.). This software is also adjusted for delineation of individual tree crowns. (Trimble, 2014)

Wang (2010) used an object-based classification using eCognition 4.0 software with a classification scheme containing two classes: tree crown pixels and background pixels. The classification allowed removing the noise coming from the bare soil and other undesired features.

2.3.4 MATLAB

MATLAB is interactive environment to carry out various tasks. It is capable of analysing and visualising various scenarios across disciplines including image processing, control systems, communications and computational finance. (MathWorks, 2015)

Jing et al. (2012) successfully carry out comparison of the multi-scale filtering and segmentation method (called MFS) and the Gaussian filtering combined with watershed segmentation. All operations were proceeded in the MATLAB software (version R2008a).

2.3.5 TIDA

Culvenor (2002) used complex approach combining local maxima definition with the local minima network definition in individual tree crowns delineation, and developed his own program TIDA (Tree Identification and Delineation Algorithm) written in C++ programming language. This research led to conclusion that this method is suitable for plantations or even-aged forest canopies, but in structurally complex forests, there would likely be errors of omission as radiometrically asymmetric tree crowns or partially obscured trees are missed.

2.3.6 TIMBRS

TIMBRS is a user-friendly, semi-automated implementation of the TIDA tree identification and delineation algorithm, originally developed for Eucalyptus forests (Culvenor, 2002). The spatial resolution of imagery required for accurate tree counts depends on the type of forest and its age class.

2.3.7 Individual Tree Crown (ITC) Suite

Gougeon (1998) used the valley-following algorithm and developed comprehensive solution for not only detection of tree crowns but also for segmentation of forest stands and even for recognition of various tree species. This algorithm has been developed into a software package called Individual Tree Crown (ITC) Suite.

2.4 Suitability for different types of forest stands

The presence of shadow between tree crowns is important condition for successful individual tree crown delineation. According to Gougeon (1998) delineation in high to medium density of forest stands depends on spatial resolution of resource images as well as the tree species. In case of deciduous forests, the success rate was lower than in case on coniferous species because structure of this tree crowns is too dense and typical with lack of shaded area.

This statement is also confirmed in general statement according to Chandra and Gosh (2007): “*Shadow is an important characteristic of image interpretation. It gives an idea of profile and relative height of an object, hence making identification easier*.”

According to Warner at al. (1998) the conical shape of conifers as well as the bordering shadows around tree crowns are particularly useful in image segmentation. If an image has deep shadows, a threshold can sometimes be applied to separate out the bright pixels as individual trees.

3 Methodology

3.3 Selection of suitable area for evaluation

The literature retrieval revealed the fact that individual tree crown detection in more successful in coniferous forest stands compared to deciduous one. So the evaluation of spatial resolution would be examined more effectively.

The most common tree species in Czech Republic is Norway spruce (*Picea abies*) which represents 51.1 % of all trees growing there. (ZPRÁVA O STAVU LESA A LESNÍHO HOSPODÁŘSTVÍ ČESKÉ REPUBLIKY V ROCE 2013, 2014) With respect to the fact that this case study is situated into the Czech Republic, the tree species selected for this evaluation was the Norway spruce.

Considering the importance of this species for the forest management another specifications of suitable area were performed. The additional criteria were based with respect to the fact, that such aerial inventory of forest stands is most effective in fellable stands where the structure of the stand is quite homogenous. In addition the last phase of rotation period is the time, when every information, especially the count of individual trees is important.

So the final multi-criterial query was based on finding for the forest stands where the tree species composition is at least 95 % represented by Norway spruce. The next step was checking whether these stands have age between 80 and 100 years, the stand density is at least nine and the total area of such stand is at least 2 ha.

This multi-criterial query was applied to the area of interest – northern part of the Training Forest Enterprise Masaryk Forest Křtiny. However this area was affected by widespread wind-thrown “Antonín” which struck in 2010. As a result most of found stands were unusable due to felled trees. But one of the largest forest stands in such area was still compact and then used for another processing.

The area of interest is situated into forest stand 187 C 10a (according to Forest management plan 2013 – 2022) in forest section Proklest which belongs to forest district Habrůvka, managed by Training Forest Enterprise Masaryk Forest Křtiny. The forest stand 187 C 10a covers the area of 11.59 ha. The forest type of the place is 4S1. The management set is 4446. The age and proportion of tree species is not the same for the whole stand which is divided into 3 large parts, however similar enough for the common use. The representation of the Norway spruce is 96 percent. The representation of other species is 1 percent of Scotch pine, 1 percent of Douglass fir, 1 percent of European larch and 1 percent of the birch. The age of this stand is 98 years and stand density is 9.

Then 11 sample plots were defined within this stand. The shape of this sample plots was circular because of the fact that ages usually intersects several tree crowns and cause mistakes. The area of every plot was exactly 3,600 m^2. Thus, the area for all 11 sample plots was 3.96 ha. The repetition of sample plots was done to discover the variation between similar stand conditions (as specified above).

3.4 Selection of suitable data for evaluation

After the wind-thrown calamity "Antonín" in 2010, the aerial imagery was exposure over the whole affected area in high resolution. The crucial part for this resource data was the fact that such high resolution allowed very precise manual definition of the tree crowns.

There are only basic metadata available about this imagery:

Date of photographing:	4.7.2010
The scale of image:	13,888
The spatial resolution:	10 cm
Overlapping:	60 % in overlap
	30 % in sidelap
Spectral bands:	Red, Green, Blue and Near-Infrared
Orthorectification of image:	according to archival digital elevation model by Geodis Group Ltd.

3.5 Selection of suitable software environment

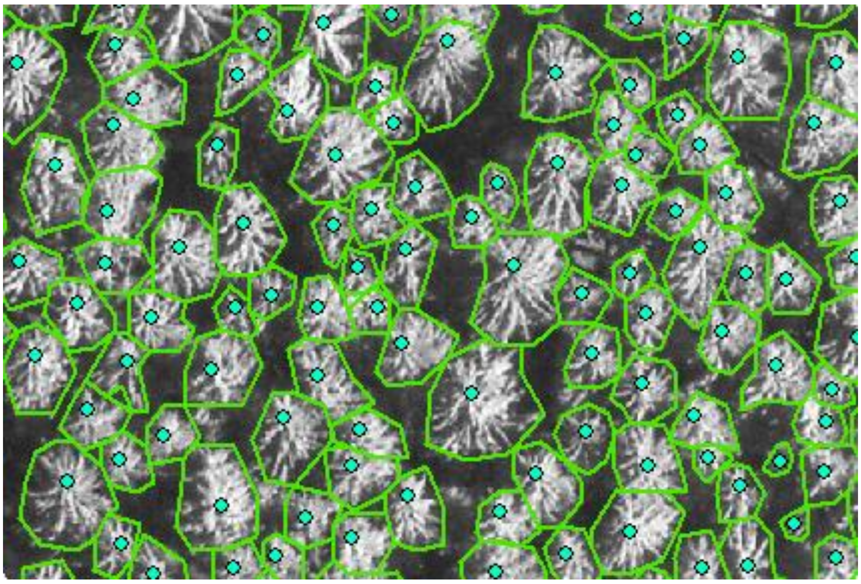
The selection of the suitable software for this study was influence by several circumstances. First of all, the evaluation of the tree crown detection and delineation needs powerful tools adjusted for processing large amount of data. In addition easy work with relations and calculations should be provided. Another consideration was the ability to work perfectly with both vector and raster data. Additionally the possibility to use the user-defined algorithm consisting of various tools with predefined parameters was expected. It was expected to proceed the whole process from raster data import to evaluation of data in just one program. And the last but not least condition was availability of such software.

IDRISI software was taken into consideration, however the process of tree crown detection stagnated on the lower ability to work with vector data. Although the local maxima groups of pixels were successfully extracted and filtered, its vectorization into single points without supervised classification became the real challenge. This fact significantly complicated the process of possible evaluation.

After taking into account the fact, that ArcGIS for Desktop software is widely used environment not only for practical use but also for educational purposes, this software was finally chosen – especially in version ArcGIS 10.2.2. The main goal from software point of view was to develop unsupervised or almost unsupervised algorithm for tree top detection, tree crown delineation and consequently also the assessment of outputs.

Unsupervised classification requires only a minimal amount of initial input from the analyst. It is a process whereby numerical operations are performed that search for natural groupings of the spectral properties of pixels, as examined in multispectral feature space. The user allows the computer to select the class means and covariance matrices to be used in the classification. (Chandra and Gosh, 2007)

3.6 Definition of reference data layer



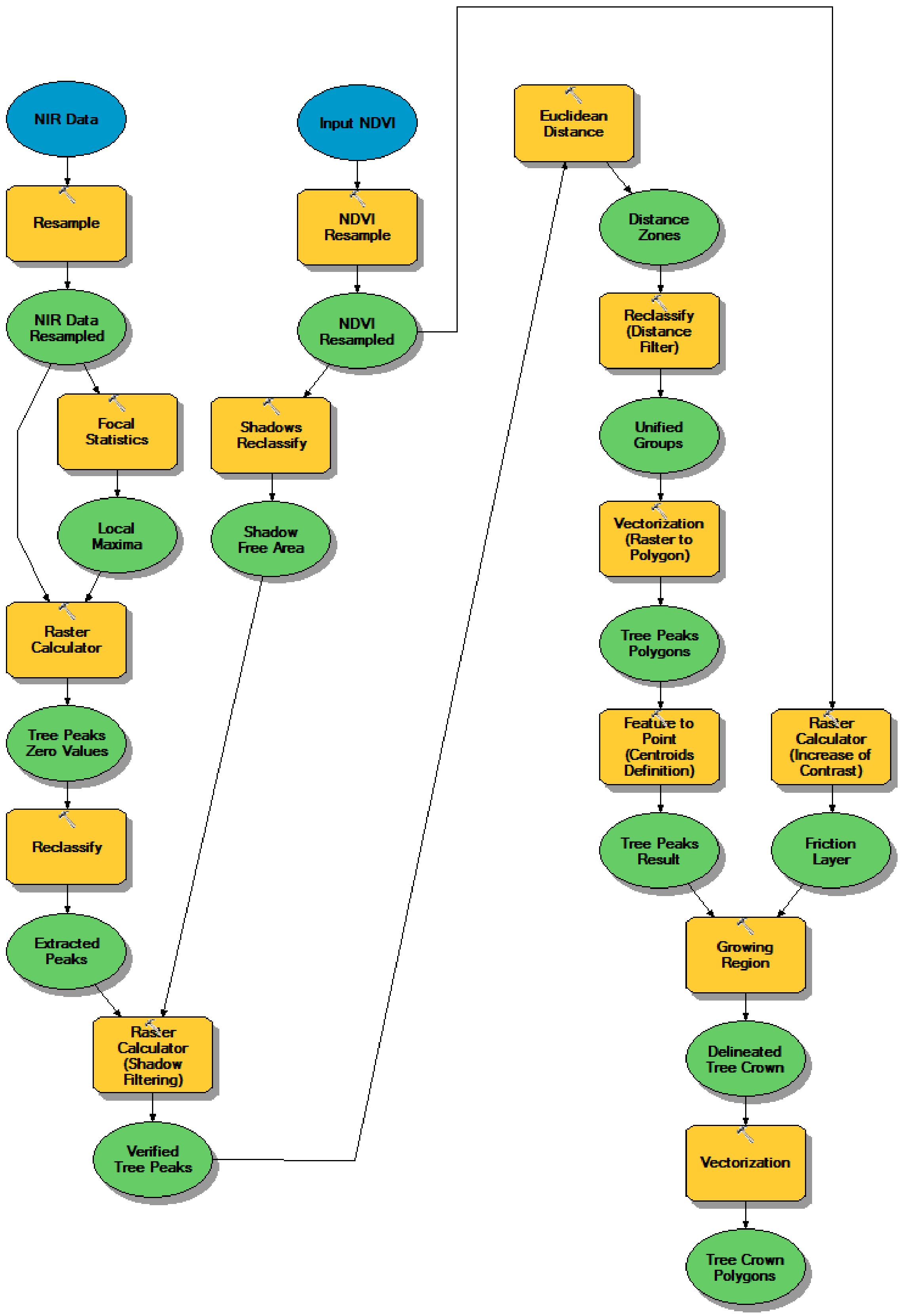
Picture No.4: This image shows the sample of manually vectorised tree tops and tree crowns in one of 11 sample plots.

