Multi-Temporal Airborne LiDAR-Survey and Field Measurements of Tropical Peat Swamp Forest to Monitor Changes

Hans-Dieter Viktor Boehm, *Member, IEEE*, Veraldo Liesenberg, *Student Member, IEEE*, and Suwido H. Limin

***Abstract*—Natural tropical peat swamp forests are important for their rich biodiversity and serve as a huge carbon pool. However, peat swamp forests are decreasing due to deforestation, conversion into farm land, excessive draining, the use of shifting cultivation on a large scale, illegal logging, forest fire and palm oil plantation. Airborne laser scanning (ALS) also termed airborne Light Detection and Ranging (LiDAR) data is nowadays a good single sensor to investigate bio-geophysical parameters in remote tropical rain forest areas (e.g. tree canopy height which is strongly correlated with above ground biomass). Bi-temporal airborne LiDAR data acquired in August 2007 and August 2011 were used to characterize peat swamp forest changes located in Central Kalimantan, Indonesia. We measured the tree height and Canopy Height Model (CHM) with LiDAR, segmented the canopies and then compared the tree height with the field measurements. Additionally, we collected ground field measurements at Sabangau forest transect in order to characterize some biophysical properties of different peat swamp forest physiognomies such as diameter at breast height (DBH), tree-height, leaf area index (LAI), crown coverage and above ground biomass (AGB). From the bi-temporal LiDAR Data we analyzed the forest regrowth and the peat subsidence. This work can be promising in the REDD+ (Reducing Emissions from Deforestation and forest Degradation) framework of knowledge of tropical PSF. The LiDAR technology supports the MRV (Monitoring, Reporting, and Verification) aspect of REDD+.**

***Index Terms*—Above-ground biomass, carbon, Central Kalimantan, forest regrowth, LiDAR technology, ombrogenous peat swamp forest, peat subsidence, REDD, tropical peat.**

I. Introduction

TROPICAL lowland ombrogenous peat lands in Southeast Asia are known for their rich biodiversity and huge amounts of stored carbon [1]. In recent years, large natural areas of this endangered ecosystem has been converted into oil palm and acacia plantations. Hence, forest remnants are currently threatened by extensive drainage, logging, hunting and fire. Undisturbed peat swamp forest display specific surface patterns linked to hydrology which reflects on biodiversity, vegetation structure and carbon dynamics. The key importance of peat swamp domes to ecological processes, their fragility and impact to global climate and carbon budgets highlights the need for a comprehensive forest inventory of peat swamp resources across Indonesia. Remote sensing data can provide useful information in such environments for hydrological and wildfire modeling, retrieval of biophysical parameters and the management of natural resources [2]–[9]. Bi-temporal airborne Light Detection and Ranging (LiDAR) data acquired in August 2007 and August 2011 were used to characterize the peat swamp forest and dome located in Central Kalimantan, Indonesia.

In this study our main objectives were: a) to characterize ground-measured and LiDAR-derived biophysical properties with both forest physiognomy and peat dome slope variations; and b) to present an approach to carbon change assessment based on multi-temporal LiDAR acquisition as the experimental data covers forest regrowth and peat subsidence.

II. Study Area

The study area encompasses two LiDAR transects in one test site located in Central Kalimantan, Indonesia (Fig. 1). The Sabangau test site is located inside the Natural Peat Swamp Forest Laboratory (NPSFL) and managed by the Centre for International Co-operation in Sustainable Management of TROpical Peatland (CIMTROP). It is also located inside the Sabangau National Park (SNP). The base camp has been the site of much PSF research in the past 20 years.

Fig. 2 shows the LiDAR point clouds taken from the CIMTROP transect with a profile of the base camp. The red and blue colors represent high trees and the peat ground respectively and violet represents the ground of the Sabangau catchment.

