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Article

Derivation of Dominant Height and Yield Class of Forest Stands by Means of Airborne Remote Sensing Methods

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Keywords: digital photogrammetry, image matching, digital surface model, canopy height model, forestry

Summary: In forest management and planning there is a permanent need of up-to-date information on forest areas. Digital photogrammetry and airborne laser scanning (ALS) can provide 3-D information on the forest canopy over large areas. In particular, canopy height models (CHM) derived by subtracting the digital terrain model (DTM) from the digital surface model (DSM) provide promising possibilities to determine forest attributes, including tree/stand height and timber volume. In the current study, an ALS-based and a photogrammetric CHM (normalized using an ALS-DTM) were used to estimate forest growth between 2006 and 2011. It was investigated if the CHM can be used to derive dominant height and to estimate the yield power in terms of the yield class of a forest stand. Two approaches were tested. The first approach relies on the conventional input that is also used in the field, i.e. dominant height and stand age, with the tree height obtained from remote sensing data and the age of the stand by field measurement. In the second approach, the yield class was derived from dominant height and height growth, both obtained from remote sensing data. While with the first approach satisfying results could be achieved, the second approach was not successful. Yield class estimation is very sensitive to the input variable height growth, which could not be derived with sufficient accuracy from the CHMs used in the study. It is expected that in the future the estimation of yield class will be more accurate due to longer observation periods, e.g. 10 years, and due to the availability of CHM time series with more than two points in time.

Zusammenfassung: *Ermittlung der Oberhöhe und der Ertragsklasse von Waldstandorten mit Hilfe flugzeuggestützter Fernerkundungsmethoden.* Für die Bewirtschaftung forstlicher Ressourcen und eine vorausschauende Planung werden regelmäßig aktuelle Informationen über die zu bewirtschaftenden Flächen benötigt. Die digitale Photogrammetrie und Airborne Laserscanning (ALS) können räumliche Informationen über ausgedehnte Waldflächen liefern. Insbesondere bieten Kronenhöhen-Modelle (CHM) – berechnet aus der Differenz zwischen Oberflächen- (DSM) und Geländemodell (DTM) – vielversprechende Möglichkeiten zur Herleitung forstlicher Größen, wie z.B. Baum- oder Bestandeshöhe und Holzvorrat. In der vorliegenden Studie wurde ein ALS-basiertes und ein photogrammetrisch erzeugtes Kronenhöhenmodell (normalisiert mit einem ALS-basierten DTM) verwendet, um das Baumwachstum im Zeitraum 2006 bis 2011 zu ermitteln. Es wurde getestet, ob mit Hilfe des CHMs die Bestandesoberhöhe und die Ertragsleistung von Beständen in Form der Ertragsklasse ermittelt werden können. Dazu wurden zwei verschiedene Ansätze getestet. Im ersten Ansatz wurden die herkömmlichen Eingangsgrößen, wie sie auch bei der terrestrischen Aufnahme verwendet werden, herangezogen, nämlich Oberhöhe (fernerkundlich bestimmt) und Alter des Bestands (durch Stammbohrung bestimmt). Bei der zweiten rein fernerkundungsbasierten Methode wurde die Ertragsklasse aus Oberhöhe und Höhenzuwachs ermittelt. Während mit der ersten Methode zufriedenstellende Ergebnisse erzielt werden konnten, erwies sich die zweite Methode als nicht geeignet. Die Ermittlung der Ertragsklasse reagiert sehr sensitiv auf die Eingangsgröße Höhenzuwachs, welche aus den in der Studie verwendeten CHMs nur mit unzureichender Genauigkeit abgeleitet werden konnte. Es ist zu erwarten, dass künftig durch längere Beobachtungszeiträume, z.B. 10 Jahre, und bei Verwendung von Zeitreihen mit mehr als zwei Zeitpunkten eine Schätzung der Ertragsklasse mit höherer Genauigkeit möglich sein wird.

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1 Introduction

Forest management and forest planning require constantly updated information of forest areas. As the collection of data in the field for large areas is time-consuming and costly, methods of remote sensing have a long tradition in providing forest enterprises with relevant data (Gillis & Leckie 1996). During the last decades, new remote sensing sensors were developed with improved geometric, spectral, radiometric and temporal resolution. These new technologies, such as airborne laser scanning (ALS), digital airborne imaging, and high-resolution satellite-borne imaging, enable in combination with advanced software for data processing improved results in terms of thematic accuracy and level of detail.

Actual volume of growing stock and annual yield are the key figures in forest management. While the actual growing stock is important for short- and mid-term planning, annual yield figures are required for long-term strategies, like the determination of the sustainable annual cut rates. In central Europe, yield tables are usually used for this purpose. Yield tables show the expected increase of timber volume in even-aged stands, where a yield class figure and the age of the stand serve as input parameters. As output parameters, yield tables provide tree height, number of stems, basal area, standing volume per unit area, and the diameter at breast height (DBH) (Marschall 1992, Skovsgaard & Vanclay 2008). In reverse, the yield class (describing productivity) can be derived from the stand age and the height of dominant trees. The required input is usually collected in periodic field inventories. However, the measurement of tree height in the field is not very accurate. Errors of the order of up to ± 2 m are quite common (Jablko & Perlwitz 1997) due to the limited visibility of tree tops in dense forest stands. The stand age is usually determined by drilling the stems, which is very time-consuming.