Considering the contemporary situation in forest stand 187 A 10a, the only solution for reference layer definition was the manual vectorization of tree tops and tree crowns in all 11 sample plots. Nowadays (2015) several trees are cut down or uprooted due to wind-thrown inside some sample plots.

Manual vectorization of data was based on two consequent parts. The first part was just to increase the overall accuracy. In this part every single tree top was marked with dot. By this method, any later hard decision about existing or non-existing tree crown was avoided. On the other hand the number of points is completely equal to the number of polygons defined around. The definition of tree crown borders was based on visible features of the tree crown and also on effort to divide the stand structure as accurate as possible. On the other hand several bright artefacts in the shadow were found and not defined as a tree crown.

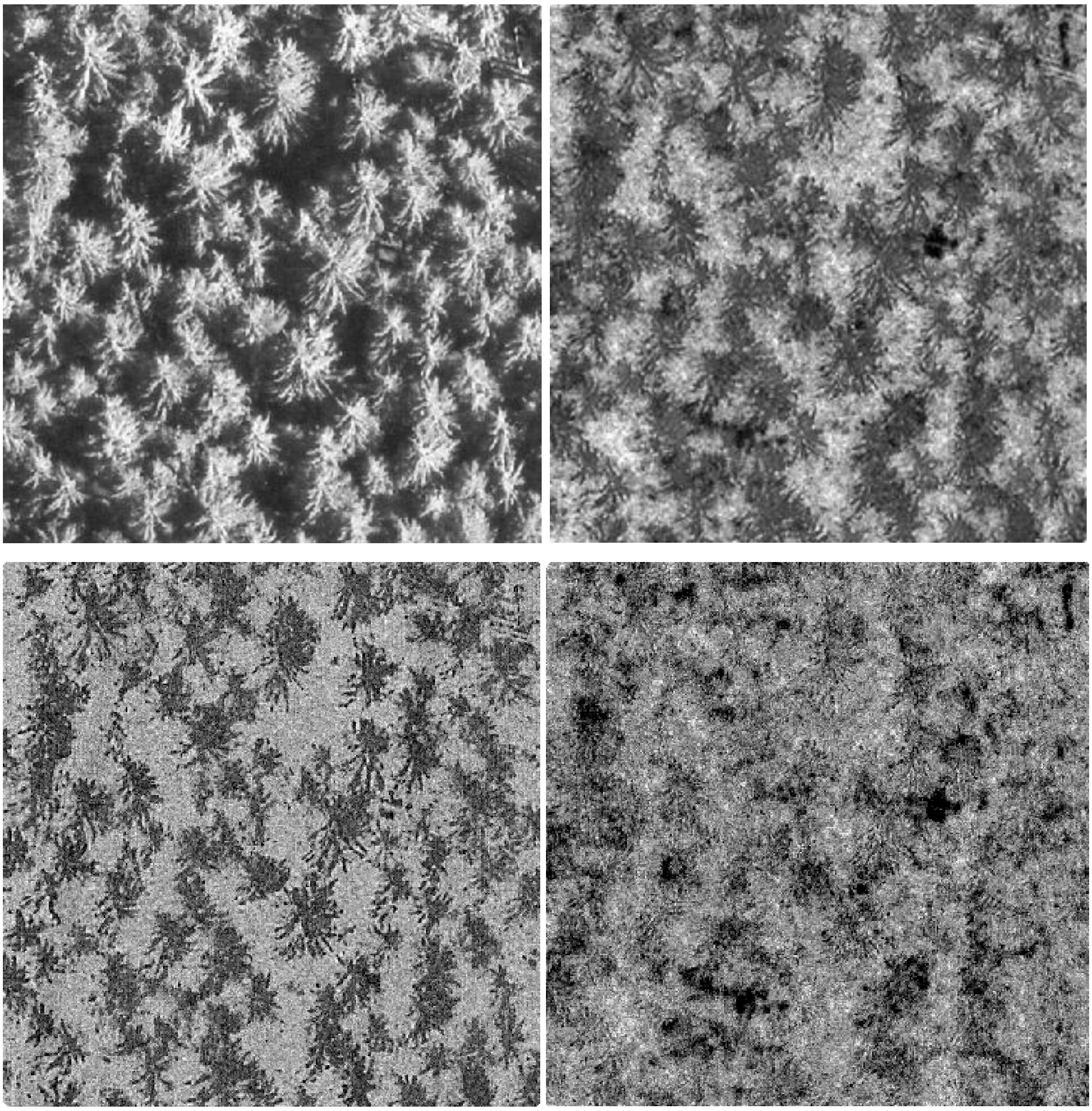
There are 1,560 tree crowns vectorised across 11 sample plots. By division between the tree crown areas and total area of sample plots, the canopy closure reaching 64 % was calculated.

3.7 Development of the tree crown detection and delineation algorithm



Picture No.5: The diagram showing the whole algorithm used for tree crown delineation

The availability of various spectral bands offered an opportunity for the definition of various vegetation indices to increase the quality of tree crown delineation algorithm.



Picture No.6: Most common vegetation indices calculated to support tree crown delineation process (details in the text below)

According to literature retrieval, most common vegetation indices were defined as possible friction layers slowing down the region growing algorithm.

The upper-left photography (see Picture No.6) contains standard near-infrared data where tree crowns seem to be white areas located in significantly darker background. However the structure of tree crowns is too heterogeneous (especially due to branches) and not suitable as friction layer.

The bottom-left image shows the Green Ratio Vegetation Index. The structure of the tree crown is much more homogenous, but in general, this index did not work with high success because of too sharp transition between shadow and tree crown. Also the structure of shadow was too shallow for more complex use.

The bottom-right image shows the simple Ratio Vegetation Index. The high values represented by darker areas are concentrated in small areas and the overall structure is even more heterogeneous than original NIR picture. It is unusable for such purpose.

The upper right image shows Normalized Difference Vegetation Index. At the beginning, this index was completely unusable and did not provide any valuable information, but after modification of coefficients in this index according to Šumbera (1998), dynamic image with gradually increasing value from the tree crown towards the darkest shadows was provided.

The modified equation: $NDVI = (((NIR - RED) * 3.5) / (NIR + RED)) + 3.7$

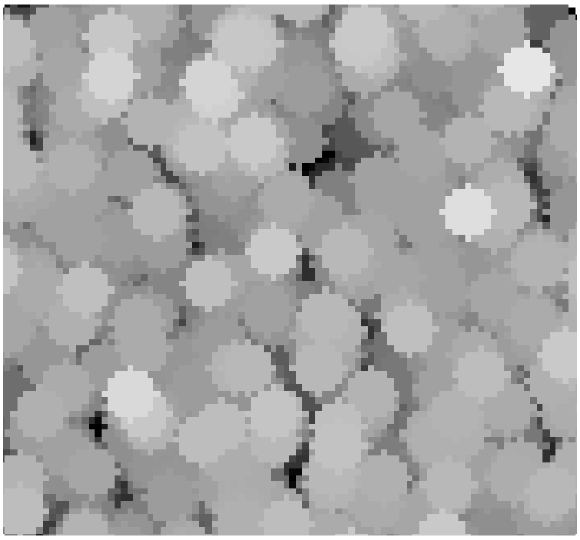
According to this experiment, modified NDVI was used as friction layer in region-growing algorithm to define the shaded area appropriately.

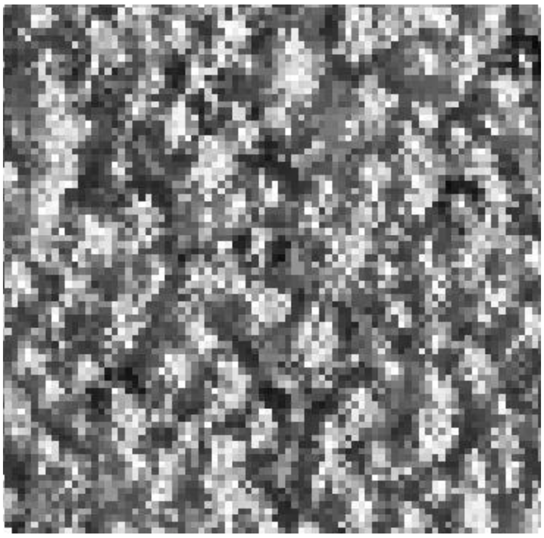
The individual tree crown detection and delineation was performed on six different resolutions: 10 cm per pixel (reference resolution), 20 cm per pixel, 40 cm per pixel, 60 cm per pixel, 80 cm per pixel, and 100 cm per pixel. Predefined model with generalized rules was created in ArcGIS for Desktop. After manual input of 4 variables defined as relative ratios to histograms and tree crown sizes, this model was able to handle the whole algorithm without any user interaction.