The ground field measurements were also acquired in the CIMTROP transect with 52 sample areas. The test site is relatively flat, ranging between the 15 m height of the Sabangau river respectively 18 m from the research base camp to a maximum of 31 m towards the peat dome plateau, as shown in Fig. 3. According to [6], [7] the peat thickness of the Sabangau test site varies from 0 to 12 m. The peat surface has a maximum slope of 1.7 m/km [10]. The forest was selective logged until 1997. Therefore trees with DBH >60 cm are missing. The tree

Manuscript received September 30, 2012; revised January 11, 2013; accepted March 02, 2013. Date of publication May 13, 2013; date of current version June 17, 2013. The work of V. Liesenberg was supported by the Brazilian Council for Scientific and Technological Development(CNPq, 290043/2007-7), and research grants from both the International Association of Mathematical Geosciences (IAMG) and the Geological Remote Sensing Group (GRSG) during his Ph.D. research at TU Bergakademie Freiberg (TUBAF).

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Digital Object Identifier 10.1109/JSTARS.2013.2258895

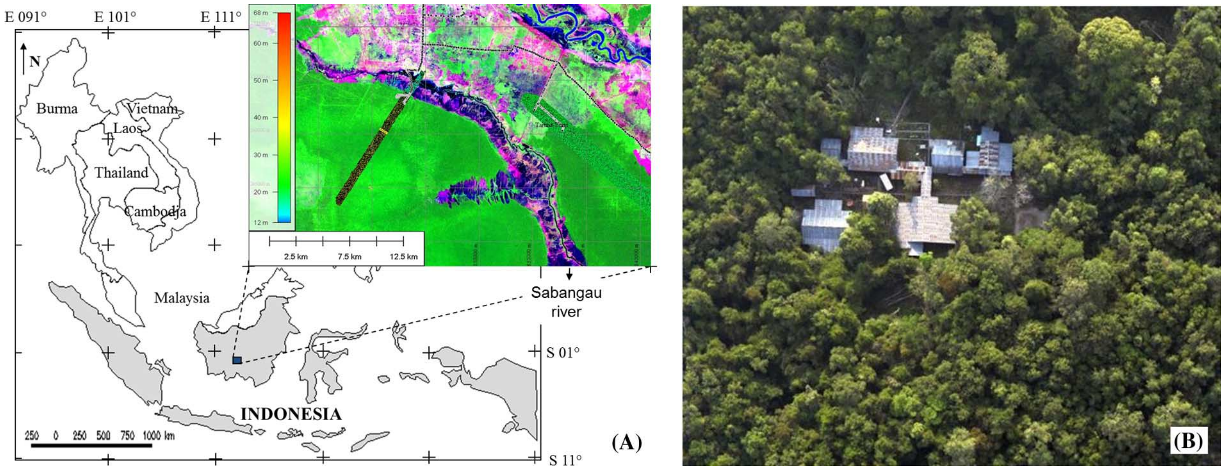

Fig. 1. LiDAR survey of peat swamp forest near river Sabangau, Kalimantan, Indonesia. (a) Kalampangan channel and (b) CIMTROP transect. The ortho-photo (right) shows theCIMTROP research base camp at the beginning of the LiDAR transect.

