Parameters Influencing Forest Gap Detection Using Canopy Height Models Derived From Stereo Aerial Imagery

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Zusammenfassung: Lücken sind wichtige Strukturelemente für die Waldbiodiversität. Zur automatisierten Kartierung von Lücken in Relation zur umgebenden Bestandeshöhe und –bedeckung entwickelten wir eine Methode, welche auf von Stereo-Luftbildern abgeleiteten Kronenhöhenmodellen (CHMs) und einem LiDAR- Geländemodell beruht. Zur Evaluierung der Methode und der Bestimmung der wichtigsten Fehlerquellen wurden in einem 1021 ha großen Modellgebiet im Schwarzwald (Südwestdeutschland) die Kartierergebnisse aus drei Befliegungen (2009, 2012, 2014) verglichen. Die Befliegungen von 2009 und 2012 hatten eine Bodenauflösung von 20cm und eine Überlappung von 60 % in Flugrichtung und 30% quer. 2014 war die Bodenauflösung 10cm und Überlappung 80%, respektive 60%. Die Validierung erfolgte durch visuelle Stereointerpreation. Schattenvorkommen und die geometrischen Grenzen der Stereobildauswertung wurden als Hauptfehlerquellen erkannt.

Abstract: Gaps in the canopy are important elements for forest biodiversity. We developed a method based on Canopy Height Models (CHMs) derived from stereoscopic aerial imagery and a LiDAR-based Digital Terrain Model (LiDAR DTM) to automatically delineate forest gaps in relation to height and cover of the surrounding forest. To evaluate the factors affecting the mapping accuracy, we compared the results from three different flight campaigns (2009, 2012 and 2014) in a 1021-ha model region in the Black Forest, Southwestern Germany. The public campaigns of 2009 and 2012 were taken with an overlap of 60% within stripe and 30% between stripes and an overall resolution on ground of 20cm. Data from 2014 had a 10cm resolution and an overlap of 80% within stripe and 60% between stripes. The validation was done by visual stereo-interpretation. Shadow occurrence and geometric limitations of the stereo aerial imagery were identified as main error sources.

1 Introduction

Forest gaps are considered important structural elements in forest ecology. They play a key role in forest regeneration processes (GETZIN et al. 2014) and provide suitable habitat structures for animal species that depend on semi open habitats (SIERRO et al. 2001; MÜLLER & BRANDL 2009; ZELLWEGER et al. 2013). Canopy gaps are therefore of great interest for research in the fields of stand structure and regeneration dynamics as well as biodiversity and nature conservation. In

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addition to the widely used traditional field-data collection for identification and quantification of the canopy gaps in ecological studies, the use of remote sensing data has been recently recognized as a good source of suitable data enabling the analysis of the canopy structure at various, often broad spatial scales. The first method that is usually chosen for forest gap detection (VEPAKOMMA 2010; VEPAKOMMA et al. 2012) and habitat mapping for biodiversity and nature conservation purposes (SEIBOLD et al. 2014; BRAUNISCH et al. 2014; BÄSSLER et al. 2010) is Light Detection and Ranging (LiDAR) that is considered to deliver a more detailed picture of the horizontal and vertical forest structure than any other remote sensing system. However the recent technical advances in the field of digital photogrammetry demonstrate the great potential of the automatic image matching for the generation of Canopy Height Models (CHMs) and for deriving important forest parameters (STRAUB et al. 2013; WANG et al. 2015; KOTREMBA 2014, BETTS et al. 2005). Thus, to assess the viability of gap detection based on publicly available data we focused our research on CHMs derived from the standard stereo aerial imagery and the official LiDAR based Digital Terrain Model (LiDAR DTM), which are delivered in regular time intervals by the regional mapping agency of Baden-Württemberg (LGL). We aimed for a gap mapping tool which would deliver standardized and replicable results when applied on publicly available data either in form of original aerial imagery, point clouds or a raster CHM.
Gaps were detected and delineated in relation to height and cover of the surrounding forest in three steps: (1) open and dense forest are identified, (2) dense forest is classified into low and high forest and (3) gaps are extracted in the latter two classes. The method is described in ZIELEWSKA-BÜTTNER et al. (2016). In this conference paper we present parameters influencing the method performance with regard to canopy gaps detection (1). In addition we test in more detail the benefits of using a shadow mask (2) and discuss effects associated with variance in flight conditions (3). We also consider the variance introduced by different image matching algorithms (4). Finally, the influence of spatial resolution and overlap of the stereo aerial images are presented comparing the results obtained with data of different flight campaigns (5).