3.7.7 Description of tree crown detection and delineation algorithm

First of all, the NIR data of circle sample plots were imported. Afterwards these data were resampled to the resolution in which the evaluation of results should be done.

Afterwards the local maxima filtering was performed. Focal Statistics tool adjusted to MAXIMUM statistic type. The mask for this operation was defined as the circle with radius equal to ½ of average tree crown diameter. This value was calculated from reference data using generalisation of tree crown to circle. The result of filtering is visible in Picture No.7.

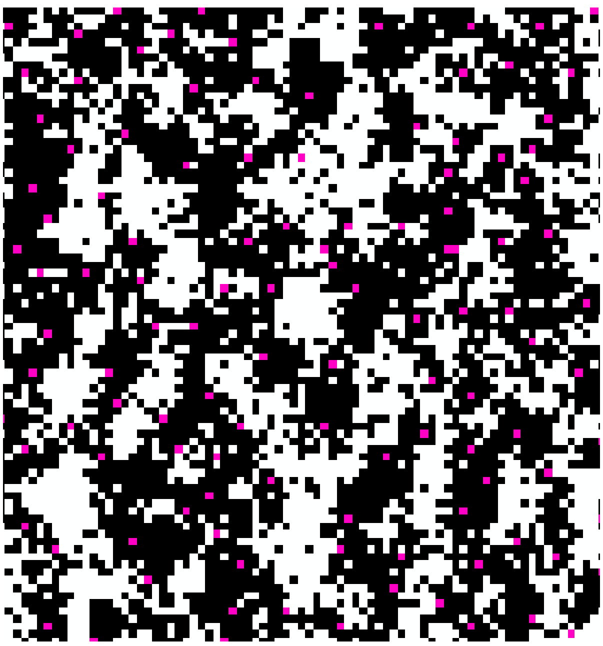


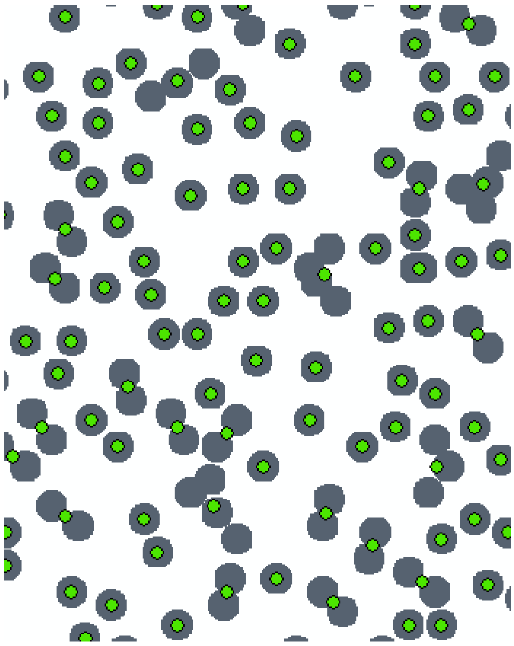


Picture No.7: (Left): Local maxima filtering;

Picture No.8: (Right): Recalculated NIR image containing defined local maxima

The next step was the extraction of local maxima. This operation was simply performed with Raster Calculator tool in ArcGIS environment. Filtered local maxima were subtracted from original NIR image. The result is the definition of local maxima values in image. The sample is visible in the right part of Picture No.8. White-most values has value 0 and can be extracted with the tool Reclassify. Because this tool work only with numerous intervals, extremely narrow interval 0; -0.00001 was used.





Picture No.9: (Left): Extracted local maxima being examined by 'shadow filtering'

Picture No.10: (Right): Defined tree tops after distance filtering

The next step is the first operation using definition of shadow from modified NDVI index. This definition was performed by Reclassify tool by definition of breaking point in histogram for the 'border of shadow'. This value was defined as mean value of the histogram. Shaded area was consequently marked as 'NoData' and supposed forested area was defined by value '1'.

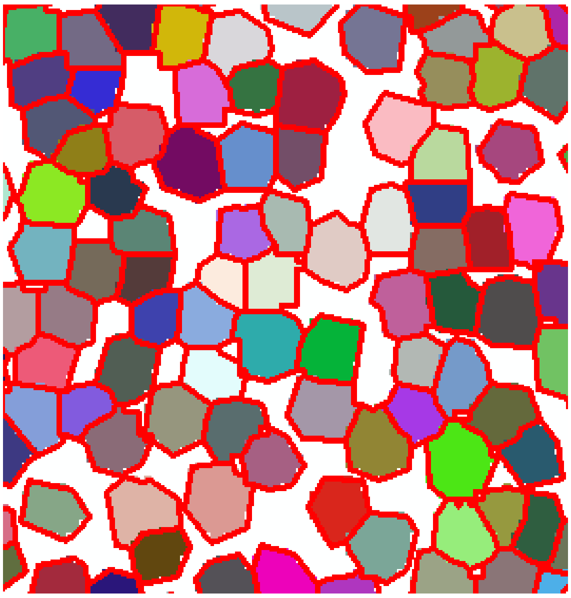
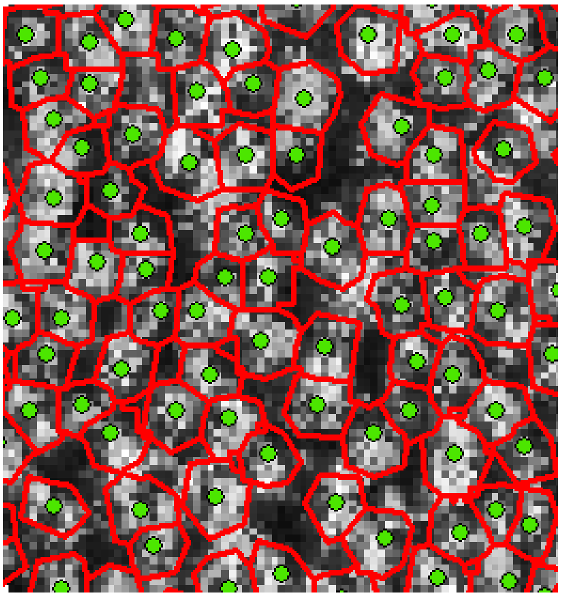
Extracted local maxima were then multiplied with 'forested area' in Raster Calculator tool. As a result, only pixels located outside shadows are kept. The left side of Picture No.9 illustrates the verification. Shaded area has white colour in this image.

The last but one step of tree top definition is the definition of 'multiple tree tops' because sometimes one tree top is represented with more than one local maxima. Distance filtering is realised by definition of buffer around every single pixel in image by the tool Euclidean Distance. Another manually input variable appeared here, the maximum distance for this buffering operation is ½ of average tree crown radius. Values obtained by this operation were consequently unified by Reclassification tool – every pixel in image got the value '1'. This unified area is illustrated in the right part of Picture No.10 by the grey colour areas.

The last step for the tree top definition was transformation of this pixel aggregates into polygons by the tool Raster to Polygon. The final step was to find centroids of newly created polygons and definition of new points representing tree tops. This operation was performed by Feature to Point tool.

This principle of generalisation of tightly located pixels is illustrated in the right part of the Picture No.10. Every isolated group of pixels is represented by just one point – its centroid.

With now doubts this 'distance filtering' is elegant way how to avoid too dense location of tree tops, however extremely small tree crowns are supressed in this algorithm. Moreover this operation suffer in one specific situation: When the incorrect local maxima is located directly between two valid tree peaks and the distance is sufficient for the contact between all three buffered zones (distance filtering), these two outer tree tops are generalised to just one.

Picture No.11: (Left): Delineated tree crowns based on region-growing algorithm

Picture No.12: (Right): Results overlaying original raster resource

The tree crown delineation is then the matter of two steps: The first one is the definition of friction layer which will be used instead of 'cost raster'. Modified NDVI was prepared for this purpose, however, the border between tree crowns and shadows was too soft – in case of high maximum distance, high amount of originally shaded are was occupied by newly created tree crowns. In case of lower maximum distance, the area of crowns was too small and represented by unnatural shapes. For this reason the friction contrast was increased by use of Raster Calculator tool and square mathematical operator. This resulted in more dynamic increase of friction in the 'cost raster'.

Finally, the delineation of crowns was performed by Cost Allocation tool. Tree tops were used as 'feature source data'. The maximal distance was defined as 2.5-times higher value than mean value of 'cost raster'. Last step was to just vectorise regions of pixels by Raster to Polygon tool.

Although the algorithm was designed to calculate all results without any human interaction, one small problem had occurred. In a few cases polygons representing delineated tree crowns were created from isolated pixels which caused disproportion between number of tree tops and the number of delineated tree crowns. This problem was easily solved by attribute query searching for the smallest areas and removal of extra polygons in ascending order.

3.8 Accuracy assessment of the results

No classification task using remote sensing data is complete till and assessment of accuracy is performed. The term accuracy correlates to correctness. In digital image processing, accuracy is the measure of agreement between standard information at given location to the information at same location image. Generally, the accuracy assessment is based on the comparison of two maps; one based on the analysis of remote sensing data and second based on information derived from actual ground also known as reference map. This reference map is often compiled from detailed information gathered from different sources and is thought to be more accurate than the map to be evaluated. The simplest method of evaluation is to compare two given maps with respect to areas assigned to each class or category. This yields a report of the areal extents of classes, which agree to each other. The accuracy assessment is presented as an overall classification or site specific accuracy. Overall classification accuracy represents the overall accuracy between two maps in terms of total area for each category. It does not take into account the agreement or disagreement between two maps at specific locations. The second form of accuracy measure is site-specific accuracy which is based upon detailed assessment of agreement between the two maps at specific locations. (Chandra and Gosh, 2007)

Quantitative evaluation of automated tree detection and delineation involves comparing estimated tree locations or crown boundaries with reference data. Two sources of reference data were commonly cited in the literature: visual interpretation of the imagery used in the analysis, and collection of data in the field. In most studies, reference data were collected by visual interpretation of the input imagery due to the practicality of such an approach. (Ke and Quackenbush, 2011)

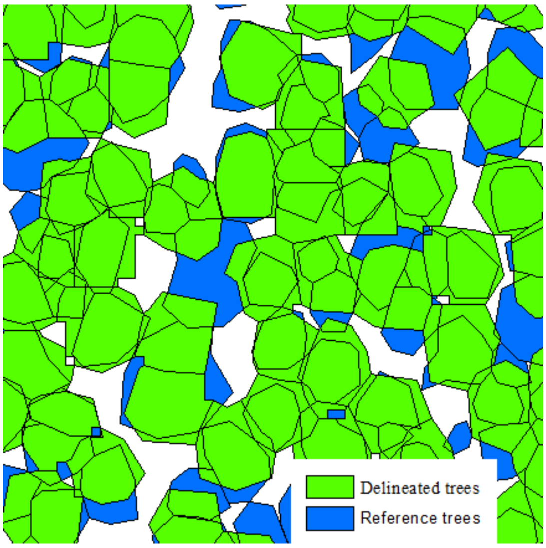
Plot-level accuracy (PLO) method was used for evaluation of total count of identified tree crowns. This method was widely used for various works interested in individual tree crown detection (e.g. Gougeon, 1998).