In recent years, the possibility to obtain continuous 3-D information in space and time on the forest canopy has become more and more important for forest applications. In particular, canopy height models (CHM) derived by subtracting the digital terrain model (DTM) from the digital surface model (DSM) provide promising possibilities to determine forest attributes, including tree height and volume of growing stock. In addition, time series of CHMs allow monitoring changes of the forest canopy, i.e. height growth and loss of trees by harvesting and natural disturbances, over large areas. The DTM, particularly in forested areas, is usually obtained from airborne laser scanning (ALS) data. The DSM can be derived either from ALS data or from point clouds generated from aerial images by using matching algorithms.

Recently, the image-based approach has attracted increasing interest for several reasons. The availability of up-to-date digital airborne imagery is usually better than of ALS data, because in many countries there is a periodical nationwide update. At present, the costs of airborne imagery are significantly lower than the costs of ALS data. In addition, digital airborne imagery provides not only geometric but also spectral information, which, in contrast to ALS data, allow the derivation of additional forest information, such as information on tree species and the state of health.

The extraction of 3-D information from airborne imagery has been substantially pushed by the emergence of digital aerial cameras that are able to acquire images with higher overlaps than analogue cameras. This improvement reduces the problem of occlusions in general (Leberl et al. 2010) and makes it easier to capture gaps in the forest canopy. Furthermore, computing capacity is continuously increasing, paving the way for CPU-intensive image matching algorithms. As a consequence, existing algorithms are constantly improving and new algorithms have been developed as well as implemented in standard photogrammetry software.

1.1 *Objectives*

The goal of the current study is to assess the usability of canopy height models (CHMs) derived by photogrammetry and ALS to determine

- stand height,
- height growth, and
- yield class

of individual forest stands.

The yield class, i.e. the productive capacity, of a forest stand is usually determined in the field based on dominant height and stand age. In this study two alternative approaches for the determination of yield class are tested:

- The first approach relies on the conventional input, i.e. dominant height and stand age, with the tree height obtained from remote sensing data (hybrid field-/remote sensing based approach).
- In the second approach, the yield class is derived from dominant height and height growth, both obtained from remote sensing data (approach purely based on remote sensing). For this approach, the conventional yield tables used in Austria (Marschall 1992) were adapted. Usually the height growth can be estimated for a known yield class using yield tables. In the current study the height growth served as an input to determine the yield class.

The following steps were carried out:

- Generation of digital surface models (DSM) using three different photogrammetric software products.
- Calculation of canopy height models (CHM) based on the photogrammetrically generated DSMs and the ALS-derived DTM.
- Quality assessment of DSMs and CHMs.
- Spatial adjustment of field data and remote sensing data.
- Derivation of yield class using the approaches mentioned above.

1.2 *Related Work*

Digital surface models are widely used to model the forest canopy. Studies that compared DSMs derived by image matching with ALS-derived DSMs have demonstrated the potential of image matching techniques for modelling the surface of forest canopies (Baltsavias et al. 2008, Straub & Seitz 2011). However, some characteristic differences between ALS-based and image-based DSMs were found, such as discrepancies at edges of forest and forest stands as well as in inhomogenous stands (Schardt et al. 2004). White et al. (2013) provide a detailed review on the key properties of image-based point clouds in comparison with ALS in forested areas. Hobi & Ginzler (2012) examined DSMs obtained from aerial images and from satellite images. For reference, terrain control points, stereoscopic measurements and ALS-data were used. For forest, that was the most challenging land cover type for surface modelling, they report a median deviation from stereo measurements of -1.1 m (ADS 80) and -1.9 m (WorldView-2).

DSMs normalized by a DTM (usually obtained from ALS data) are widely used for estimating forest attributes, like mean tree height, dominant height, mean diameter, stem number, and growing stock. Compared to the number of ALS-based studies (e.g. Hyyppä et al. 2008, Hollaus et al. 2009, Straub et al. 2010), there are only few studies that investigated the use of image-based DSMs for this purpose so far. Bohlin et al. (2012), for example, used image-based point cloud data to estimate height, stem volume, and basal area by multiple linear regression with percentiles, canopy density measures and texture measures as independent variables. They achieved satisfying accuracies and conclude that photogrammetric matching of digital aerial images has significant potential for operational use in forestry. Straub et al. (2013) combined height information and spectral data, both obtained from stereo images, to estimate timber volume and basal area at the plot level in a mixed forest in Germany.

Some studies directly compared ALS-based and image-based CHMs for estimating forest attributes. However, it is difficult to draw general conclusions from them because the capability to extract forest attributes is dependent on numerous technical parameters, such as point density, flight altitude, image overlap, as well as on properties of the forest canopy itself, such as vertical and horizontal structure, tree species. Järnstedt et al. (2012), for example, found out that the results achieved with the ALS-based features data were more accurate than with the features based on the photogrammetric data. The stand dominant height was the variable that could be estimated most accurately and showed the smallest difference between the ALS and photogrammetric CHMs. Nurminen et al. (2013) also evaluated the feasibility of image matching and ALS for forest variable estimation. They conclude that both methods provide similar performance.