2 Material and Method

2.1 Study area

The study area of 1021 ha (excluding the mountain lake surface of the Huzenbacher See) is located in the State of Baden-Württemberg, Southwestern Germany, in the northern Black Forest (8° 34’ E, 48° 58’ N). It is characterized by a heterogeneous topography with elevation ranging from 493 to 941 m, and a high variance in forest successional stages. Most slopes (77,5 %) are very steep (> 20°) or strongly inclined (10 - 20°) (AG BODEN 1996). Among the dominant tree species are Norway spruce (*Picea abies* L.) with admixture of Silver fir (*Abies alba* Mill.) and Scots pine (*Pinus sylvestris*). The broadleaved tree species account for less than 30 % in most (> 80 %) forest stands. The area is covered by a dense forest road network of 187 m/ha and underlying different protection regimes.

2.2 Remote sensing data

As primary input data for the method development, aerial imagery datasets from three flight campaigns (2009, 2012, 2014) were used. Data (including the absolute orientation of the images) were provided by the state agency of spatial information and rural development of Baden-Württemberg (LGL) as pan sharpened, 4 channels (red, green, blue and near-infrared (RGB NIR)) stereo aerial images with radiometric resolution of 8 (2009) and 16 (2012 and 2014) bit. Data of 2014 originated from a special flight campaign of the Black Forest National Park. The overall spatial resolution of the imagery was 20 cm with an overlap of 60 % (end lap) and 30 % (side lap) in 2009 and 2012; and 10cm, 80% and 60% respectively, in 2014. In line with our goal of using only publicly available data, we limited the additional data used in the study to the products of the LGL (LiDAR DTM) or internal data of the forestry administration (forest road network dataset).

Tab. 1: Technical characteristics of the aerial image data used in the method development (2009, 2012) and the higher resolution and overlap data comparison (2014) (from ZIELEWSKA-BÜTTNER et al. 2016, modified)

Year	**2009**	**2012**	***2014***
Camera	UltraCamXp	DMC II 140 – 006	*UltraCamXp*
Panchromatic / color lens focal length	100 / 33 mm	92 mm	*100.5 mm*
Resolution	20 cm	20 cm	*10 cm*
Overlap	60 % / 30 %	60 % / 30 %	*80 % / 60 %*
Image type	Digital color infrared (RGB NIR)	Digital color infrared (RGB NIR)	*Pansharpened digital color infrared (RGB NIR)*
Angle-of-view from vertical, cross track (along track)	55° (37°)	50,7° (47,3°)	*55° (37°)*
No. of stripes in the block file	3	6	*4*
No. of pictures in the block file	23	48	*69*
Flight date	23.05.2009	01.08.2012	*17.07. – 19.07.2014*

2.3 Gap mapping method

The gap mapping method was based on Canopy Height Models (CHMs) of 1 m ground resolution including the potential vegetation points of height between -1 and 55 m vs. the LiDAR DTM. The Digital Surface Models (DSMs) serving as basis for the CHMs generation were calculated from the stereoscopic aerial imagery using two image matching algorithms: Leica Photogrammetry Suite enhanced Automatic Terrain Extraction (LPS eATE (ERDAS 2012)) and Semi Global Matching (SGM XPro (Hexagon Geospatial 2015). As the two algorithms returned different point clouds partially complementing each other, in the initial study for the method development we decided, based on visual assessment, for a combination of three point clouds from eATE and SGM processed with the pyramid levels 0, 1 and 2 respectively to reach the best point coverage in a reasonable processing time. The detailed settings of both algorithms and the single processing steps are given in ZIELEWSKA-BÜTTNER et al. (2016). The point cloud editing was carried out with LAStools (ISENBURG 2014) whereas the LAS to a raster transformation was done in ArcGIS ("LasDataset to Raster"). For the gap detection a constantly closed surface was produced by filling the no-data areas with a including inverse distance weighting (IDW) interpolation method.

