PILOT STUDY ON THE RETRIEVAL OF DBH AND DIAMETER DISTRIBUTION OF DECIDUOUS FOREST STANDS USING CAST SHADOWS IN UAV-BASED ORTHOMOSAICS

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ABSTRACT:

One fundamental metric to characterize trees and forest stands is the diameter at breast height (DBH). However, the vertical geometry of tree stems hampers a direct measurement by means of orthographic aerial imagery. Nevertheless, the DBH in deciduous forest stands could be measured from UAV-based imagery using the width of a stem´s cast shadow projected on the ground. Here, we compare in-situ measured DBH of 100 trees with the DBH visually interpreted from cast-shadows derived in UAV-based aerial imagery. Then, based on simulated datasets, we determine suitable DBH sampling sizes for a robust and efficient retrieval of stand diameter distributions. The UAV-based DBH estimation resulted in an r² of 0.74, RMSE of 7.61 cm, NRMSE of 12.8% and approximately unbiased results. According to our simulations it can be assumed that a sample size of 25-50 individual DBH measurements per forest stand allows estimating reliable diameter distributions. The presented pilot study gives a first insight on the potential of such an approach for operational assessments of diameter distribution in deciduous forest stands and might be particularly interesting for stands in difficult terrain situations. The presented approach can be extended to estimate the basal area, timber stock or biomass.

1. INTRODUCTION

Sustainable forest management requires repeated assessments of forest inventory metrics including stand attributes, as e.g. tree density, basal area or standing timber volume. Traditionally, these measures are periodically recorded using ground-based field surveys (Speidel et al. 1972). However, such field surveys are typically labor- and cost-intensive. During the last decades various remote sensing techniques have been examined and were found to be useful to support such forest monitoring tasks. Nowadays, new remote and proximate sensing technologies along with unmanned aerial vehicle (UAV) technology emerge at an unprecedented pace and offer new possibilities to develop applications for foresters. What makes these systems particularly interesting for practitioners is that recent UAV systems equipped with RGB cameras and functions such as automatic flight planning (through waypoints) have become readily available as off-the-shelf-products. The strength of such systems lies in the opportunity to acquire aerial data with high temporal and spatial resolution at relatively low costs. Additionally, photogrammetric software bundles have become more and more intuitive and therefore user friendly. This makes the technology also attractive and applicable for persons with only a little experience in photogrammetry or geomatics, who can now produce standard aerial photogrammetric products such as orthophotos or digital elevation models through standardized processing chains.

The general value of UAV systems for the acquisition of remote sensing data has been presented in various studies (Dandois & Ellis 2013; Wallace et al. 2016). Likewise, the potential of UAV-based photogrammetry for forest management applications has recently been highlighted in studies ranging from automatic mapping of tree individuals and deriving their crown height and diameter (Fritz et al. 2013; Kattenborn et al. 2014; Sperrlich et al. 2014; Lisein et al. 2013), tree species identification (Gini et al. 2014) to biodiversity assessments (Getzin et al. 2012).

However, until now applications using UAV-based photogrammetry to retrieve the diameter at breast height (DBH), diameter distributions or the basal area remain limited. This contrasts the great importance of these parameters for practitioners to describe individual trees or stands, respectively. A particular limiting factor for the aerial photogrammetry-based retrieval of the DBH, and thus basal area of a forest stand, is the fact that trees are predominantly growing vertically and the upper parts of the tree including branches and foliage typically obscure the direct view on the stem. A direct measurement of the DBH based on orthographic aerial imagery is therefore not possible. An approach to overcome this issue is to estimate the DBH indirectly through allometries between DBH and variables which are more likely to be retrieved from photogrammetric data, such as single tree height or crown diameter (Kattenborn et al. 2014; Sperlich et al. 2014; Turski et al. 2012; Verma et al. 2014). Particularly in regard to coniferous forests, methods such as pouring algorithms (a segmentation procedure based on canopy height models) have been proven as relatively accurate to map single trees and their crowns which enables the derivation of individual tree heights and a crown diameters (Sperlich et al. 2014). However, the indirect estimation of the

DBH is inherently limited, since it requires a priori established species specific allometries, which are firstly not available for all tree species and secondly often limited in transferability due to disparate site and management conditions. Furthermore, orthographic remote sensing data such as orthophotos or canopy height models might not depict trees in the understory which are obscured by overlapping tree crowns. This is particular relevant for uneven aged deciduous or mixed stands, meaning that smaller trees are less likely to be considered in the estimated DBH distribution and basal area for a given stand. Further limitations with particular respect to deciduous forest stands are the rather smooth transitions among neighbouring canopies, which hamper an accurate delineation of individual crowns (Sperlich et al. 2014).