Studies that adress the mapping of the productivity of forests by means of CHM time series are very rare. To the authors' knowledge there is only the study by Véga & St-Onge (2009) that deals with this subject. They tested if the site index (corresponding to the yield class used in Europe) and the age of jack pine stands can be mapped based on known age-height curves and height data extracted from time series of historical image- and ALS-based CHMs over a period of 58 years. They conclude that their method can be used to produce quasi-continuous maps of site index and age as well as to estimate productivity in a spatially explicit way.

2 Material and Methods

2.1 *Test Site*

The test site is located in the north-western part of Lower Austria (15°00' East, 49°00' North), close to the town of Litschau and to the border with Czech Republic (Fig. 1). The forest area with an extension of 4000 ha is part of the forest enterprise Seilern-Aspang.

The altitude of the area is about 500 m above sea level with an average rainfall per year of approximately 700 mm (average of the years 1961 to 1990) and a mean temperature of 7° Celsius (ZAMG 2013). The area is located in the forest growth area 9.2 (Kilian et al. 1994), the so-called Waldviertel, which is characterized by a rawer climate and a shorter growing season compared to areas of similar altitude. According to the forest inventory of 2011/12, the main tree species are spruce (*Picea abies*) with 69%, pine (*Pinus sylvestris*) with 21%, beech (*Fagus sylvatica*) with 4%, and larch (*Larix decidua*) with 1.7% of the area.

2.2 *Datasets*

2.2.1 Permanent sample plots

In the study area, 23 permanent sample plots were installed by the Institute of Forest Growth (WAFO) at the University of Natural Ressources and Life Sciences (BOKU Wien) in 1977. The size of the sample plots, mainly in spruce-pine mixed forest, varies between 400 m^2 and 2000 m^2. On these plots, the tree species, the tree height, and the diameter at breast height (1.3 m) of all trees are assessed and documented every five years. The most recent inventory was carried out in 2012. The rough coordinates of the corner of each sample plot are known in the Austrian national grid. The location of each registered tree was measured relatively to the plot corner. In total, 13 permanent sample plots are located in the area, where also the DSMs were available (see section 2.3.1). These sample plots were considered in the current study.

2.2.2 Non-permanent sample-based inventory

In the study area, a non-permanent sample-based inventory was carried out between 2011

Fig. 1: Location of the test site in Austria.

and 2012. In total 759 sample plots were assessed (435 in 2011 and 324 in 2012) by means of the so-called angle-count-sampling (Bitterlich method; Winkelzählprobe), which is a common method for determining the basal area per ha at a height of 1.3 m above ground (Bestandesgrundfläche) and timber volume of a forest stand. The centre of each sample plot was measured using GNSS methods. For each sampled tree, several attributes were assessed, such as tree species, tree height, diameter at breast height, age, ten-years increment of the diameter. For the study, 63 sample plots were selected fulfilling the following criteria: homogenous stands; pole stage, timber stage or old growth; no harvesting since 2006; inventory carried out in 2012 corresponding to the acquisition year of the permanent sample plots.

2.2.3 Airborne laser scanning data (ALS)

In 2006, airborne laser scanning data were acquired. The original ALS point density was about four points per m^2. For the current study, the EVN GeoInfo GmbH delivered a digital terrain model (DTM) and a digital surface model (DSM) with an interpolated grid of 1 m x 1 m. Based on these datasets, a normalized DSM (nDSM) corresponding to the canopy height model (CHM) in forest areas was derived.

2.2.4 Digital aerial photos and orthophotos

On August 26th, 2011, the study area was covered by a photo flight with a forward lap of 70% and a side lap of 40%. The images were taken with a Vexcel UltraCam-Xp (image format: 11310 x 17310 pixels, physical pixel size: 6 µm, focal length: 100.5 mm, average ground resolution: 0.25 m). In total, the Austrian Federal Office of Surveying and Metrology (BEV) provided 146 digital images (four spectral bands, i.e. blue, green, red, and near infrared), orientation data as well as orthophotos with a ground resolution of 0.25 m.

2.3 *Methods*

2.3.1 Generation of digital surface models (DSM)

Digital surface models were produced using the aerial images of 2011 and the exterior orientation parameters provided by the Austrian Federal Office of Surveying and Metrology. Three software products were tested:

- ERDAS LPS (Intergraph 2013): The authors prepared DSMs (LPS-DSM) with a grid size of 0.2 m for selected areas (in total 1000 ha) with LPS-eATE software (enhanced automatic terrain extraction).
- INPHO MatchT (Trimble 2014): The Austrian Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW) generated a DSM (MatchT-DSM) with a grid size of 0.5 m for the entire study area.
- RSG Remote Sensing Software Package Graz (Joanneum Research Digital 2014): For approximately 1000 ha of the study area, a DSM with a grid size of 0.2 m was generated by Joanneum Research Graz using in-house software (RSG DSM).

The software-specific parameters for the DSM generation were optimized for forest surfaces. All datasets were produced with dense pixel-level resolution.

Comparison of DSMs

The original DSMs (LPS-DSM, MatchT-DSM, RSG-DSM) were converted to a common raster grid with a grid size of 0.5 m. Differences between the DSMs (including the ALS-DSM) were calculated pixel by pixel.

Comparison of DSM-based profiles

On selected sites, profiles were taken to examine the capability of the matching software to reproduce important features such as forest roads and gaps and to analyse the level of detail for stands of different age. Additionally, objects were considered that have definitively not changed within the five-year observation period such as buildings, roads or other open area objects. The profiles were compared qualitatively (visually) and quantitatively.