The gap detection was carried out in ArcGIS 10.3 (ESRI 2014) (raster and vector based) in three steps: (1) identification of open and dense forest, (2) classification of dense forest into height classes of low and high forest and (3) gap extraction in the latter two classes. We defined gaps as canopy openings in dense forest (>=60% canopy cover) of at least 10 m² reaching through all forest strata down to maximum 2 m vegetation height in high forest stands (>=8 m height) and down to maximum 1 m in low forest stands (<8 m height). A minimum stand size of 0.3 ha is related to the size of the conventional minimum stand size in Baden-Württemberg (MATHOW 2016). Areas with canopy cover less than 60% and exceeding 0.5 ha were classified in line with AHRENS et al. (2004) as "open forest", where the free spaces between the trees are considered as inherent stand characteristic and thus not mapped as gaps. 10 m² is the minimum size of a gap defined in line with MÜLLER & WAGNER (2011) and SCHLIEMANN & BOCKHEIM (2011). The maximum gap-vegetation height was set to 2 m after BROKAW (1982) and adapted by the authors to 1 m in the lower stands.

2.4 Validation

To evaluate the gap mapping performance we compared the automatic mapping results with the visual stereo-interpretation of the original aerial imagery on an independent dataset of sample plots using Stereo Analyst for ArcGIS 10.2 (GEOSYSTEMS GMBH 2014). As we expected the results to vary in relation to the terrain situation, 120 plots with a radius of 25 m (covering 2.4 % of the dense forest area) were placed according to a stratified random design into stands of three steepness classes (0-10°, 10-20°, >20° (AG BODEN 1996)) and four aspect classes (N, E, S, W), resulting in 12 terrain classes represented by 10 sampling plots each. Gaps with an area of at least 10 m^2 inside the plot (168 in 2009 and 171 in 2012) were visually assessed, delineated and compared with the automatically mapped gaps located with at least 10 m² inside the evaluation plot. The gap–absence was evaluated on circles of 95 m² (mean size of the visually mapped gaps in both years) randomly placed in dense forest within the sampling plots in an amount equal to the visually verified gaps per year. At least 8 m² (80% of the minimum gap size) of overlap with the visually identified gaps was needed to confirm the correct classification of the automatically detected gaps or to classify a "non-gap" circle as incorrect. The agreement between visual and automatic mapping was then quantified in form of overall, producers´ and users´ accuracy as well as Cohen's Kappa. An effect of selected parameters such as height of the surrounding forest, shadow occurrence (assessed visually), gap size, slope, aspect and gap location in relation to forest road, skidding trail or an open area (storm throw, open forest) on gap mapping results was tested using the Conditional Inference Trees (ctree) vignette of R-package "partykit" (HOTHORN et al. 2006).

To evaluate the influence of the missing original height information on the gap mapping performance, a no-data mask was generated as a raster of 1 m resolution from the final point clouds (combination of eATE and SGM pyramid 1 and 2 point clouds) of 2009 an 2012. It included only the raster cells, where no points were directly matched during the image matching process. As for the gap detection a constantly closed surface was used, by a comparison with the no-data mask the resulting improvement in accurracy was evaluated.

To quantify the effect of sun elevation on the image quality, we calculated a shadow mask for the data of 2009 and 2012. We definded as shadow an area without any textural differenciation. The classification was done by a visually defined threshold. As the data from the two study years had diffent radiometric resolution, two different methods had to be used to calculate the shadow fraction in the aerial images. For the images from 2009 that had been resamped to 8-bit resolution we used for this year a Ratio S calculated according to SARABANDI et al. (2004) as S=arctan(Blue/max {Red/Green}). For 2012 data with 16-bit resolution we used the Intensity channel of the transformed images (CONRAC CORP. 1980).