An alternative for the detection of tree individuals and their DBH estimation from aerial photogrammetry was demonstrated by Tarp-Johansen 2002a,b, who used airborne imagery acquired in leaf-off state to estimate the stem dimensions of individual oak trees based on the diameter of their cast shadow. We hypothesize that this concept is transferable to UAV-based photogrammetry. Especially for rather inaccessible terrain a DBH assessment of individual trees using digital imagery could be economically more efficient than the traditional ground-based measurements as once the imagery is acquired, the measurement of the shadows can be conducted in the lab. The following pilot study aims firstly to assess the capabilities, limitations and accuracy of using cast-shadows data to retrieve the DBH of individual trees in heterogeneous forest with varying topography. In a second step, we examine whether it is possible to estimate the diameter distribution of a stand using the suggested approach. A fundamental requisite for this step is to determine a suitable sampling size of individual DBH measurements per stand that are required for a robust and efficient retrieval of a stand´s diameter distribution. We address this question by applying forest inventory data for forest stands simulated with a forest growth simulator to estimate a robust and efficient sample size for widely varying stand conditions.

2. METHODS

2.1 Data acquisition and processing

The study site is a heterogeneous deciduous ‘Maulino’ forest stand in the Maule Region, south-central Chile (Gajardo 1994). Forest management activities are limited to selective logging. The dominant species is *Nothofagus glauca* (southern beech), with some accompanying species such as *Azara petiolaris* and *Aristotelia chilensis*. The study site was chosen as it features a high heterogeneity in terms of forest structure as well as topographic properties, assuming that these two properties affect the perceptibility of stem shadows. Prior to data acquisition, the forest stand was affected by a forest fire (March 2017). Although, the fire primarily affected litter in and on the ground and did not ignite living vegetation, the heat was sufficiently high to permanently damage the xylem of the trees leading to defoliation several days after the fire. The ground truth data consisted of 100 trees, which were arbitrarily selected by a local forest practitioner along a curvaceous transect. The course of the transect was created in a way to maximize the variation in DBH, terrain slope, terrain aspect as well as tree density as perceived in the field. For each tree the DBH was measured using a caliper. The position of each sampled tree was marked using paper sheets (30 x 40 cm) placed next to the tree that were used to directly link the samples with the acquired UAV data. The respective diameter distribution of all sampled trees is shown in Fig. 1.

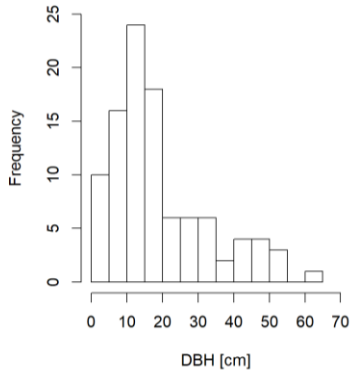

Figure 1. Histogram of the DBH values of all sampled trees (n=100)

The UAV orthomosaic was acquired using an octocopter (HiSystems GmbH) equipped with a standard consumer grade camera (Canon 100D, 28 mm focal length, 5196 x 3464 pixels). A single autonomous image flight at 120 m above the starting position was performed using parallel stripes with a distance of 90 meters. The starting position was located at the highest position of the study site at around 190 m above sea level (in the top left corner in Fig. 2). The flight took approximately 5 minutes and took place on 4 pm on the 23/03/16. Images were acquired with a frequency of 1.4 Hz, resulting in a side overlap of at least 50% and a forward overlap of at least 95 %. The imagery was processed in a standard photogrammetry processing pipeline (Agisoft Photoscan, St. Petersburg, Russia) resulting in an orthophoto of 2 cm resolution and a photogrammetric point cloud. The latter was processed setting the densification quality to high (1/4 of the raw image size) and the depth filtering mode to low as the raw data and the accuracy of the alignment was considered to be of very high quality, resulting in little noise during the densification process. Based on the point cloud, a Digital Terrain Model (DTM, Fig. 3, 4) was derived using the software TreesVis (Weinacker 2004) that interpolates a DTM using the implemented surface filtering (Elmqvist 2000) and the active contour algorithm (Blake & Isard 1998).