2.3.2 Generation of canopy height models (CHM)

The canopy height models were produced by calculating the difference between each DSM and the ALS-DTM. It can be assumed that in the test area the terrain did not change between the ALS-flight (2006) and the photo flight (2011). Therefore, the ALS-DTM could be used not only for the calculation of the canopy height model of 2006 (ALS-CHM, difference between ALS-DSM and ALS-DTM) but also for the canopy height models of 2011 (difference between photogrammetrically generated DSMs and ALS-DTM) that were produced using the MatchT-DSM (MatchT-CHM, for the whole area), the LPS-DSM (LPS-CHM, for selected areas), and the RSG-DSM (RSG-CHM, for selected areas).

Examination of the ALS-DTM

The correspondence between the ALS-DTM, which was used for the generation of the CHMs, and the image-based height models were checked by a sample of stereoscopic point measurements. All over the study area, points were selected that did not change in terms of height between 2006 (ALS flight) and 2011 (photo flight). The bias between these two datasets was used to adjust tree (or canopy) height derived by means of photogrammetry.

Evaluation of CHMs

The accuracy of the CHMs was estimated on the basis of tree height measured in the field (permanent sample plots) and with photogrammetric methods (stereoscopic measurements). As the bare ground was not visible, only the tree tops were measured stereoscopically and the height of the ground was extracted from the ALS-DTM. Errors in the co-registration of the field data and the remote sensing data were adjusted manually using tree patterns identified in both data sources by visual inspection.

2.3.3 Estimation of dominant height

In forestry, growing stock and yield class are estimated by means of yield tables using the dominant height and the age of a forest stand. There are several ways to determine dominant height based on field data (diameter at breast height, tree height), such as the dominant height by Assmann (1961) or by Weise (1880). In this study, a simplified approach recommended by Marschall (1992) was applied. The dominant height based on field data (reference) was determined by the mean height of the dominant trees, i.e. the trees with the largest height. Two options for the percentage of considered trees were tested (20% and 33% of all trees of a plot).

For estimating dominant height from the CHM, it was tested, which statistical measure (height percentiles: 75^{th}, 90^{th}, 93^{th}, 95^{th}, 98^{th}, 99^{th}, 100^{th}) derived from the CHM is correlating best with the field-based dominant height. To take into account a possible bias between the CHM-derived tree height and the tree height measured in the field, e.g. due to smoothing effects in the DSM, the CHM-derived tree height was adjusted by linear regression using the dominant height based on field data as a reference (Nuske & Nieschulze 2004). For the calculation of the regression parameters, the permanent plots were used. We did a global regression instead of individual regressions for each development class, because the number of permanent sample plots per development class was not sufficient to get reliable class-specific estimates for the regression parameters. By means of the resulting regression parameters, the 'dominant height' could be derived from the CHM.

2.3.4 Estimation of yield class

The yield class was estimated based on the yield table 'Fichte Hochgebirge' (Fig. 2) for 63 sample plots of the non-permanent inventory. Two approaches were used:

Yield class derived from dominant height and age

The yield class was estimated based on the CHM-derived dominant height and the age of the median basal area tree of the inventory. The results were compared with those derived from the field data.

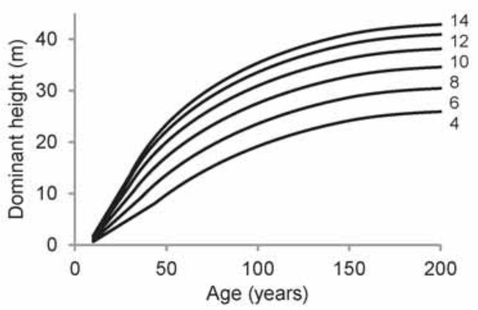

Fig. 2: Yield table 'Fichte Hochgebirge' shown as age-height curves for the yield classes 4 to 14 (Marschall 1992).

Yield class derived from dominant height and height growth

The difference model calculated from the image-based CHM (2011) and the ALS-CHM (2006) represents the five-year growth of the forest stands. The mean height growth and the CHM-derived dominant height (2011) were used as input for estimating the yield class.

3 Results and Discussion

3.1 *Visual Evaluation of the Digital Surface Models*

The DSMs obtained from the image-based point clouds (LPS-DSM, MatchT-DSM, RSG-DSM) show a smoothed surface compared to the ALS-based DSM. Although the spatial resolution is the same for all grids, the crowns of individual trees are easier to identify in the ALS-DSM than in the image-based DSMs. Discontinuities, for example at stand borders, are captured more accurately in the ALS-DSM as well.