2.5 Comparison with data of higher overlap and resolution

To evaluate the potential influence of higher resolution and overlap of the aerial imagery on the method performance, PETERSEN (2015) applied the gap mapping method to a study polygon of 95 ha located in the south-western corner of the original research area (Fig. 1) using data from a special flight campaign of the National Park Black Forest in 2014 (Tab. 1). Gap mapping results based on these pansharpened RGB NIR aerial imagery of 10 cm resolution and 80% and 60% end and side lap were compared with those obtained from the lower-resolution public data of 2012, using the eATE algorithm for point cloud generation. The CHMs used for gap extraction in 2014 were calculated based on the LiDAR derived DTM of the National Park Black Forest, as obtained from their own flight campaign in 2015.

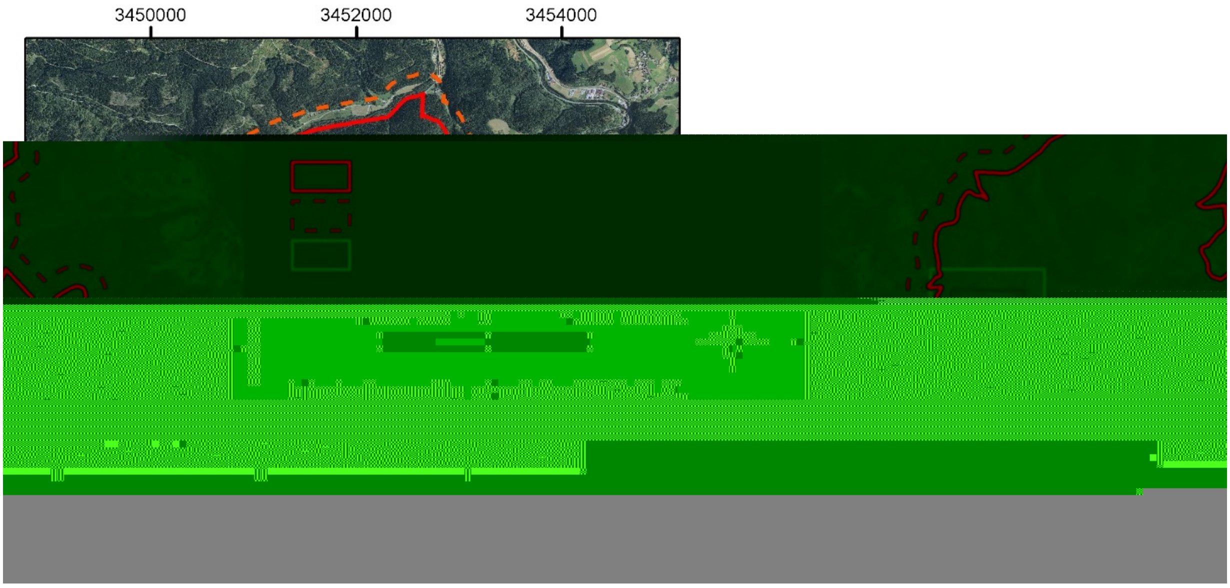

Fig. 1: Location the test area for comparison of 2012 and 2014 data within the original study area presented on the background of the available orthophotos from 2012 and 2014.