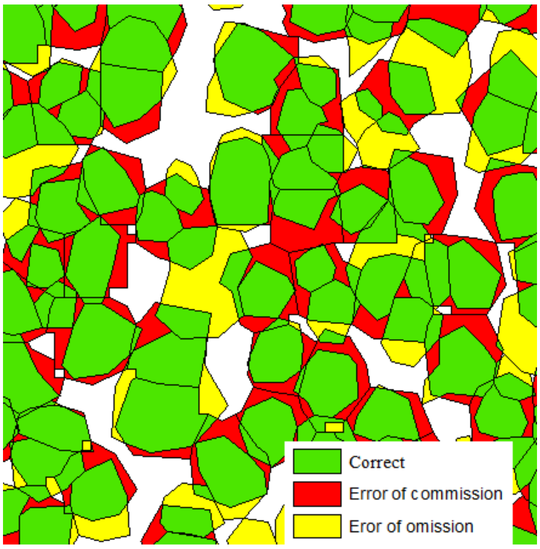
$$PLA = d / n$$

This assessment method simply compares the total number of identified trees (d) to the number of reference count of tree crowns (n). (Pouliot et al., 2005)

In case of delineated area of individual tree crowns, assessment criteria are quite different. When single vector point is exactly placed (e.g. reference data) to the plain area, it is really improbable to place another point to the exact place as the original point (e.g. identified tree top), for this reason, it is impossible to analyse 'one per one' relations between two sets of points. On the other hand, tree crown is represented by area. This means that it is very likely to place delineated tree crown to the area of another reference tree crown. For this reason, it is possible to divide the whole detected area into three groups with various level of accuracy (or error):

1. Correctly detected area
2. Error of commission – the feature is located in the wrong place (where is not supposed to be located)
3. Error of omission – the feature is not located in the correct place (where is supposed to be located)





Picture No.13: (Left): Cut polygons according to reference tree crowns

Picture No.14: (Right): Classification of accuracy / errors in delineated tree crowns

This picture illustrates the method of accuracy and error evaluation. The left image (see Picture No.13) visualises the fragmentation of original tree crown polygons by the tool Identity. The green colour represents delineated tree crowns while the blue colour represents reference tree crowns. The Right image (see Picture No.14) contains the final classification. Green colour represents correctly delineated are, the red colour represents error of commission and the yellow colour represents the error of omission.

For the successful evaluation of the results it was necessary to realise various operations.

First of all it was necessary to define relations between all newly created features (tree tops and crowns) and sample plot numbers. Afterwards the area of every delineated tree crown was calculated by use of tool Add Geometry Attributes.

For the calculation of accuracy and errors in case of are it was necessary to ‘cut’ newly created tree crowns by reference tree crowns and vice versa by the tool Identity.

After recalculation of areas, the evaluation of error was based on following rules:

- Area belonging to the newly created tree crown area located within the polygons of reference tree crowns is marked as ‘Correctly placed area’.
- Area belonging to the newly created tree crown area located outside the polygons of reference tree crowns is marked as ‘Error of commission’.
- Area belonging to the reference tree crown area located outside the polygons of newly delineated tree crowns is marked as ‘Error of omission’.

4 Results

According to the methodology described above, all calculated data were assessed and evaluated. The evaluation is divided into two parts: The count of tree crowns and the Area of tree crowns detected. Each group is evaluated separately for the sample plots and for the resolution in average.

Absolute results are included in chapter 10 (Annexes), while this chapter include several comparisons and evaluations.

4.3 Count of tree peaks

Sample plot	Spatial resolution					
	10 cm	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
1	120 %	116 %	107 %	101 %	96 %	66 %
2	113 %	111 %	99 %	94 %	88 %	66 %
3	106 %	110 %	97 %	90 %	84 %	55 %
4	106 %	102 %	95 %	77 %	78 %	45 %
5	110 %	103 %	89 %	84 %	84 %	53 %
6	105 %	104 %	91 %	93 %	84 %	59 %
7	105 %	105 %	95 %	76 %	82 %	63 %
8	127 %	121 %	104 %	91 %	89 %	59 %
9	135 %	134 %	115 %	101 %	100 %	73 %
10	109 %	111 %	93 %	88 %	82 %	59 %
11	119 %	115 %	107 %	104 %	95 %	64 %

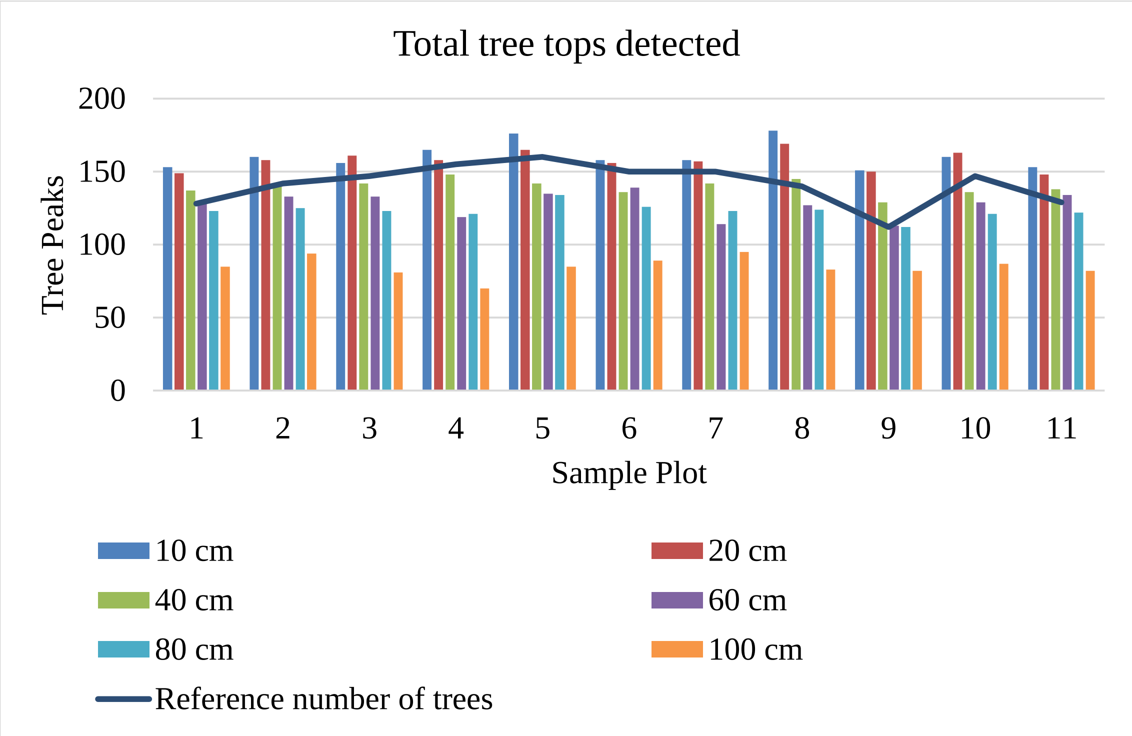
Table No.1: Relative count of tree tops compared to the reference data for each resolution and plot

This chart shows the percentage comparison between reference number of tree crowns and detected trees. This calculation is also called PLA – Plot-level Accuracy. The highest count was calculated in 10 cm resolution – in one case 135 %. This fact was definitely caused by too detailed spatial information which led to the detection of the tree peaks in inappropriate locations (e.g. branches). Quite different situation is in the case of the low resolution. Too general spatial information in combination of uncompromising distance filter caused several drop in count. In one case only 45 % of correct count.

Spatial Resolution	Accuracy	Variance	Standard deviation
10 cm	113%	0.9%	9.4%
20 cm	111%	0.8%	9.0%
40 cm	98%	0.6%	7.8%
60 cm	90%	0.8%	8.8%
80 cm	87%	0.4%	6.5%
100 cm	60%	0.5%	7.2%

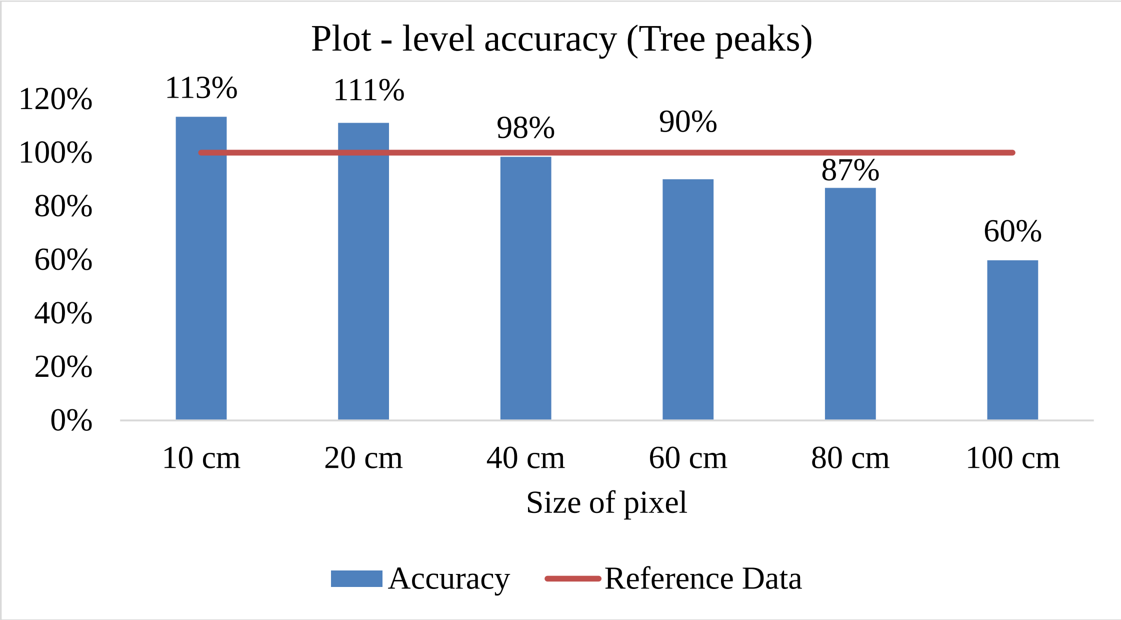
Table No.2: Statistical evaluation of the number of counted tree tops for each spatial resolution

The result closer to the reference data was calculated from the image with spatial resolution of 0.4 m per pixel. The least accurate result was provided by the spatial resolution of 1 m per pixel. However, the variance and logically also standard deviation was smallest in case of 0.8 m ground pixel resolution. This means that the consistency of given results is higher than in other cases.