Differential images between the ALS-DSM and the photogrammetric DSMs (Fig. 3) show that in the image-based DSMs trees at the border or trees in areas with low stand density are often reduced in height or that they are even missing (highlighted in red). In most cases, these differences between the ALS-DSM (2006) and the image-based DSMs (2011) could not be explained by harvesting or any other change. According to the orthophoto (Fig. 3a), most of the missing trees

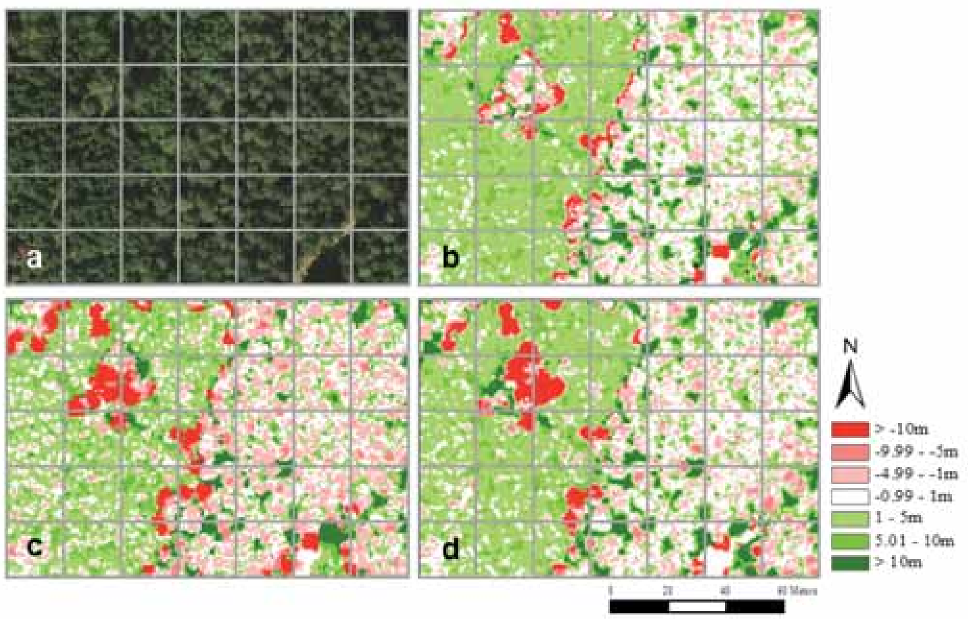

Fig. 3: Comparison of ALS-DSM (2006) and image-based DSMs (2011). (a) Orthophoto, (b) RSG-DSM minus ALS-DSM, (c) LPS-DSM minus ALS-DSM, (d) MatchT-DSM minus ALS-DSM.

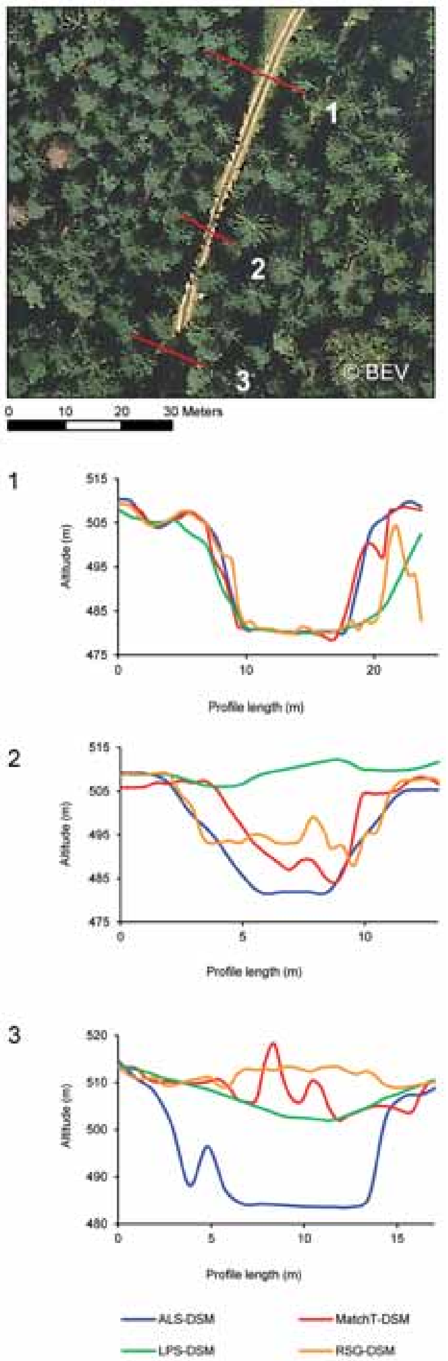

Fig. 4: DSM-based profiles at three positions along a forest road.

were still there in 2011. Pixels highlighted in light green, as prevailing in the left part of the shown area, indicate areas with moderate increase in tree height between 2006 and 2011. This area is dominated by a young stand, where tree growth is naturally stronger than in mature stands (right part of the shown area). In the right part, the tree height is partly a bit lower in the image-based DSMs than in the ALS-DSM (highlighted in light red). It shows that the tree tops are more smoothed in the image-based DSMs than in the ALS-DSM. This artifact is most evident in the LPS-DSM (Fig. 3c). Gaps are captured better in the ALS-DSM than in the image-based DSMs (highlighted in dark green).

The capability of the image-based DSMs to capture gaps depends on the size of the gap and on shadow effects in the images. Profiles at three positions along a forest road (Fig. 4) revealed that the discontinuities caused by the road are reproduced most accurately at position 1, where the area without canopy cover is wide. At position 2 and 3, where the canopy closure is higher and the image is severly affected by shadows, none of the image matching algorithms was able to model the cutting satisfyingly.