3 Results

3.1 Gap mapping results

We detected 4575 (2009) and 4667 (2012) gaps in the dense forest of the study area using the automated method, what results in a total gap density of 4.9 gaps per ha (7.2 % of the dense forest area) in 2009 and 4.7 gaps per ha (6.3 %) in 2012. Considering the forest height classes, more gaps (13.7 and 14.6 N/ha in 2009 and 2012) covering a greater area (45 and 46 ha respectively) were mapped in the forest stands lower than 8 m compared to the higher forests with a gap density of 2.0 and 2.8 N/ha and mapped gap area of 25 and 16 ha in 2009 and 2012, respectively. The most (> 75%) of all detected gaps in both study years were very small or small (less than 100 m²) accounting for 13 % and 23% of the total gap area per year in 2009 and 2012, respectively. The visual validation resulted in an overall accuracy of 0.90 and 0.82 in 2009 and 2012 and the corresponding Kappa values of 0.80 and 0.66 (Tab. 2). Producer´s accuracies greater than 0.96 confirmed almost all automatically detected gaps as correctly classified. Yet, a fraction of the visually identified gaps were not detected during the automated mapping process, which is reflected in lower user´s accuracies of 0.84 in 2009 and 0.72 in 2012. However, more than 70 % of the visually but not automatically identified gaps in both study years were adjacent to the automatically mapped gaps, what suggest that gaps were correctly localized, but they were detected with a too small extent.

Tab. 2: Mapping accuracies of automatically generated gaps per year and forest high class derived from a comparison with the results of visual interpretation (accessed with 95 % confidence interval (CI)) (from ZIELEWSKA-BÜTTNER et al. 2016, modified)

		Producer´s accuracy	User´s accuracy	Producer´s accuracy	User´s accuracy	Kappa	Overall accuracy
		Gap	Gap	"Non-gap"	"Non-gap"		with 95 % CI
2009	DF	0.97	0.84	0.84	0.97	0.80	0.90
	LF	0.98	0.93	0.68	0.89	0.73	0.93
	HF	0.98	0.70	0.87	0.98	0.73	0.88
2012	DF	0.96	0.72	0.73	0.96	0.66	0.82
	LF	0.98	0.85	0.59	0.94	0.93	0.86
	HF	0.96	0.52	0.76	0.96	0.84	0.79

3.2 Shadow occurrence

Among the variables tested only the height of the surrounding forest and shadow occurrence significantly affected the gap mapping results. The occurrence of full shadow in the lower sections of the forest canopy was identified as the main cause for gap mapping omission errors in both years (ctree, $p<0.001$). This was confirmed also by means of visual verification, as the most of the visually identified but not automatically mapped gaps (70%–87%) were identified in areas of total or partial shadow. The height of the surrounding forest stands (LF and HF) is strongly linked to shadow occurrence as it determines the depth in the canopy, to which the light can penetrate. Despite similar producer´s accuracies of 0.96-0.98 and overall accuracies of more than 0.79, gaps in LF were mapped with higher user´s accuracies than those in HF (0.93 vs. 0.70 in 2009 and 0.85 vs. 0.52 in 2012).

The shadow masks identifiying complete shadow cells covered 29 % of the study area in 2009 and 16 % in 2012. However, the comparison with the location of automatically mapped gaps showed that only less than 5 % of the gaps were automatically detected in these areas. Shadow occurrence was mostly linked to steep slopes and exposition as well as to heterogeneous vertical structure and stand height (Fig. 2), indicating a strong influence of the sun angle and associated time of data acquisition. The two flight campaigns of 2009 and 2012 were carried out in May and August, so the sun position at the time of data aquisition didn´t correspond which produced shadow in different areas (Fig. 2).