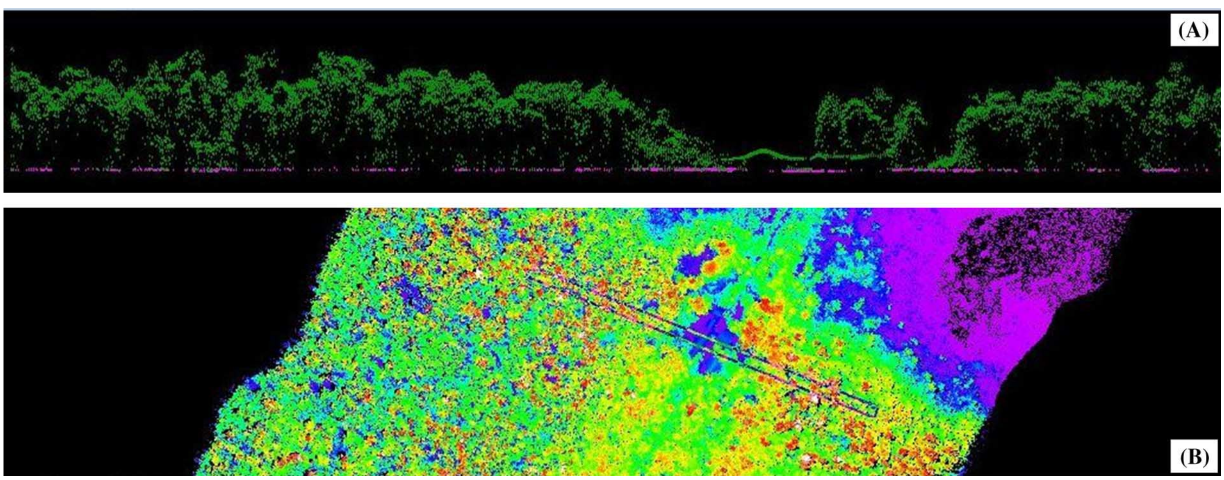

Fig. 2. LiDAR-DSM data shown as Laser Clouds taken from CIMTROP base camp with peat swamp forest, catchment and tree profile (above) (a). The width of the transect is approximately 500 m (below) (b). The tallest trees are approx. 40 m above the ground. The red color indicates tall trees, while blue and violet shows the ground, as shown in Fig. 1 at the beginning of the LiDAR transect.

heights vary today between 25 m and 40 m, but on average they are around 20 m high. The climate of the study area following the Köppen climate nomenclatureis humid tropical rain forest (Af) and has up to 3000 mm rain fall in the year and an average temperature of 27°C.

III. Material and Methods

In August 2007 and August 2011 we mapped by helicopter two Peat Swamp Forest (PSF) transects with Riegl LiDAR Scanner (LMS-Q560) and a high-resolution Hasselblad 39 MP camera. The surveys were conducted by Kalteng Consultants in conjunction with Milan Geoservice GmbH using an Eurocopter BK117 helicopter flying at a nominal height above ground of approx. 500 m in both acquisitions. The LMS-Q560 system is a laser rangefinder recording up to four returns of the laser signal from the ground surface, although we only account for the first and last pulse laser echoes. The laser measurement density was 3–5 pulses per m^2 during 2011 and laser beam divergence was 0.5 mrad, as shown in Table I.

The datasets were calibrated with each other in order to make further comparisons between them possible. The geographic reference point, which had an elevation of 25.0 m, was located at Palangkaraya Airport. The preprocessing of the data was done with the Riegl SW to get geo-referenced ASCII- and LAS-files. The filtering and classification to a good Digital Terrain Model (DTM) was performed with an IDL-SW from EXELIS developed by company Milan. The processed laser data gave us the Canopy Height Model (CHM) by subtraction of the DTM from the Digital Surface Model (DSM) [10], [11]. We utilized the Global Mapper SW for viewing the geo-referenced data.

With a 39 MP Hasselblad camera we collected RGB-photos which we processed with the Inpho-SW to an Ortho-Photo Mosaic. We then segmented the canopies, used a filter technique and compared them with both the LiDAR-canopies and the field-measured tree height.

Additionally, we collected other data from ground field measurements at the Sabangau forest transect in 52 10 m × 50 m plots approx. all 300 m distance with more than 15 km length. This was in order to characterize some of the biophysical properties of different peat swamp forest physiognomies such as diameter at breast height (DBH), tree-height, leaf area index (LAI), crown coverage and above ground biomass (AGB).