Occlusions and shadows caused by discontinuities in the forest canopy are the most limiting factors when deriving DSMs by image matching. While the risk of occlusions can be reduced (but not eliminated) by higher image overlaps, the problems caused by shadows can be controlled to a certain degree only by choosing the time of image acquisition properly. ALS, on the other hand is insensitive to shadows. Besides, it is less affected by occlusions, because data are acquired with only small off-nadir angles and just a single measurement suffices to measure surface height whereas for reconstructing surface height by means of photogrammetry, the surface element has to be captured at least twice. Problems with ALS-derived DSMs of forest canopies can arise due to unknown penetration depth of the emitted pulse that can lead to systematic underestimation of canopy height (Gaveau & Hill 2003, Yu et al. 2004). This effect, however, could not be examined in the current study due to the lack of synchronized reference data.

3.2 *Evaluation of CHM-derived Tree Height*

At first, the agreement between the ALS-based height and the image-based height was checked using 52 control points on the ground spread over the whole study area. The stereoscopically measured height was on average 0.5 m lower than the ALS-based height (RMSE = ± 0.7 m; paired t-test: p = 1.89e-10). The deviations did not show any regional pattern. Thus, a systematic shift between the ALS-data and the airborne images was assumed. To avoid systematic underestimation of tree height if calculated by combining both data sources, the tree height derived by ALS-normalized stereoscopic measurements and the tree height from image-based CHMs were adjusted.

For assessing the accuracy of CHM-derived tree height, 53 trees, which had been measured in the field in 2012 (permanent sample plot) and could be identified in the CHMs of 2011, were measured manually with photogrammetric methods. We found that the stereoscopically measured, shift-adjusted tree height was on average by 0.9 m lower than the height measured in the field (RMSE = ± 3.3 m; paired t-test: p = 0.05). This deviation is clearly larger than the expected growth in height within a 1-year period, suggesting some uncertainties in the field-measured tree height. In Tab. 1 the deviation between the stereoscopically measured and the CHM-derived tree height is documented. The MatchT-CHM showed the best agreement with the stereoscopic measurements and was therefore chosen for yield class estimation (section 3.4 and 3.5).

Tab. 1: Deviation of CHM-derived tree height from stereoscopic measurements.

	Bias (m) *Stereo – CHM*	**RMSE (m)**
ERDAS LPS	2.1	±3.1
INPHO MatchT	1.1	±1.9
RSG	2.0	±2.4

3.3 *Evaluation of CHM-derived Height Growth*

The ALS-CHM (2006) and the image-based CHMs (2011) were used to estimate the height growth during the corresponding period of five years. For accuracy assessment, once again the 53 individual trees, which were measured in the field (permanent sample plot) and could be identified in the CHMs, were used. The difference between tree height based on stereo measurements (2011) and the ALS-based height (2006) came to 2.3 m. According to MatchT, the height growth amounted to 1.0 m on average. The tree height derived by LPS and RSG was on average about 0.3 m lower in 2011 than in 2006, which can be explained by smoothing effects.

In addition to measurements at individual trees, we selected six stands per development stage (pole stage, timber stage, old growth) and draw a profile line with a length of approximately 50 m across each stand. Fig. 5 shows a representative example for the development stages 'Pole stage' and 'Old growth'. The distance between the blue line (ALS-DSM) and the other lines (LPS-DSM, MatchT-DSM, and RSG-DSM) illustrates the height growth from 2006 to 2011. The growth in height was most notable in the youngest development stage (Fig. 5a), which is in agreement with the well known fact that the growth in height is most significant at a young age. The histograms of the differences between image-based height (2011) and ALS-based height (2006) summarize the results of all profiles per development stage. The histograms for the pole stage (Fig. 5a) show a clear prevalence of positive values indicating tree height growth with a maximum at a difference of about 0.5 m to 1.0 m. On the contrary, the histograms for the old growth stage (Fig. 5b) show the maximum around 0. In addition, there is a larger number of entries at higher values. These entries mainly correspond to gaps that were not reproduced satisfyingly by the image-based DSMs. These discrepancies are also evident in the profiles, e.g. at length of 7 m, 28 m, and 38 m.