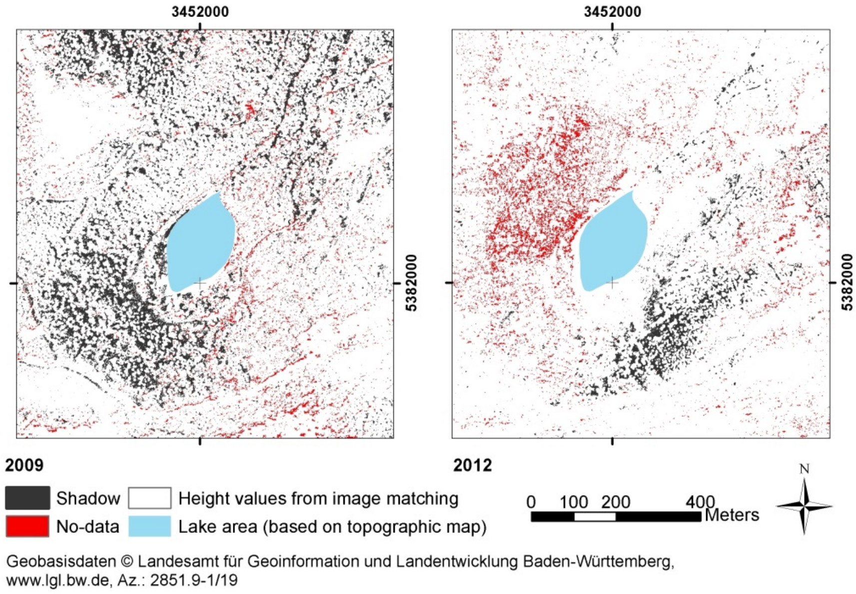

Fig. 2: Example of complete shadow and no-data cells distribution in a steep part of the study area around the mountain lake "Huzenbacher See"

3.2.1 Image matching algorithm

The amount and distribution of no-data cells was influenced by the algorithms and pyramid levels of the images used for point matching. The area with no data ranged between 38% with SGM pyramid level 2 in 2012 and 9 % with SGM pyramid level 1 in 2009. Combining different algorithms and pyramid levels led to a reduction of no-data within the study area to less than 3%. Evaluating whether missing information in some raster cells could be a reason for a fraction of the undetected gaps, we found that only about 10 % of the visually, but not automatically identified gap cells (gap area) in both years belonged initially to the no-data cells.
The distribution of no-data and shadow raster cells (Fig. 2) revealed that the points were mismatched not only in shadowy areas of the forest stands (8 % (2009) and 5 % (2012) of no-data cells intersected with the shadow mask) but also in low forest stands and on hilltops where aerial photographs should theoretically deliver good material for image matching. No-data cells were often located along flight strips (2009) or at the outer parts in the overlapping zone of the images (both years).

3.2.2 Image resolution and overlap

Comparing the results based on the original data from 2012 and the high-resolution dataset of 2014, a slightly larger amount of open forest (3 % in 2012 and 2 % in 2014) was mapped for 2012. Also the percentage of low forest was higher in 2012 (21 %) than in 2014 (14 %) (Fig. 3).

To be able to compare the results of the gap mapping of both years the study area was reduced by the area that had been classified as open forest within either of the datasets. For the remaining area of 94 ha a larger total gap area was obtained with the dataset of 2012 (4.9 ha) compared to the dataset of 2014 (2.5 ha) though a larger number of gaps was identified in the latter (2012: 240 gaps, 2014: 281 gaps). The reason for this can be found in the size of the mapped gaps. While more very small (10 m² - 30 m²) and small (31 m² - 100 m²) gaps were detected with the dataset of 2014 there were more large (100 m² - 1000 m²) and very large gaps with a size of more than 1000 m² mapped with the data of 2012 (Fig. 4). The large and very large gaps were located mostly within the class of low forest or along forest tracks.