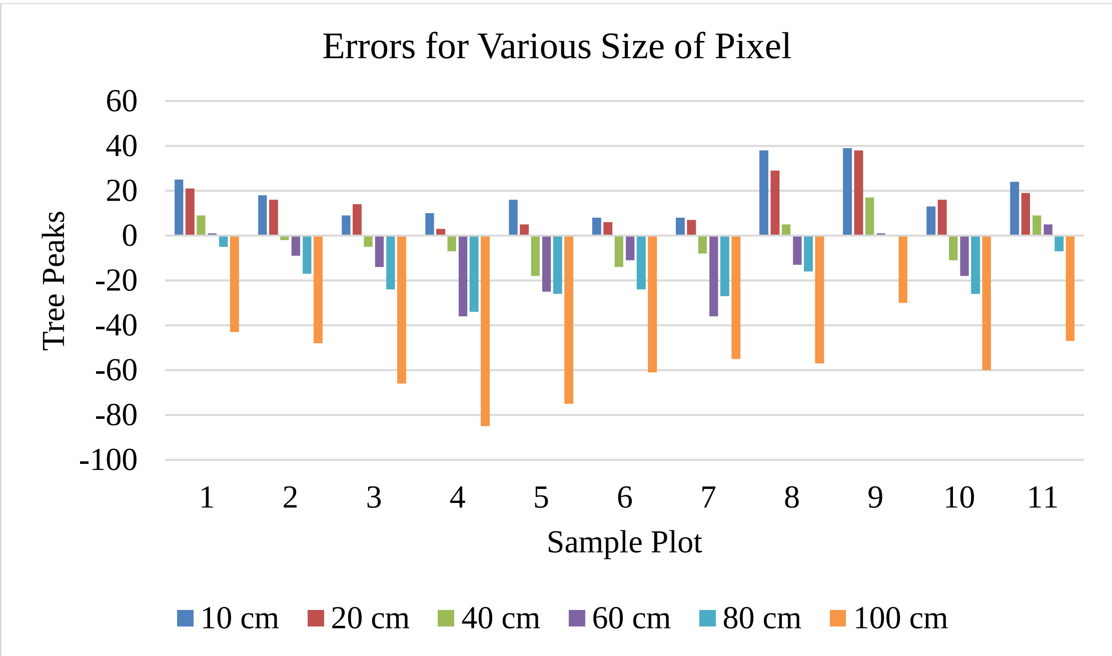
Graph No.1: Total count of tree tops detected for all spatial resolutions on sample plots

Graph No. 1 shows the amount of tree tops detected in carious sample plots. It is clearly visible, that the trend is decreasing with decreasing spatial resolution (except for really rare cases). The dark blue line represents the count of tree tops on reference layer containing manually vectorised trees.



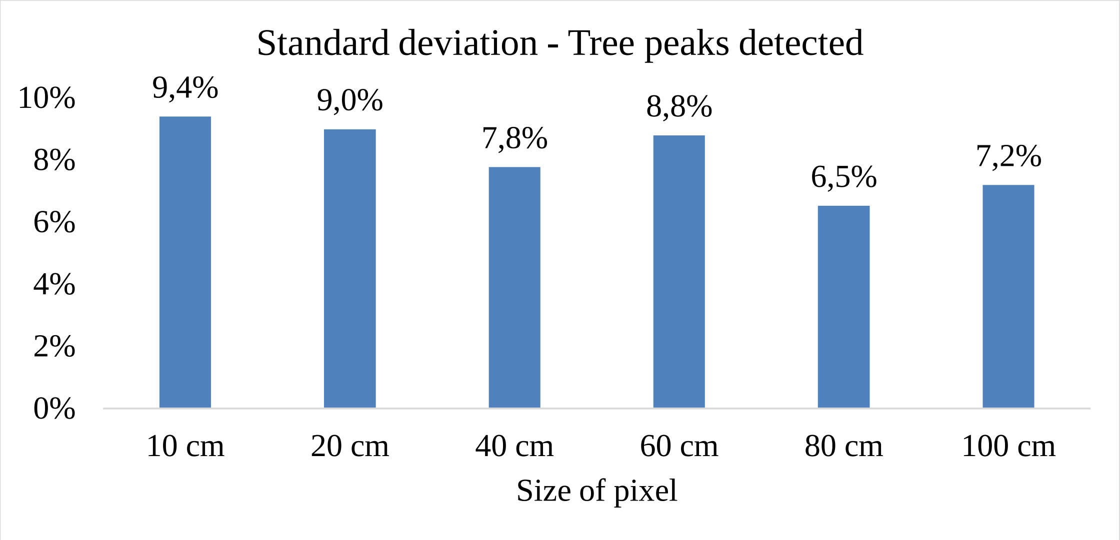
Graph No.2: PLA evaluation of tree count for various spatial resolution

As visible on Graph No.2, the 0.4 m ground pixel size provided the best results with 98 % of accuracy. The decreasing trend is visible among various resolutions.



Graph No.3: Detailed view to the size of errors for each sample plot

Graph No.3 provides basic idea about the progress of the error depending on various spatial resolutions.



Graph No.4: Standard deviation for each spatial resolution

In contrast to the amount of trees detected, the standard deviation does not seem to be affected by changing resolution (see Graph No.4). The highest standard deviation occurred in the case of the highest spatial resolution (10 cm per pixel) while the lowest deviation occurred in case of 0.8 m size of ground pixel.

4.4 Evaluation of total detected area

Sample plot	Spatial resolution					
	10 cm	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
1	120 %	118 %	112 %	109 %	103 %	76 %
2	107 %	108 %	100 %	96 %	91 %	74 %
3	109 %	110 %	103 %	98 %	92 %	66 %
4	115 %	115 %	107 %	95 %	94 %	61 %
5	128 %	124 %	116 %	110 %	111 %	73 %
6	123 %	122 %	112 %	113 %	105 %	81 %
7	133 %	135 %	128 %	113 %	116 %	92 %
8	120 %	120 %	109 %	99 %	99 %	72 %
9	119 %	119 %	108 %	101 %	97 %	71 %
10	127 %	126 %	114 %	111 %	106 %	77 %
11	142 %	139 %	133 %	129 %	122 %	87 %

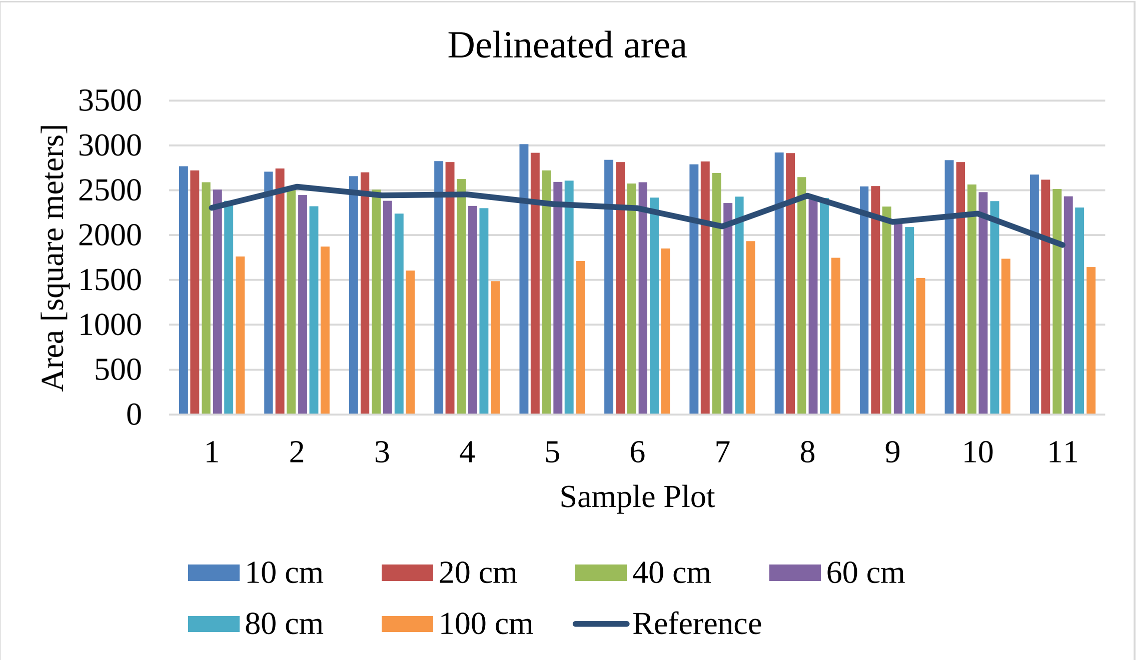
Table No.3: Relative amount of total tree crown area delineated for various spatial resolutions and sample plots

The Table No.3 shows the percentage of area delineated compared to the reference tree crown area. The highest value measured appeared in case of spatial resolution 10 cm per ground pixel while the lowest value appeared in the case of resolution 1 m per ground pixel.