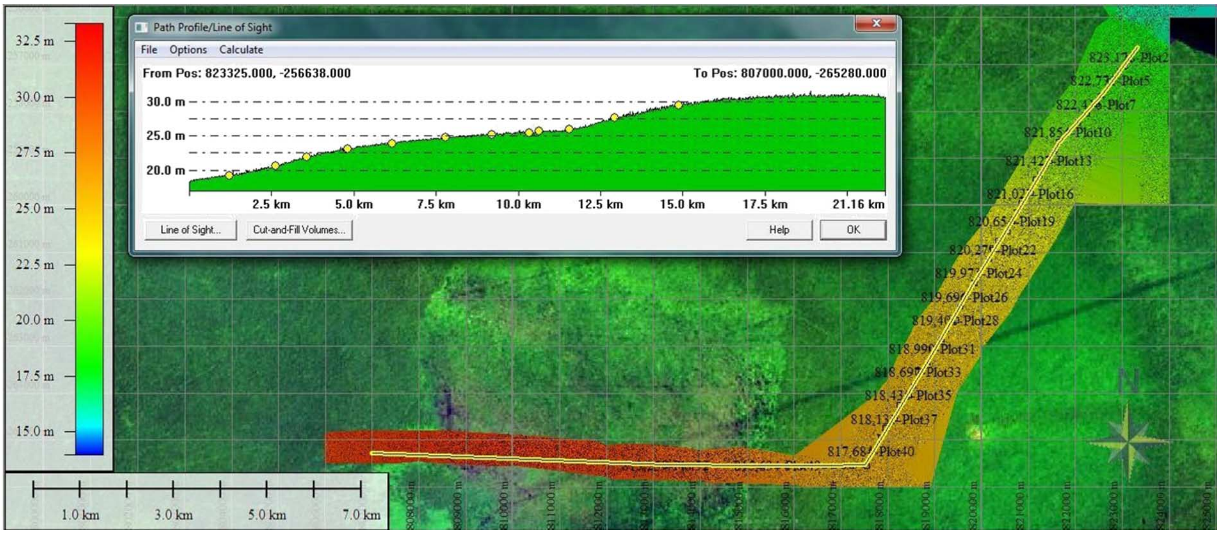

Fig. 3. LiDAR-DTM of Peat Surface Profile including Peat Dome. CIMTROP transect near Sabangau river with base camp at 18 m and the peat dome at 31 m elevation. The peat dome is located after the tilt of the transect to the West on the burn scar area.

TABLE I
SPECIFICATIONS OF THE AIRBORNE LMS-Q560 LiDAR (RIEGL) SYSTEM AND ITS DATA PRODUCTS

Scan Angle (field of View)	±30 degrees
Swath width (m)	~500m
Scan Frequency (kHz)	66 to 100
Vertical laser beam accuracy (m)	≤0.10m
Horizontal laser beam accuracy (m)	≤0.5m (for both x- and y-directions)
Laser beam (mrad)	0.5 (footprint up to 30cm)
Laser wavelength (μm)	1.5 (near-infrared)
Point density (points·m^{-2})	1.4[a] and 3.5[b]
Ground resolution (pixel size)	0.5m for both DTM and DSM

[a,b] for flight measurements taken in 2007 and 2001, respectively.

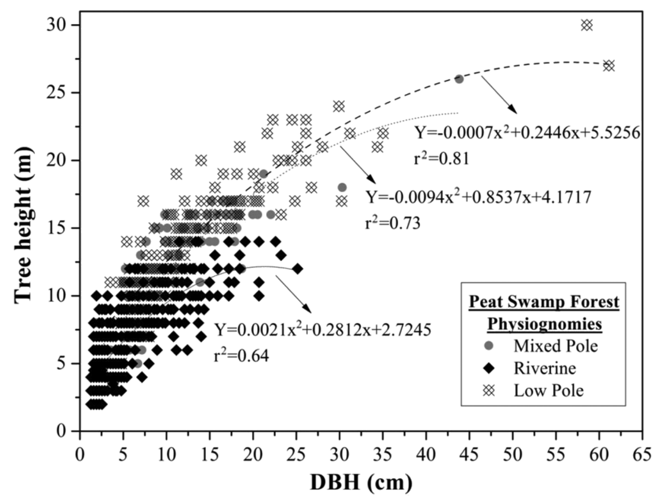

Fig. 4. Field measurements taking into account three peat swamp forest types in CIMTROP transect. Big trees are missing.

Our analyses were made taking into account pairwise comparisons of nearly coincident LiDAR footprint (e.g. with a length of 15 km versus 1.5 km, Fig. 3). We demonstrated the spatial patterns of biophysical property dynamics at a 1-ha scale as well as the PSF performance comparison based on multi-temporal LiDAR acquisition. In field measurements we found a ratio between the DHB and tree height, as shown in Fig. 4.