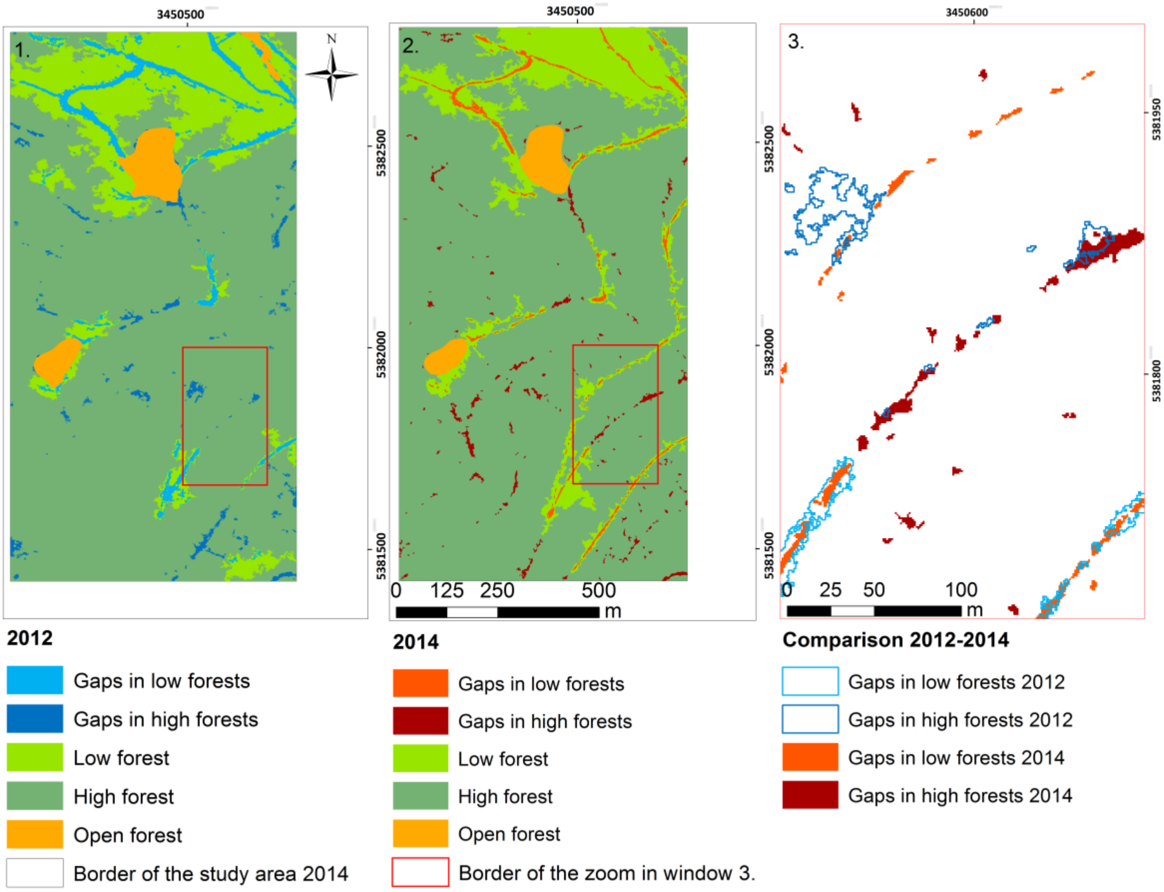

Fig. 3: Results of the automated gap mapping in the test area for the comparison of data with different resolution and overlap: 1) results from 2012 (20 cm, overlap 60% /30%), 2) results from 2014 (10 cm, 80% /60%), 3) Zoom-in window as example for a comparison of 2012 and 2014 results.

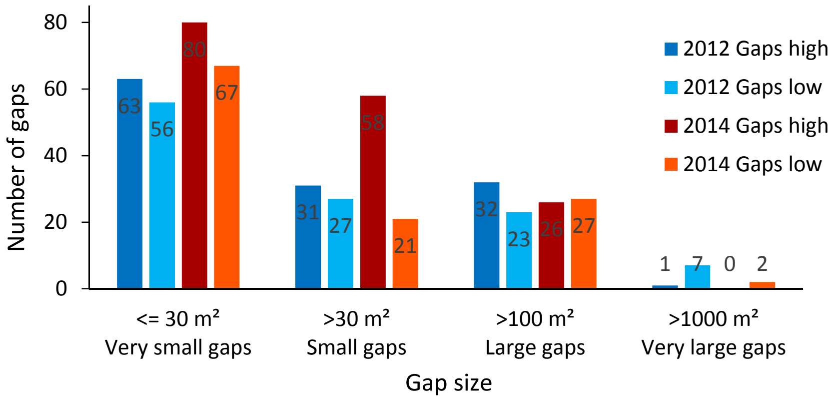

Fig. 4: Distribution of gap sizes in the dataset of 2012 (blue bars) and 2014 (red/orange bars). “High” and “low” indicate high and low forest stands.