Figure 2. The UAV-based orthomosaic. The positions of the sampled trees (n=100) are shown in white.

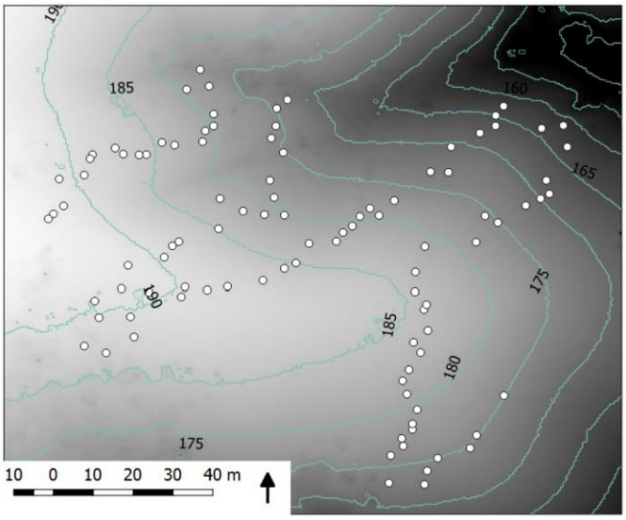

Figure 3. The Digital Terrain Model (DTM) derived by the photogrammetric point cloud. The positions of the sampled trees (n=100) are shown in white.

2.2 UAV-based DBH measurements

The position of each individual sampled tree was identified and digitized using the paper sheet markers laid out in the field. The DBH projections on the ground were calculated using the R-package insol (compare Fig. 5) (Corripio 2014) using the digitized tree positions, the DTM, the sun azimuth and the zenith angle as input. By this means, the explicit locations of the tree shadow sections that correspond to the DBH height (1.3 m) were projected on the digital terrain model incorporating the sun orientation corresponding to the time of the UAV flight (sun zenith of 38° and azimuth of 324°) as well as the local terrain conditions (DTM). The projected DBH locations were automatically marked and then used to manually measure the diameter of the respective tree shadow in a GIS.

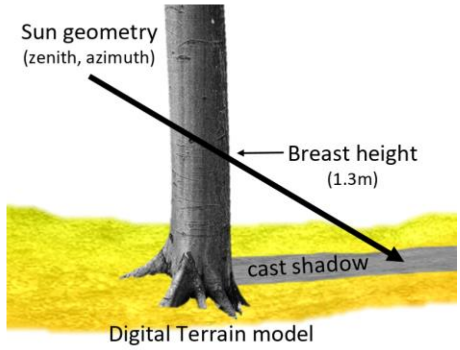

Figure 5. Scheme showing the projection of the DBH position (at 1.3 m height) on the ground (DTM).

The manual estimation of DBH from the cast shadows, i.e. shadow width, was performed by five different interpreters. Each of the interpreters completed a "training phase", by measuring the DBH of a subset of 10 trees of which they knew the in-site DBH measurements. After the "training phase" the interpreters measured the DBH value for the full set of sampled trees without having access to the reference data. Each interpreter performed three runs to assess whether the interpreters produce better results over time and whether the measurements are consistent. The accuracy of the DBH estimates was assessed using the r^2 (squared Pearson's product moment correlation coefficient) and the root mean square error (RMSE) between the estimated DBH values and the in-situ measurements.

We assumed that the successful retrieval of the DBH can be affected by the image quality in several ways: First, the shadow of a stem might be overlapped by the shadow of another stem or canopy. Second, the line of sight between the camera and the area corresponding to the DBH-position may be occluded by the canopy elements (e.g. branches). Third, the image quality can hamper an accurate measurement of the width of the stem, e.g. due to blurry images, low contrast of forest floor and shadow. Hence, "Confidence level classes" were introduced in order to give the interpreter the opportunity to judge the quality of the imagery at each sample tree location. Therefore, the