Spatial Resolution	Accuracy	Variance	Standard deviation
10 cm	121 %	1.0 %	9.8 %
20 cm	121 %	0.8 %	8.9 %
40 cm	112 %	0.9 %	9.6 %
60 cm	106 %	0.9 %	9.6 %
80 cm	103 %	0.9 %	9.6 %
100 cm	75 %	0.7 %	8.6 %

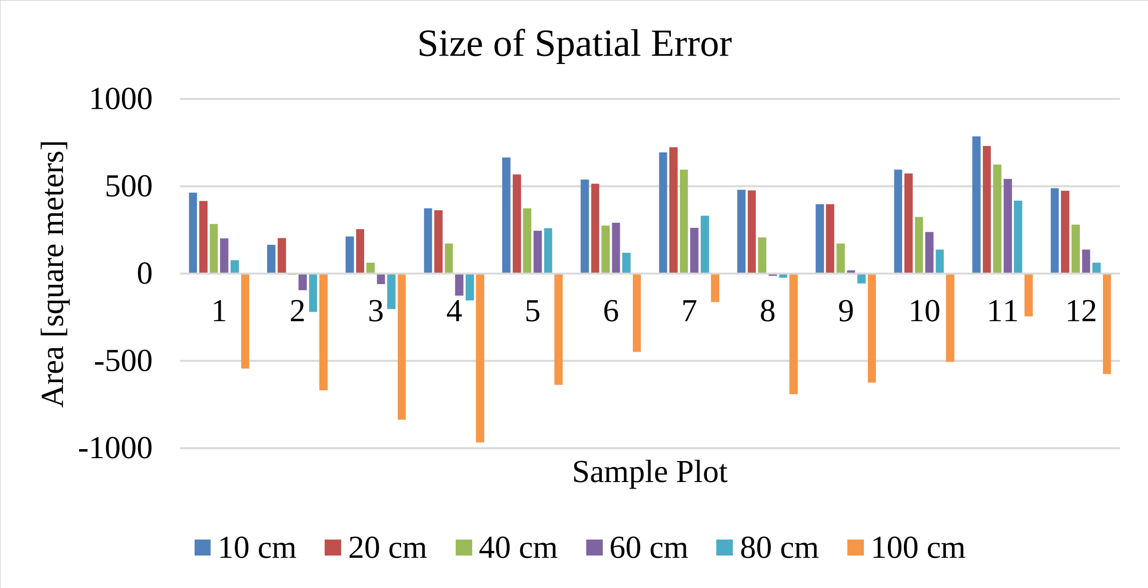
Table No.4: Statistical evaluation of the total area of tree crowns delineated

The Table No.4 shows the percentage of area delineated compared to the reference tree crown area. The highest accuracy occurred in spatial resolution of 80 cm per ground pixel while the lowest accuracy appeared in spatial resolution of 1 m per ground pixel. Despite the low accuracy the lowest resolution provided lowest standard deviation. Considering the fact that second lowest standard deviation occurred in 20 cm spatial ground resolution, the influence of resolution is questionable.



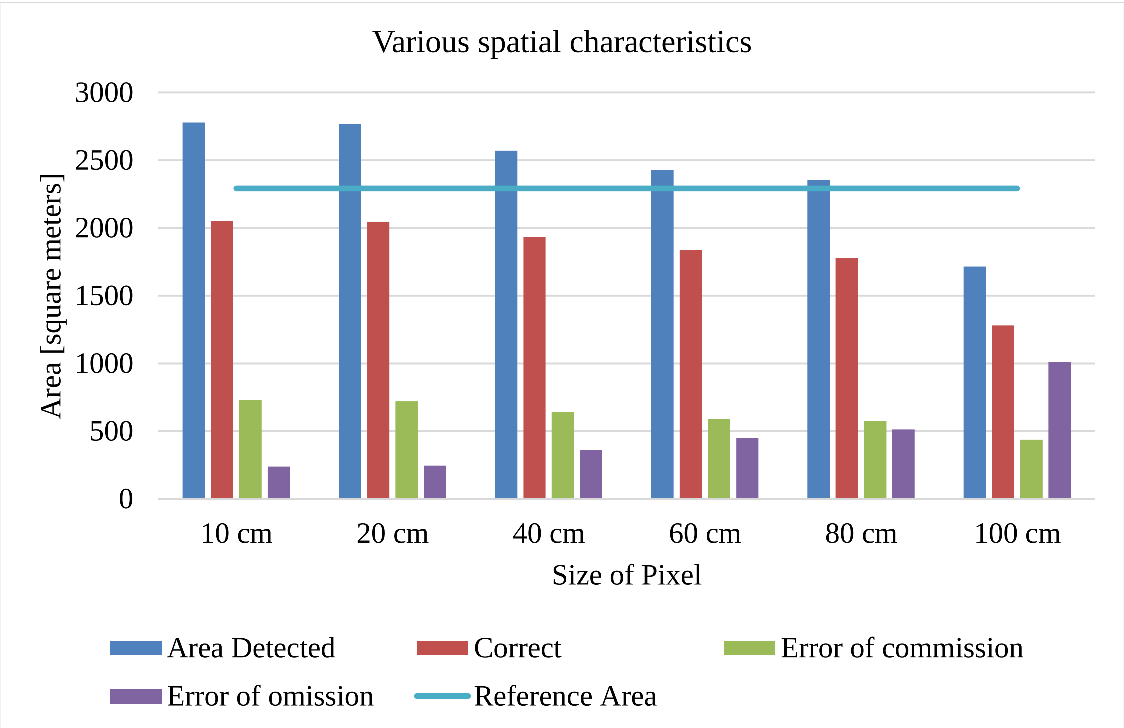
Graph No.5: Delineated area for given resolutions in various sample plots

The trend of decreasing area delineated with decreasing resolution appeared in the case of all plots (see Graph No.5). The dark blue line represents the reference area of tree crowns.



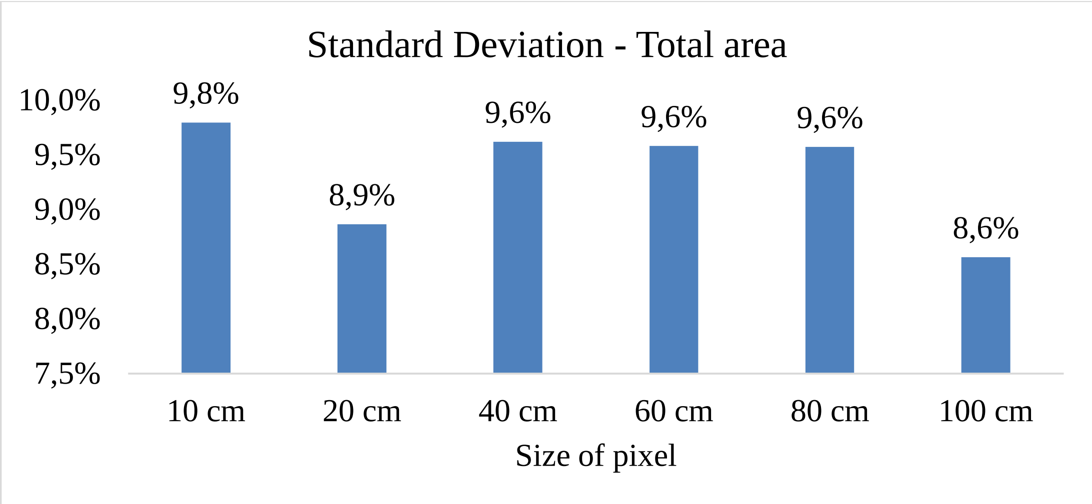
Graph No.6: The size of spatial error for given resolutions in various sample plots

Graph No.6 illustrates the significant change of spatial error among various resolutions. The lowest resolution (1 m per pixel) shows significantly undersized result compared to other resolutions.



Graph No.7: Total delineated crown area, correctly delineated crown area, commission error of delineation and omission error of delineation – all compared with reference area

Various trends are visible from the Graph No.7. The total delineated area is decreasing with decreasing resolution as well as correctly delineated area and level of commission error. The different situation is in the case of omission error which is increasing with increasing resolution of image. Especially in the case of 1 m pixel size, the rapid change is visible.



Graph No.8: Standard deviation of total area detected

The standard deviation is quite variable among resolutions and no trends are visible here (see Graph No.8). The highest is in the case of the highest spatial resolution (10 cm per pixel) and the lowest is in the case of lowest resolution (1 m per pixel).

5 Precision forestry concept

The number of trees in forest stand is one of the most essential information for forest management. Dendrometrical methods very often use method based on mensuration of smaller sample of trees and consequent generalisation of this ‘mean stem’ to the whole area with same typological characteristics. In this case number of trees in the stand is completely crucial. On the other hand, just the number of the trees in forest stand is quite unusable variable.

The forested area itself also does not have any significant value but combination but when total area of all trees is divided by the number of this tree, the result is average area per one tree. Considering the fact that trees tend to create circle shaped crowns, the tree crown area can be generalised to circle and then diameter can be easily calculated. The tree crown diameter is still not often used in forestry management despite the fact, that the diameter of tree crown is influenced by the diameter of the stem.

Almost linear relation exists between crown diameter and diameter at breast height, although this differed between tree species and between geographically distant trees. The crown diameter of young trees was wider than that of older trees. The relation was also confounded by competition between trees, the availability of light and site factors. (Jakobsons, 1970)

Based on previous information, tree crown delineation can be theoretically used for calculation of breast height diameter. Of course this method can never be as accurate as manual calipering of tree stems. However with the respect to the degree of inaccuracy and sample plots terrain verification, this method can be significant vector for forest management.

According to Goulding et al. (2009) field costs for forest inventory are directly related to the amount of walking through the stand, the time to lay out a circular plot and the number of trees to be cruised for stem qualities. All three cost components were significantly reduced using individual tree sampling.

Considering the fact that cost efficiency of (semi-) automated tree crown delineation is diametrically better than in case of any other inventory method, the question arises if the future research and possible practical use of this method is not the near future of forestry management.

6 Discussion

Although the results of the individual tree crown delineation based on inventory seem satisfactory, several circumstances should be taken into account when assessing this approach. First of all, the biological structure of forest stands does not allow any aerial image to interpret the subdominant, intermediate and supressed trees. As a consequence, the results are valid only for the general level of the upper canopy and dominant individuals.

Another important circumstance is the disproportion between the ground pixel size and overall accuracy provided by remotely sensed image. Šíma (2012) disproved the general myth about linear proportion between the ground pixel size and actual accuracy of such images or maps. He concluded that the median coordinate mistake is between 1.5 and 2 times the ground pixel size.

It is necessary to acknowledge the fact that, forest inventory of any kind, suffer from either a smaller or larger error. Knowing this fact, it is necessary to realize that definition of a reference data from forest inventory can be a very complicated process. There is basically no other option than to choose between the field measured data and manually vectorised tree crowns (or combination of both approaches). Nevertheless, both methods have its weak points.

In the case of manual vectorisation, a higher or lower level of generalisation occurs. In addition to this, subjectivity can influence the result because even the human eye is sometimes not able to decide where exactly the border of the tree is located, especially in dense forest stands. However the advantage of this approach is the level of unbiasedness because the computer works with completely the same data as the person who carried out the vectorisation process. On the other hand, humans may recognize some imagery features as tree crowns at first glance but after closer examination of the features this possible mistake can be avoided. Computer automated algorithm working purely on mathematically based approach would virtually not be able to recognize such tricky parts of an image.