4 Discussion and Conclusions

Gap mapping from stereo aerial imagery with 20 cm resolution and 60/30% overlap proved to deliver promising results, with a good overall method performance and even very good results in low stands. Depending on the quality of the aerial imagery and the input CHM as well as the height of the surrounding forest and the associated shadow occurrence, the results in stands higher than 8 m were moderate to insufficient, depending on the study year. The mapping results might also depend on the topography and the structure of the forest stands. GINZLER & HOBI (2015) observed better mapping accuracies in a flat terrain than in rugged mountainous topography, which also characterised our study area, whereas ADLER et al. (2014) found that even in flat terrain different DSM matching algorithms produce different results, especially in highly structured canopy situations. In addition, mountainous forests are likely more structured than intensively managed stands in the lowlands.

Shadow occurence in aerial images is related to exposition, surface characteristics and caused by sun inclination and angle. Therefore the occurence and distribution of shadow varies a lot between the different flight campaigns, especially in hilly areas comparable to our study area. Comparing the overall amount of shadow within the images with the shadow pixels within the classified gaps, we see that only a very small portion of gaps was detected in the shadow areas. This can be influenced by a strong fragmentation of the shadow areas with single patches not bigger that 10m² (minimum gap size). It can also be interpreted, that shadow pixels may have influenced negatively the image correlation for point matching within stand surface openings. The latter argument was confirmed by the visual interpretation of the gaps as 70-80% of visually interpreted gaps that hadn’t been detected automatically were located in partial or total shadow.

The superimposition of no-data areas with shadow areas showed no direct correlation. The appearance of no-data areas was more related to the geometric characteristics of the image, as they mainly occurred along image und flight strip borders.

By combining point clouds generated with two different image matching methods we expected a compensation effect and improvement of the point cloud structure in areas where no points were matched using only one of the algorithms. The results of our study underline the importance of the image matching method. Not all algorithms perform equally well with regard to specific mapping goals e.g. detection of canopy gaps, mapping of the tree tops or calculation of forest stand parameters. Developments in technology and image matching algorithms are rapid, which makes the choice of the "best" algorithm combination very difficult, with "best" being often only valid for the used data and software combination.

The data used to analyse the influence of image resolution and overlap originated from two different years. The images with 20 cm resolution and 60/30 % overlap were taken in 2012, whereas the images with 10 cm resolution and an overlap of 80/40 % were from 2014. However, as there were no disturbances in the two years between the flights, and the forest stands wasn't in an age-class where natural mortality causes the disappearance of single trees, a decrease in detected gaps would have been expected. Nevertheless, the number of forest gaps increased from 240 to 281 with simultaneous decrease in size. This change in average gap size could be either explained by vegetation growth, at the gap edges, which reduces gap size. The increasing number of very small and small gaps could be explained ingrowth of vegetation, partially closing larger forest gaps, leaving more and smaller gaps behind. A visual examination, however, showed that the many of these very small and small gaps detected in 2014 where not mapped in 2012. Especially within high forest stands the number of detected gaps rose by almost 30 % while the amount of high forest only increased by 8 % between the years. This increase can not only be explained by ingrowth but by a better insight into the canopy structure due to a higher image overlap and resolution in the 2014 data.

The results from different flight campaigns indicate shadow occurrence and geometric limitations of the aerial imagery as serious constraints, both bearing a high potential for improvement. Flight campaigns should consider the issues arising from varying flight time and associated solar altitude. Moreover, an increase in spatial resolution and overlap of the aerial images could considerably improve the spatial accuracy of the results. Further improvements can be expected from an amelioration of the image matching algorithms. The use of shadow and no-data masks proved useful for the interpretation and evaluation of the automatically produced gap maps and we recommend them especially for change detection. Further research on these topics could help to optimize and standardize future flight campaigns, so that they can be used for reliable monitoring of gaps and other forest structure parameters.

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