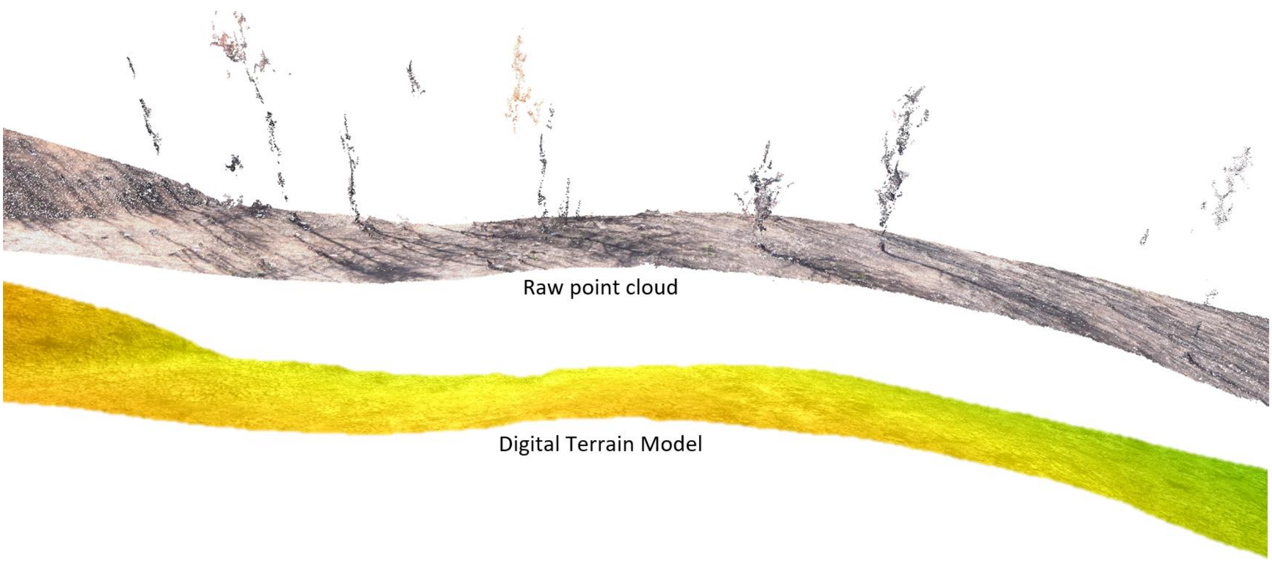

Figure 4. Transect (10m width) showing the raw point cloud (top) and the interpolated Digital Terrain Model (DTM, bottom).

interpreters reported for each tree a confidence class defined as follows:

0 = *the shadow of the tree stem was not visible* (DBH = NA, Fig. 6a)
1 = *the shadow could hardly be interpreted* (low confidence, Fig. 6b)
2 = *the shadow could be reliably interpreted* (moderate confidence, Fig. 6c)
3 = *the shadow was clearly visible* (high confidence, Fig. 6d)

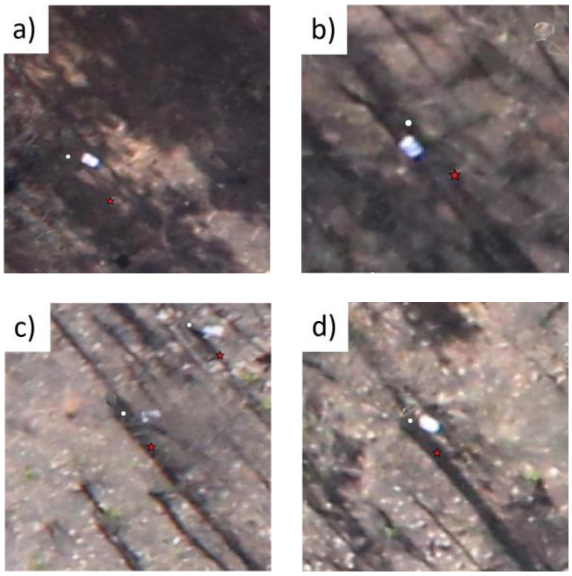

Figure 6. Examples of the four confidence levels used for grading the DBH measurements; i.e. DBH not measureable = 1 (a), estimated with low confidence = 2 (b), estimated with moderate confidence = 3 (c), estimated with high confidence = 4 (d). White points show the position of the tree stem and red points indicate DBH position (1.3 m) projected on the ground.