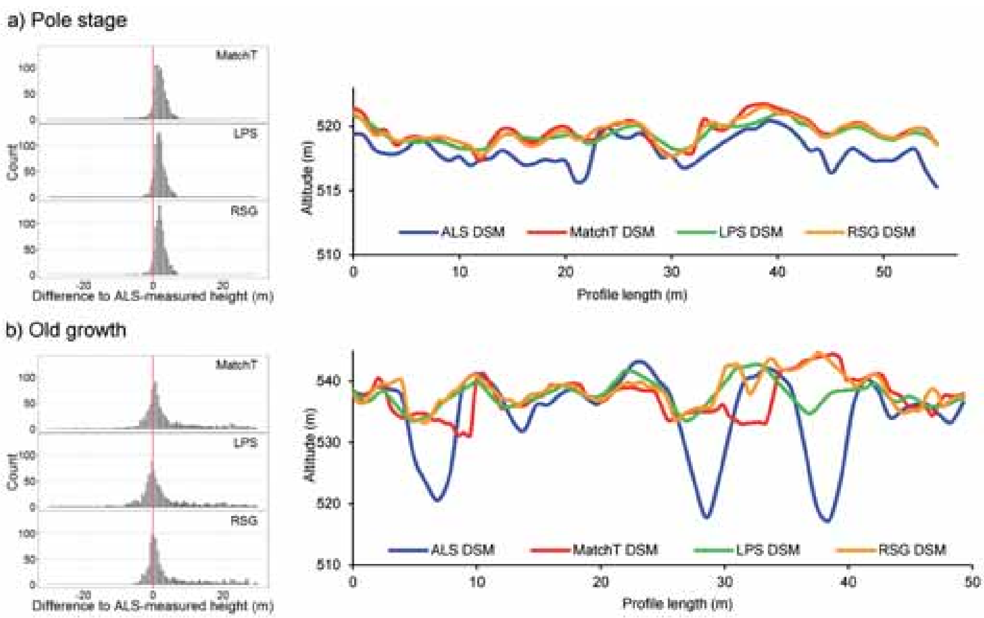

Fig. 5: Representative profiles through the MatchT-DSM, the LPS-DSM, the RSG-DSM, and the ALS-DSM a) for a young and b) for an old forest stand. The histograms summarize the differences between image-based height (2011) and ALS-based height (2006). For the histograms, six profiles per development stage were considered.

3.4 *Estimation of Dominant Height from CHM Data*

For the estimation of dominant height, the 95th percentile of the ALS-CHM and the MatchT-CHM provided the best results for the regression (ALS-CHM 2006/ground reference 2007: $R^2(75^{th}) = 0.92$, $R^2(90^{th}) = 0.93$, $R^2(95^{th}) = 0.94$; MatchT-CHM 2011/ground reference 2012: $R^2(75^{th}) = 0.91$, $R^2(90^{th}) = 0.94$, $R^2(95^{th}) = 0.95$). Using the mean height of 20% of the highest trees of the sample plot, the coefficients of determination were 0.94 (between ALS-CHM 2006 and the ground reference 2007; RMSE = ± 1.2 m) and 0.95 (between MatchT-CHM 2011 and the ground reference 2012; RMSE = ± 1.0 m). The option with the mean height of 33% of the highest trees revealed slightly better results (ALS-CHM 2006 / ground reference 2007: R^2 = 0.94, RMSE = ± 1.1 m; MatchT-CHM 2011/ground reference 2012: R^2 = 0.95, RMSE = ± 0.9 m, see Fig. 6), and were used during the further procedure.

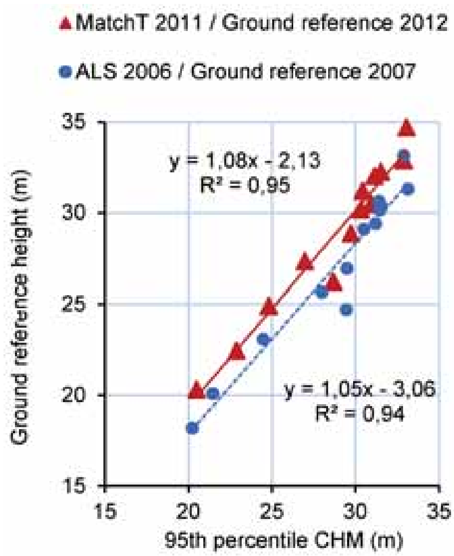

Fig. 6: Linear regression of 95th percentile (CHM) and mean height of the 33% highest ground-measured trees.

In other studies, different percentile values were used to correct tree respectively stand height. For example, Næsset (2002) used the 75th percentile to correct a DSM, and Nuske & Nieschulze (2004) used the 90th percentile for linear regressions to determine mean stand height.

For plausibility checks, 30 stands representing the development stages pole stage, timber stage, and old growth were selected. For these stands the height growth was estimated using the CHM-derived dominant height calculated by linear regression for 2006 (ALS-CHM) and 2011 (MatchT-CHM). The results are summarized in Tab. 2.

The estimates of tree height growth averaged per development stage are plausible for a period of five years. Field measurements in a recently thinned pole stand were in line with the figures outlined in Tab. 2. For 36 trees (27 cut trees, 9 remaining trees) the height growth corresponding to the last five years was measured. The resulting mean height growth was 2.9 m (CHM-derived height growth: 3.5 m).

3.5 *Derivation of Yield Class*

Yield class derived from dominant height and age

For 63 non-permanent sample plots, the yield class was estimated from age and CHM-derived dominant height (approach 1). The result was compared with the yield class based on age and field-measured height (reference) (Fig. 7). The yield class estimated from the CHM-derived dominant height was on average by 0.6 below the reference. The RSME was ± 0.8.

Tab. 2: Results of tree height growth estimation.

	Pole stage	Timber stage	Old growth
Number of stands	12	9	9
Mean area of stands (ha)	1.1	1.7	1.8
Mean height growth (m)	3.5	1.5	0.9
Standard deviation (m)	± 0.7	± 0.4	± 0.7

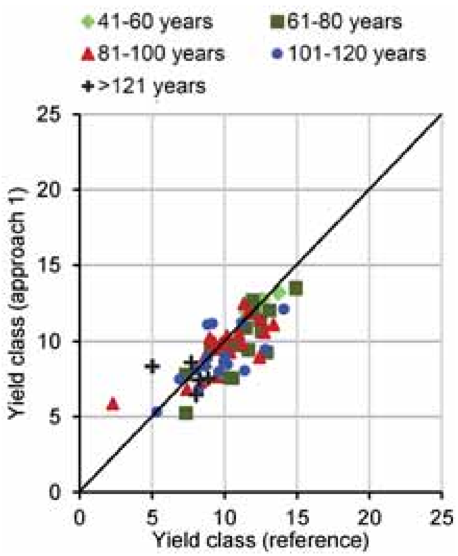

Fig. 7: Result of yield class estimation based on CHM-derived dominant height and age.