Fig. 5 shows the Above Ground Biomass (AGB) methodology to combine the measurements from the ground survey with those of the 2011 LiDAR survey. The CHM was calculated by subtracting the DTM from the DSM and a Gaussian filtering was applied to smooth the CHM with less noise and more realistic trees. We used a local maxima method to find the tree tops [15] and searched in a window of 5 × 5 or 3 × 3 pixels the highest point and determined then the DBH. We found little information about allometric equations suitable for PSF in the literature. In the article by Chave *et al.* [12] was given a correlation of AGB with DBH for tropical humid forests (1). We used their formula to determine the AGB for the year 2011.

$$AGB = \rho \exp^{[-1.499+2.14\ln(DBH)+0.207\ln(DBH^2)-0.0281\ln(DBH^3)]} \quad (1)$$

The LiDAR analyses of the difference, CHM 2007–CHM 2011, deliver the forest regrowth and similarly the peat subsidence of peat surface elevation from 2007 to 2011. In this ombrogenous peat lands are many hummocks which make the surface rough. A big question is the peat roughness of an area from 100 m × 100 m. The reasons to determine peat roughness are hydrological and slope questions of the peat surface. With LiDAR technology we can measure the difference between the maximum and minimum filtered DTM for 1 ha area every 300 m distance and find an average for 15 km length of the selected transect.

IV. RESULTS AND DISCUSSION

The ground field measurements allow a correlation of the DBH to the tree heights. Fig. 6 shows average tree heights for trees >20 cm and the average tree height of all measured trees, represented respectively by black stars and by blue diamonds. In comparison are shown the LiDAR average data for the 52 plots as line-columns. The LiDAR monitoring does not see the

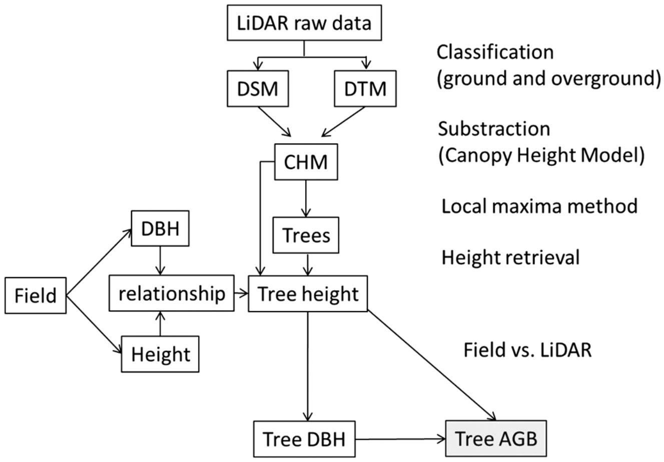

Fig. 5. AGB methodology flowchart using measured DBH and filtered tree height values from field measurements and LiDAR survey.

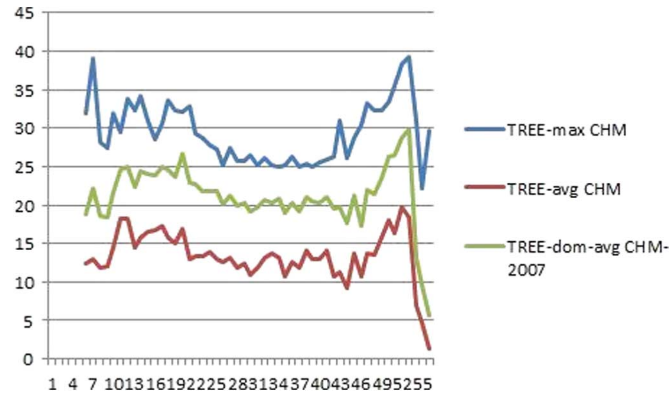

Fig. 7. LiDAR analyzes of PSF tree canopy height in m versus 52 plots along the CIMTROP Transect: Maximum, average-dominant and average tree height (CHM) in CIMTROP transect with 52 plots each 1 ha size including the burnt scar from 1997 at the end. The tree height varies along the CIMTROP transect.