In the case of field verifications, a completely different issue occurred. Since the field measurements were performed at ground level and the crown, visually examined ‘against the skies’, the view is completely different from resource aerial images. Moreover, the dominant species standing out of the general level of the upper canopy are sometimes not clearly visible hence omitted. The crown structure is also different when viewed from bottom or from the top. For that matter, it is necessary to perform field verifications in a short period after the aerial images of standing trees are taken. This recommendation is also well-founded in this work. Since the high-resolution multispectral images were taken 5 years before its use for tree crown delineation, the structure of the forest had changed a lot. The wind-throw caused uprooting of several trees in examined sample plots, so the field verification completely lost its relevance.

Another issue with significant influence on the individual tree detection algorithm is the size (the diameter) of the crown. The local maxima filtering with circle-shaped mask of known size is generally based on the fact that we know or we have instruments to estimate the crown size for this purpose. In the case where the filters are too small, larger crowns are divided into smaller parts. In the case where the filters are too big, too small crowns are omitted. So an average tree crown size is questionable for this purpose.

Another big issue is with the filtering of distance between the tree tops. In the case of pre-defined distance value, the smaller crowns are omitted. In addition this approach conclusively determined that, lower spatial resolutions (the ground pixel size higher than approximately 1 m) are completely unusable. The reason could be that, a huge area of tree crown is represented by just one pixel – in the case of neighbouring pixels, the distance filter automatically merge them together as one crown.

Both parts of the algorithm, thus, tree crown detection as well as delineation are affected by heterogeneous structure of the shadow. Not every dark pixel in the image represents the shadow and not every bright pixel represents the tree crown. Especially the higher resolution proved the theory that local maxima can sometimes be located in the shadow whiles tree crown can sometimes be relatively dark.

The region growing algorithm used in this work with seed pixels is considered to be in the centre of the tree crown. This assumption is based on the fact that branches are equally using the space around the tree stem so the tree top remains in the middle. This assumption presents some limitations since sometimes the treetop can be asymmetrically oriented consequently renders the delineation inaccurate. But the worse situation can happen in the case that an extra tree top is located in an incorrect place. In the case that the friction layer around such pixel is penetrable, other correctly placed tree crowns can be pushed away.

The heterogeneous structure of the tree crowns can be solved by the Gaussian smoothing of image, however this instrument was logically excluded in case of this work simply because, re-sampling to the lower spatial resolution replaces average filtering. Despite the fact that this process leads to raw pixelization, the combination with any pre-processing based on filtering by moving mask would lead to the loss of information stored behind the value in the pixel.

It is natural that even in dense forest stands, gaps occur occasionally. Appropriate vegetation index or spectral classification of the image can easily solve the situation in most cases except for one case – the green herbaceous vegetation located under the trees. Even after use of such tools, this green area can be easily recognised as tree crown due to the high reflectance which is sometimes similar to the reflectance of the tree top. A more sophisticated approach like template matching can be the remedy for such cases.

Another issue is the suitability of the method for mixed stands. This method provides reasonable results especially for even-aged homogenous monocultures without any sub-dominant or suppressed under the main canopy layer. However this is exact antithesis for the sustainable forest management based on high biodiversity and stable forest stands. The application of this method as an inventory tool in the case of selection forest is highly unlikely.

The influence of the resolution to both tree count and tree crown areas is obvious from the trends in all graphs showing this issue. This conclusion is supported also by results published by Tuček et al. (2011). This is only comparable study searched because of the similar results assessment methodology and similar forest stand characteristics. Although their best result for coniferous species was achieved in 0.6 m pixel size not 0.4 m, the trend in the decreasing tree count appeared also in this study. In their case, the average result for the pixel size 0.4 m was 94.3 %, 126.5 % for the pixel size 0.6 m and 78.8 % for the pixel size 0.8 m. The shift between the best resolution results can be explained by the absence of distance filtering between tree crowns which significantly increased in size.

Considering the accuracy of the tree crown detection and delineation, this method has its limitations. The level of accuracy in case of tree counting strongly depends on the knowledge of tree crown average size. This model is not suitable for forest stands high variance in the tree crown sizes, however in the even-aged forest with equally developed tree crowns this model represent the biological laws with the degree of accuracy. The accuracy of full callipering method, used for standing volume estimation of mature stands, is 5 % to 10 % which is accurately enough for forest management planning in Czech Republic (Linhart, 2011). However, taking into account the fact that just the basic counting in this study provides results with standard deviation reaching 7.8%, the overall result of standing volume can never reach the required accuracy. It is necessary to realize, that in stand volume equations all variables are being multiplied, so the accuracy of every single variable should be as precise as possible. Though, in all cases, for the forestry inventory use, this method should be definitely combined with the field verification.

7 Summary

A comprehensive research of various informational resources was carried out. The research for the historical first use of tree crown delineation methods was done as well as previous studies dealing with various pixel sizes influencing tree crown delineation process.

Thorough review of tree top detection and tree crown delineation algorithms was made highlighting previous studies that deals with each of those methods. A review of possible data resources and the software capable for tree crown delineation were also made.

Based on the in-depth research and acquired knowledge, this study developed an algorithm in ArcGIS software. Although this algorithm was mainly based on previously published local maxima filtering and region growing method, the use of vegetation index as a friction layer for consequent region growing is yet to be published based on research done by this study.

Evaluation of results were performed for 6 different spatial resolutions: 10 cm, 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. This evaluation was based on the comparison with a manually vectorised 1,560 tree crowns.

In the case of simple tree counting based on local maxima extraction, the most accurate results were provided for the spatial resolution of 40 cm. The accuracy reached 98 % of the reference layer with a standard deviation of 7.8 %.

In the case tree crown delineation, the most accurate results were provided for the spatial resolution of 80 cm. The accuracy reached 103 % of the reference layer with a standard deviation of 9.6 %.

In conclusion, the theoretical concept of application in precision forestry was outlined based on experiences as well as knowledge gained from other literature sources reviewed.

8 Závěr

Za využití různých informačních zdrojů byla provedena rešerše daného tématu. Tato rešerše byla zaměřena na historii využití metody vymezení korun stromů stejně jako na předchozí práce zabývající se vlivem rozlišení na proces vymezení korun.

Byl sepsán přehled algoritmů určených k nalezení vrcholku stromu a vymezení koruny stromů, zmiňující předchozí studie zabývající se těmito metodami. Byl sepsán také přehled použitelných datových zdrojů společně s přehledem softwaru schopného provést vymezení korun.

Na základě rešerše a nabytých znalostí byl vyvinut vlastní algoritmus pro software ArcGIS. Přestože byl tento algoritmus založen především na dříve publikovaných metodách filtrování lokálních maxim a metodě spojování oblastí, použití vegetačního indexu jako frikční vrstvy pro metodu spojování oblastí nebylo podle rešerše nikde publikováno.

Bylo provedeno vyhodnocení výsledků pro 6 různých rozlišení: 10 cm, 20 cm, 40 cm, 60 cm, 80 cm a 100 cm. Toto vyhodnocení bylo založeno na porovnání s manuálně vektorizovanými korunami 1560 stromů.

V případě jednoduchého sčítání stromů založeného na extrakci lokálního maxima bylo dosaženo nejlepších výsledků u rozlišení 40 cm. Tady přesnost dosáhla 98 % v porovnání s referenční vrstvou při směrodatné odchylce 7,8 %.

V případě vymezení koruny stromu bylo dosaženo nejlepších výsledků u rozlišení 80 cm. V tomto případě přesnost dosáhla 103 % v porovnání s referenční vrstvou při směrodatné odchylce 9,6 %.

Na závěr byl nastíněn teoretický koncept aplikace v precizním lesnictví na základě vlastních zkušeností a znalostí získaných literární rešerší.

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10 Annexes

Annex No. 1: Map of the Training Forest Enterprise Masaryk Forest Křtiny with location of Area of Interest

Annex No. 2: Stand map showing the forest stand 187 C 10a with localisation of sample plots

Annex No. 3: Photo taken inside the forest stand 187 C 10a

Annex No. 4: Table containing number of counted trees for each sample plot

Annex No. 5: Table showing the error of counting for each sample plot

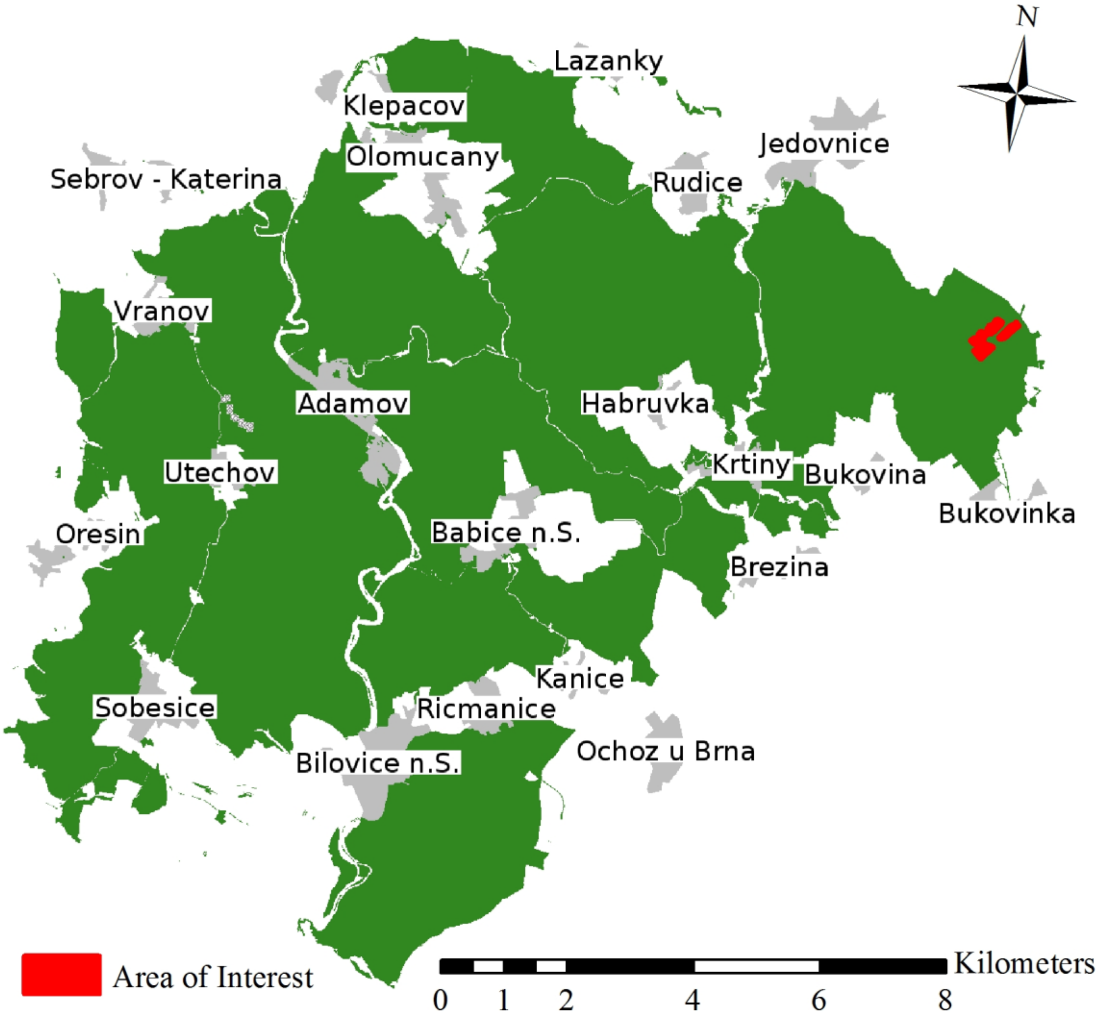
Annex No. 6: Table containing total delineated area for every sample plot (in square meters)