2.3 Identifying an efficient sample size

To assess the generic trade-off that can be expected between sampling efficiency and accuracy resulting from different sample sizes for estimating the DBH distribution of forest stands, we simulated forest stands using the forest growth simulator SILVA 2.2. (Pretzsch 2009). The latter has been parameterized using long-term forest inventory data for the states of Bavaria and Lower Saxony in Germany, as well as from Switzerland (Biber et al. 2000). SILVA simulates the spatio-temporal dynamics of forest stands considering each tree and its attributes, e.g. DBH, individually. The variability among individuals is incorporated as a function of site conditions and competition among neighbouring trees (for details see Pretzsch 2009; Biber et al. 2000).

We simulated 100 deciduous forest stands (Fagus sylvatica) of 1 ha, featuring 216 to 1596 individual trees per stand, depending on the initialization parameters, age and treatment (see Fassnacht et al. 2018 for details). From the SILVA outputs of each forest stand, random DBH samples between 2-200 trees were drawn. Subsequently, the quantiles (Q10 to Q90 with a 10% step size) of the samples were compared to the quantiles of the entire forest stand by calculating the r^2 (squared Pearson's product moment correlation coefficient) and the root mean square error (RMSE) to infer how accurately the sample-based DBH distribution represents the DBH distribution of the entire forest stand (Kangas & Maltamo 2000).

3. RESULTS

3.1 UAV-based DBH measurements

The correlation (r^2) between the UAV-based estimates of all users and the in-situ measurements was 0.74, while the corresponding RMSE was 7.61 cm. There was no clear difference in r^2 or RMSE between the three consecutive runs of the interpreters (Tab. 1). Overall, no severe bias between estimated and reference DBH could be observed, except for small trees which were slightly overestimated (mean residuals = 2.161, intercept 0.92, compare Fig. 7). At average the users categorized 9.6% of the tree diameters as not measurable. 28.6% of the DBH values were estimated with low confidence and 29.3% of the trees were rated as reliably estimated. The largest share of the DBH retrievals was classified as measured with high confidence (32.5%). The accuracies in terms of r^2 increased from low to high confidence with an r^2 of 0.69 to an r^2 of 0.76. The bias in terms of mean residuals increased from low to high confidence (1.3, 2.3, 2.5 cm), whereas the bias in terms of intercept between measured and reference did not notably differ (0.91, 0.93, 0.91). The accuracy did not markedly change (r^2 of 0.74 vs 0.76) between intermediate confidence (reliably estimated DBH) and high confidence (clearly visible DBH).

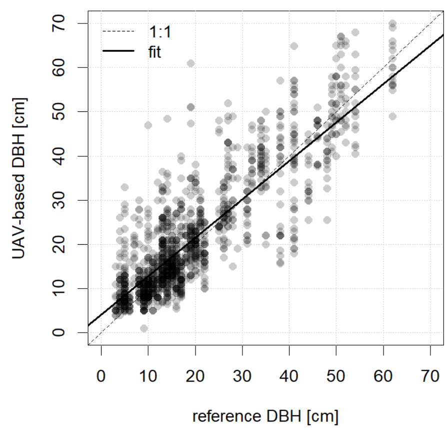

Figure 7. Scatterplot between in-situ measured DBH and the UAV-based estimates of the 5 interpreters.

run	r^2	RMSE [cm]	NRMSE [%]
1st	0.74	7.74	13.1
2nd	0.76	7.10	12.0
3rd	0.73	7.98	13.5

Table 1. Summarized accuracy of the DBH measurements of all interpreters for the three consecutive runs

confidence	r^2	RMSE [cm]	NRMSE [%]	% of total
0 (not measurable)	NA	NA	NA	9.6
1 (low confidence)	0.69	7.69	13.0	28.6
2 (intermed. confidence)	0.74	7.67	13.0	29.3
3 (high confidence)	0.76	7.45	12.6	32.4

Table 2. Summarized accuracy of the DBH measurements for the different confidence classes and the respective share (% of total trees).

3.2 Identifying an efficient sample size

The accuracies for the examined sample sizes (r^2 and RMSE) of the estimated diameter distribution using the simulated forest stands are shown in Fig. 8 For small sample sizes the correlation between the DBH distribution estimated from the sample as compared to the real DBH distribution of the stand shows a steep increase and a turning point at approximately 25 samples with an RMSE of ca. 1.6 cm. Using a doubled sample size an average RMSE of 1.5 cm can be expected. Sample sizes higher than 50 individual measurements only result in little and almost linear improvement in accuracy.