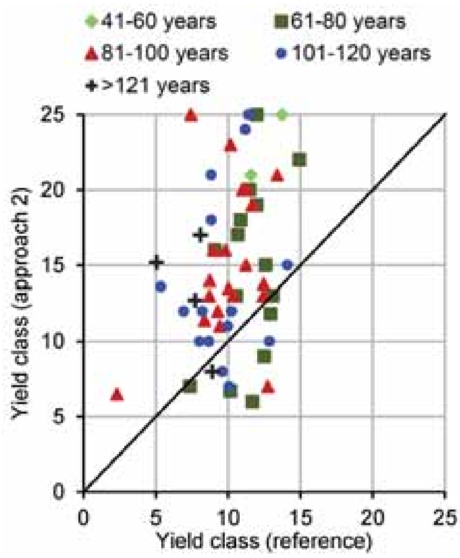

Fig. 8: Result of yield class estimation based on CHM-derived dominant height and height growth.

Yield class derived from dominant height and height growth

For 63 non-permanent sample plots, the yield class was obtained from the CHM-derived dominant height and the average height growth between 2006 and 2011 (approach 2). In Fig. 8 the results are plotted against the reference. The yield class estimated from the CHM-derived dominant height was on average by 5.2 higher than the reference. The RMSE was ± 7.9.

The results of the first approach corresponded to the terrestrial yield class estimates quite well. The results of the second approach were not satisfying. This can be explained by two reasons: First, the yearly tree height growth (depending on climate and other external influences) shows a high variability. Therefore, mean values of a five-year tree height growth are uncertain. Second, the estimation of tree height growth by means of photogrammetry showed uncertainties as well. In any case, the yield class estimation by means of yield tables is very sensitive on the parameter height growth due to the shape of the height curves (Fig. 2). Thus, a small uncertainty in height growth causes disproportional errors in the resulting yield class. Additionally, ambiguities can occur for specific combinations of dominant height and height growth. The error in estimating yield classes based on height growth may also be increased by the problem that the commonly used yield tables date back to the beginning of the 20th century and underestimate the height growth of today's forest stands (Bösch 2002).

4 Conclusions and Outlook

Based on ALS data acquired in 2006 and on digital aerial images taken in 2011, canopy height models (CHMs) were calculated. From the CHMs, the dominant height as well as the height growth of forest stands was derived, and it was tested if these parameters are suitable for the estimation of the yield class. The DSMs were generated photogrammetrically by means of image matching with three different software products. The resulting DSMs were evaluated with respect to their quality to characterise forest surfaces. For all investigations, ground reference data were available in form of forest inventory data and permanent sample plots.

The use of ALS data acquired some years ago for normalizing up-to-date DSMs was feasible, as the terrain relief below forest canopies can be assumed as constant for a longer period. However, multi-temporal CHMs from different data sources, e.g. ALS-based DTM and photogrammetrically generated DSM, essentially need to be co-registered accurately. Besides, a possible bias in height between the ALS data and the image data, e.g. determined by stereoscopic measurements, has to be considered.

The comparison of ALS-based and image-based DSMs revealed that photogrammetric methods have problems in representing small gaps, the surface of areas close to stand boundaries, and the surface of areas affected by shadows. All photogrammetric DSMs showed the tendency to smooth the surface of the forest canopy in general and to underestimate tree height of individual trees in particular. This systematic difference between the ALS-based and the image-based height affects the estimation of height growth based on these data sources.

The 95th percentile of the CHM proved to be a proper approximation of the dominant height. The estimation of yield class by means of CHM-derived dominant height and age provided satisfying results. The estimation of yield class from CHM-derived dominant height and height growth, however, revealed unsatisfactory results, caused by uncertainties in the determination of height growth and by limitations regarding the suitability of the available yield tables. It is expected that more accurate yield class estimates can be achieved if the observation period is longer, e.g. 10 years, and if CHM time series with more than two points in time are available.

The presented method will benefit from several technical improvements that are expected for the future. The systems for in-flight logging will provide more accurate results of the exterior orientation and consequently the geometric accuracy of the information derived from the images will be higher. The radiometric, spectral and geometric resolution of digital cameras are continuously improving and will contribute – in combination with image matching algorithms that are being constantly enhanced – to more detailed and more accurate surface models. Besides, in the future the CHM time series will be consistent in terms of sensor technology and systematic differences of DOMs caused by the diversity of the acquisition systems will be avoided.

The current study revealed that there are still some issues that need improvement, both in terms of data basis and data processing. However, it can be stated that remote sensing is able to substantially supplement conventional field-based methods as it provides information about forests and their development over large areas very efficiently and it is able to map important forest attributes in a spatially explicit and continuous way.

In general, the use of yield tables and the derivation of yield classes can be put into question due to the fact that small changes of input parameters result in a high variability of output parameters. Yield tables are mainly used to estimate future growth rates, and with no other methods available, yield tables may serve as a makeshift for this purpose. In a different and more promising approach, future growth rates should be derived by novel growth functions directly derived from multi temporal canopy height models.

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