Annex No. 7: Table containing correctly delineated area for every sample plot (in square meters)

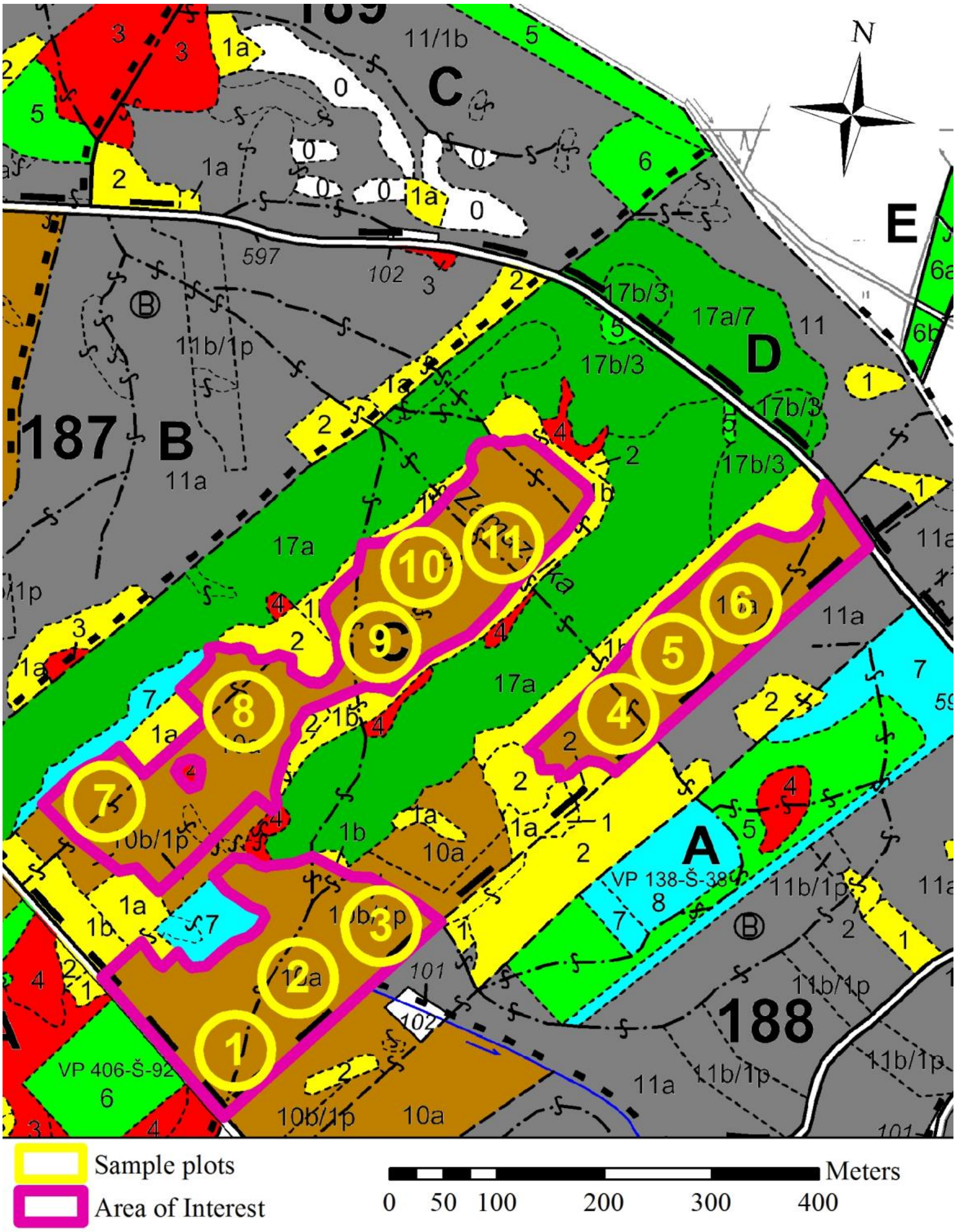
Annex No. 8: Table showing delineation commission error for each sample plot (in square meters)

Annex No. 9: Table showing delineation omission error for each sample plot (in square meters)

Annex No. 1: Map of the Training Forest Enterprise Masaryk Forest Křtiny with location of Area of Interest



Annex No. 2: Stand map showing the forest stand 187 C 10a with localisation of sample plots



Annex No. 3: Photo taken inside the forest stand 187 C 10a

Annex No. 4: Table containing number of counted trees for each sample plot

Sample plot	Spatial resolution						Reference data
	10 cm	20 cm	40 cm	60 cm	80 cm	100 cm	
1	153	149	137	129	123	85	128
2	160	158	140	133	125	94	142
3	156	161	142	133	123	81	147
4	165	158	148	119	121	70	155
5	176	165	142	135	134	85	160
6	158	156	136	139	126	89	150
7	158	157	142	114	123	95	150
8	178	169	145	127	124	83	140
9	151	150	129	113	112	82	112
10	160	163	136	129	121	87	147
11	153	148	138	134	122	82	129
Total	**1,768**	**1,734**	**1,535**	**1,405**	**1,354**	**933**	**1,560**

Annex No. 5: Table showing the error of counting for each sample plot

Sample plot	Spatial resolution					
	10 cm	20 cm	40 cm	60 cm	80 cm	100 cm
1	25	21	9	1	-5	-43
2	18	16	-2	-9	-17	-48
3	9	14	-5	-14	-24	-66
4	10	3	-7	-36	-34	-85
5	16	5	-18	-25	-26	-75
6	8	6	-14	-11	-24	-61
7	8	7	-8	-36	-27	-55
8	38	29	5	-13	-16	-57
9	39	38	17	1	0	-30
10	13	16	-11	-18	-26	-60
11	24	19	9	5	-7	-47

Annex No. 6: Table containing total delineated area for every sample plot (in square meters)

Sample plot	Spatial resolution						Reference data
	10 cm	20 cm	40 cm	60 cm	80 cm	100 cm	
1	2,769	2,721	2,588	2,506	2,382	1,761	2,305
2	2,707	2,743	2,533	2,445	2,321	1,873	2,541
3	2,656	2,699	2,507	2,383	2,240	1,606	2,443
4	2,826	2,816	2,626	2,327	2,299	1,486	2,452
5	3,013	2,917	2,722	2,593	2,608	1,711	2,348
6	2,839	2,815	2,574	2,590	2,419	1,852	2,299
7	2,790	2,820	2,692	2,359	2,428	1,933	2,096
8	2,919	2,915	2,647	2,426	2,415	1,748	2,439
9	2,544	2,545	2,319	2,165	2,089	1,521	2,146
10	2,837	2,814	2,565	2,479	2,378	1,736	2,240
11	2,675	2,619	2,513	2,432	2,307	1,644	1,889
Total	**2,780**	**2,766**	**2,571**	**2,428**	**2,353**	**1,715**	**2,291**

Annex No. 7: Table containing correctly delineated area for every sample plot (in square meters)

Sample plot	Spatial resolution					
	10 cm	20 cm	40 cm	60 cm	80 cm	100 cm
1	2,077	2,060	1,992	1,948	1,817	1,273
2	2,211	2,244	2,116	2,035	1,934	1,557
3	2,142	2,191	2,063	1,955	1,834	1,307
4	2,172	2,194	2,070	1,835	1,799	1,179
5	2,212	2,170	2,034	1,946	1,982	1,270
6	2,090	2,030	1,924	1,875	1,823	1,376
7	1,893	1,919	1,830	1,674	1,698	1,303
8	2,222	2,228	2,062	1,876	1,864	1,384
9	1,850	1,822	1,698	1,643	1,561	1,133
10	2,045	2,036	1,901	1,859	1,786	1,271
11	1,658	1,612	1,564	1,582	1,463	1,036
Total	**2,052**	**2,046**	**1,932**	**1,839**	**1,778**	**1,281**

Annex No. 8: Table showing delineation commission error for each sample plot (in square meters)

Sample plot	Spatial resolution					
	10 cm	20 cm	40 cm	60 cm	80 cm	100 cm
1	692	661	596	558	565	488
2	497	502	419	412	388	317
3	516	509	446	430	407	300
4	659	627	560	495	504	310
5	804	748	691	649	627	441
6	750	786	651	716	598	477
7	898	901	862	685	730	630
8	699	688	585	550	551	364
9	695	723	622	523	529	389
10	792	778	664	620	592	465
11	1,018	1,009	950	851	845	609
Total	**729**	**721**	**641**	**590**	**576**	**435**

Annex No. 9: Table showing delineation omission error for each sample plot (in square meters)

Sample plot	Spatial resolution					
	10 cm	**20 cm**	**40 cm**	**60 cm**	**80 cm**	**100 cm**
1	228	245	312	356	488	1,032
2	329	297	425	505	606	983
3	302	252	381	488	610	1,137
4	280	258	383	617	653	1,273
5	136	177	314	402	365	1,077
6	210	270	375	424	477	924
7	203	177	266	422	398	793
8	217	211	376	563	574	1,054
9	296	324	448	503	585	1,013
10	195	204	339	381	454	970
11	230	277	325	307	426	853
Total	**239**	**245**	**359**	**452**	**512**	**1,010**