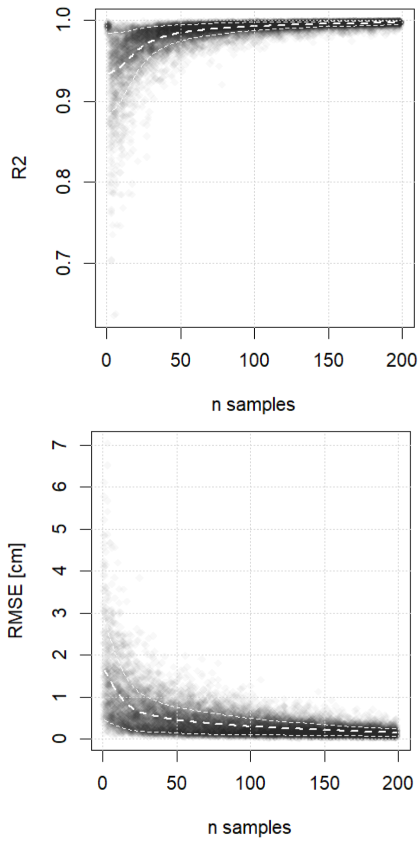

Fig. 8. The trade-off between sample size and accuracy for the estimation of stand-wise DBH distributions. The plots depict the accuracy in terms of r^2 (top) and RMSE (bottom) of the sample based DBH distribution compared to the DBH distribution of the simulated forest stands as derived by SILVA. The mean and standard deviation (white lines) were derived by smoothing splines.

4. DISCUSSION

Earlier attempts to retrieve DBH from cast shadows of trees using high resolution aerial imagery were restricted to even-aged oak stands and flat terrain (Tarp-Johansen 2002a; Tarp-Johansen 2002b). In the present pilot study we transferred this concept to UAV-based aerial imagery on a forest stand with complex structure and topography. We used a digital terrain model (DTM) obtained from the photogrammetric UAV point cloud to compensate for the effect of the terrain and the thus varying length of the projected shadows. The results show that cast shadows in UAV-based orthomosaics can be used to manually estimate the DBH of individual trees with reasonable accuracy in deciduous forest stands during leaf-off state. Given that no strong trend (bias) for over- or underestimation of DBH values was observed, it can be assumed that for a retrieval of stand inventory variables (e.g. DBH distribution or basal area) an appropriate sampling size partly compensates the errors of individual measurements.

Cast shadows of tree stems that were not fully visible (class 1: low confidence) were still a valuable source to estimate the DBH of individual trees as we found hardly any difference in accuracy between the three confidence classes. The quality of individual tree measurements, however, was found to be rather unstable. The reported RMSE values of over 7 cm (approximately 4 pixels) are not sufficient for individual tree characterization as for example required in precision forestry. The errors of individual DBH measurements could presumably be further reduced by increasing the spatial resolution of the UAV imagery. Here, we used UAV data with a pixel size of 2 cm, which inherently limits the accuracy of the DBH retrieval that can be achieved. We assume that this is also the primary reason for the slight bias observed for small trees. Based on our experiences with this dataset we recommend to use a spatial resolution of 1 cm or higher.

According to our results, there is a chance of approximately 10 % and 30 % that the DBH could not be estimated (confidence = 0) or only with low confidence (confidence < 2), respectively in stands similar to the one examined here. This is primarily a result of the spatial arrangement of multiple trees. For some trees the shadow section corresponding to the projected DBH could not be visually recognized as it was obscured by overlapping shadows or branches. This issue could be reduced by performing several flights at different times of the day which would result in varying directions of the cast shadows. Accordingly, a stem which is not visible at a certain sun angle might be fully recognizable at a different sun angle. Assuming that for additional flights at different sun angles the ratio of visible tree stems is the same, using two flights at different times (e.g. morning and afternoon) would theoretically increase the fraction of measurements with moderate and high confidence (class 2 and 3) to 85 %. Yet, it is questionable if this is economically feasible. In order to estimate the diameter distribution of a stand eventually not all trees have to be fully visible, since the diameter distribution of a stand can be estimated based on samples as demonstrated in the second part of our study.