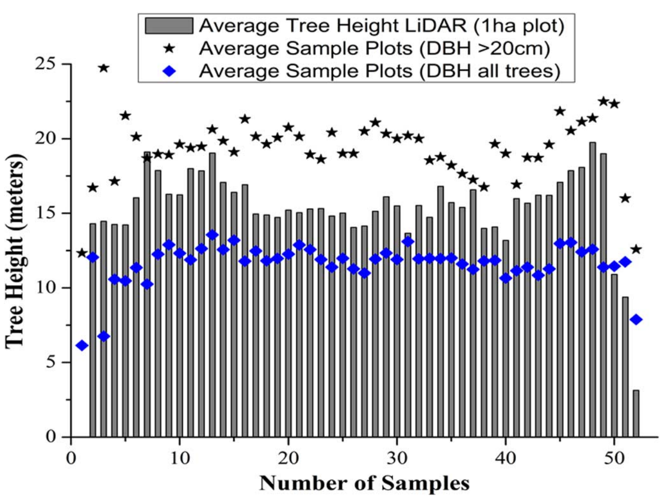

Fig. 6. CIMTROP transect with 52 plots each 1 ha size; field measurements (dots) and LiDAR-CHM (line-column). Average tree height measured on ground with all tree DBH (diamonds) and with >20 cm (stars) only for comparison reasons.

smallest trees, therefore we used for comparison reasons this approach only with trees >20 cm in the collected field data.

The respective LiDAR-CHM data are shown in Fig. 7 for the 52 plots. We have analyzed the maximum, the average-dominant (using a filtering method with a window of 10 × 10) and the average tree heights for the 52 plots including the burn scar from 1997 at the end of the transect.

There is a variation in tree heights between the different PSF types defined by [7]: Riverine Forest (relatively small trees at the beginning), Mixed Pole Forest (tall forest near the highest peat slope), Low Pole Forest (in the middle), Tall Pole Forest (near the end) and Burn Scar from 1997 (at the end).

Fig. 4 shows the correlation between DBH and tree height for three different PSF types at the beginning of the transect. Large trees of diameter over 60 cm are missing. This is caused by the selective logging of this PSF under the "Setia Alam" logging concession from 1993 to 1997. Trees with this diameter and greater may regrow in coming years.

In Fig. 8 we segmented the tree crowns from the LiDAR-CHM by Gaussian filtering. The smaller trees with their crowns are partially absent in the LiDAR data. This segmentation approach, using multiple window size, is necessary to detect small, intermediate and dominant trees per physiognomy.

The above ground biomass (AGB) was estimated by correlation of the ground field measurements and the laser survey in 2011 using the formula by Chave *et al.* [12]. Fig. 9 includes an AGB legend with the results. The value ranges from 50 $\mathrm{Mg} \cdot \mathrm{ha}^{-1}$ to > 300 $\mathrm{Mg} \cdot \mathrm{ha}^{-1}$ with an accuracy of approx. 20%. Near to the base camp and at the beginning of this transect the value is below 50 $\mathrm{Mg} \cdot \mathrm{ha}^{-1}$ (Riverine Forest).

Near to the Sabangau River the AGB is lower than at the highest peat slope area. The highest slope area is approx. 3 km from the base camp with up to 1.7 $\mathrm{m} \cdot \mathrm{km}^{-1}$ on this transect [10]. There is more flowing water in the high slope area. This brings good nutrition to the roots of the trees, allowing them to grow better and higher here. Kronseder *et al.* [13] have analyzed AGB by ground field measurements and the same LiDAR data from 2007 resulting in lightly smaller values while Engelhart *et al.* [14] found similar results with LiDAR and SAR technology in that area.

Our LiDAR results showed forest regrowth of 1.86 m (average value) during the four-year period from 2007 to 2011 in which the canopy height changes up to 12% for the selected 52 plots, see Fig. 10. Hence, the canopy height increased from 13.9 m (2007) to 15.7 m (2011) on average during this period.

The average peat subsidence in this CIMTROP transect is shown to be 18 cm ± 4 cm or 4.5 cm per year, as shown in Fig. 10. This is mainly caused by drainage channels built parallel to this transect by illegal loggers [16].