The effectiveness of the presented methodology to estimate the diameter distribution depends on the number of DBH samples that have to be interpreted. We thus examined the trade-off between accuracy and sampling effort using simulated forest stands derived from SILVA. The results indicate an initially drastic increase in accuracy until 25 sampled trees. This trend levels off and sampling sizes greater than 50 only result in a small, almost linear increase in accuracy. The appropriate sampling size obviously depends on the precision demands of the study at hand as well as the local forest structure. However, according to our results it can be expected that sampling 25-50 trees per forest stand can provide an acceptable DBH distribution with an expected RMSE below 2 cm across a wide range of stand structures. Even though the SILVA simulations only refer to Beech (Fagus sylvatica) stands, we believe that the general magnitudes are transferrable to other temperate deciduous forest ecosystems. Concerning the selection of trees that are interpreted within the UAV imagery, it should be considered that retrieving robust estimates of a stand´s diameter distribution requires a representative sampling design to account for characteristics such as the age distribution in a stand. In this regard a standardized sampling scheme, such as random points or a regular grid may be used, where those trees are sampled that have the smallest distance to a given sampling point and can be identified in the UAV images. This would also be important to avoid the introduction of a bias towards trees located in less dense areas of the forest stands, which are potentially easier to interpret in the UAV images.

The presented concept may easily be extended to estimate the total basal area of a stand by estimating the tree density. Furthermore, the DBH and diameter distribution are direct inputs for modelling biomass and timber stock of forest stands (Zianis et al. 2005), which could hence be readily estimated using the described methodology. We argue that the digital sampling of tree diameters and determining the diameter distributions of entire forest stands using cast-shadows is a simple method which could be suitable for forest practitioners. The current pilot study highlights the potential of the presented concept but cannot be considered as a general proof of concept. Conclusive validations require a random sampling scheme of in-situ DBH instead of subjective sampling, further test sites as well as a direct comparison of estimated and reference diameter distributions. More sophisticated approaches using feature detection techniques may be used to automatically identify trees and measure their diameter (see Tarp Johansen (2002b) for an example). Yet, it can be assumed that automatized approaches are less transferable among stands with varying characteristics. Furthermore, it is questionable if an automatized procedure would allow for comparably accurate delineation of trees shadows which are less distinct, e.g. through overshadowing of other tree stems (compare Fig. 6).

It has to be emphasized that evergreen shrubs or coniferous trees might locally hamper the visual assessment of cast shadows. As such the presented approach is less suitable for forests with dense and complex understory. A rather obvious but severe limitation is that the presented methodology can only applied in leaf-off state and during sunny conditions. Furthermore, it should be noted that the length of a stem´s shadow and therefore the retrieveability of the DBH depend on the solar zenith angle at the time of the acquisition. Thus, depending on the latitude of the area of interest, the acquisitions are best performed with a sufficient time gap before or after solar zenith in order to acquire tree shadows of sufficient size. Despite these limitations, the approach holds some potential if we assume that a consumer grade UAV system may soon be part of the standard equipment of a district forester. Recent UAVs systems are small, portable and can be launched with an automated flight plan within a few minutes. This would for example allow a forester to spontaneously collect an acquisition suitable for the suggested methods during idle times (e.g. while waiting for colleagues). The task might also be suitable as an active-break for more demanding tasks like timber-harvesting. Furthermore, the subsequent image analysis does not require highly-trained professionals and could hence be comparably cost-effective.

An alternative for an individual DBH estimation was presented by Fritz et al. 2014, who used photogrammetric point clouds derived from oblique imagery in leaf-off state, where the trunk diameter was directly estimated from the reconstructed points of the individual stems. The results are very promising, but require a more sophisticated algorithms and hence may be less user-friendly. A further and conceptually similar alternative is the application of an UAV-based LiDAR (Jaakkola et al. 2017), which for example is not limited to sunny weather conditions and leaf-off state. It should, however, be noted that such a system is notably more expensive in acquisition and potentially more expensive and time-demanding in their application as they usually cover less area in a given time due to increased weight of the payload. The obvious advantage of UAV-based LiDAR systems is their capability to partly penetrate the canopy so that it is neither restricted to leaf-off state acquisitions nor to deciduous forests. However, whether an accurate retrieval of DBH values from UAV-based LiDAR is possible and efficient under a wide range of condition is still to be proved.

5. CONCLUSION

We conclude that the presented methodology could be an effective and low-cost tool for forest monitoring in deciduous forest stands. As today's UAVs can cover large areas in a short time span the presented methodology could potentially reduce travel costs and men hours of inventory surveys. The method might be even integrated as an active break in other work tasks. Especially for relatively inaccessible areas a UAV-based sampling scheme might be a promising alternative to traditional field surveys.

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