Peat subsidence was also monitored in degraded peat land without PSF along the Kalampangan channel in Block C of the Mega Rice Project approx.16 km apart. The analysis showed an average subsidence of 43 cm ± 25 cm over the 2007 to 2011 period, which is approx. 11 cm per year. Peat subsidence is mostly due to the peat-compaction, the CO2 emission and peat-leaching effects caused by drainage channels. It also can be partially attributed to CO2 emission into the atmosphere and

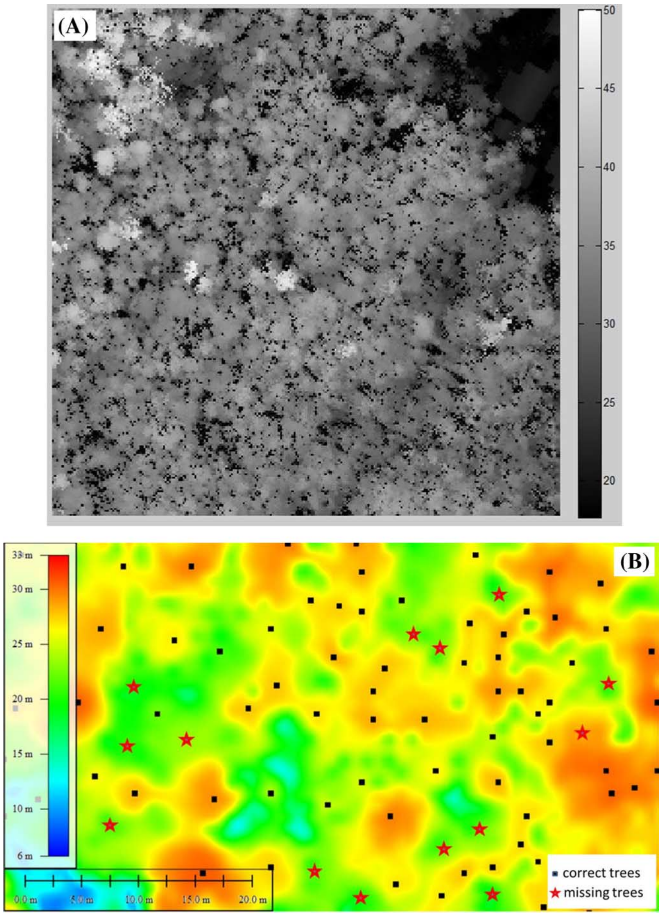

Fig. 8. LiDAR-DSM showing as grey-level intensity the tree-height including the peat ground of 18 m. The area size is 100 m × 100 m. The base camp is located above right (a). Results of CHM segmentation derived from LiDAR survey, black points are the tree crowns and the red one are missing small trees by LiDAR survey (b). The area size is 30 m × 50 m.

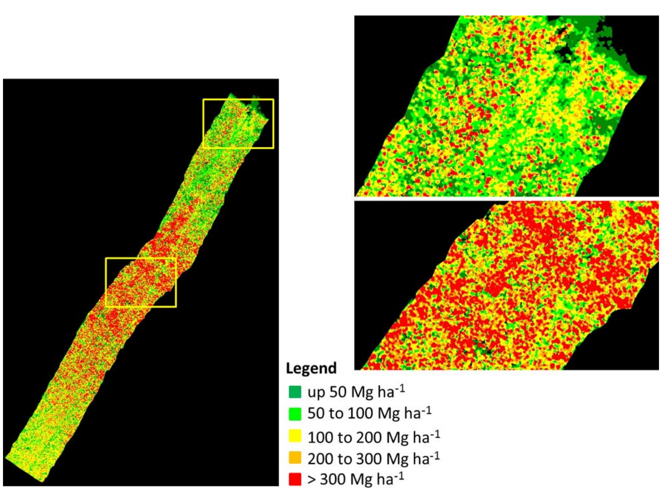

Fig. 9. Above Ground Biomass calculation using the formula by Chave *et al.* 2005 [12]. The error budget is approx. 20%. The figure left shows approx. 5 km at the beginning of the whole CIMTROP-transect. UTM (Universal Transverse Mercator) coordinate Zone 49, Center: x = 821600 and y = 9740500.

magnified by fires as happened in summer 2009. The peat roughness for an area of 100 m × 100 m describes the surface of the lowest and highest points in this 1 ha plot. The average peat

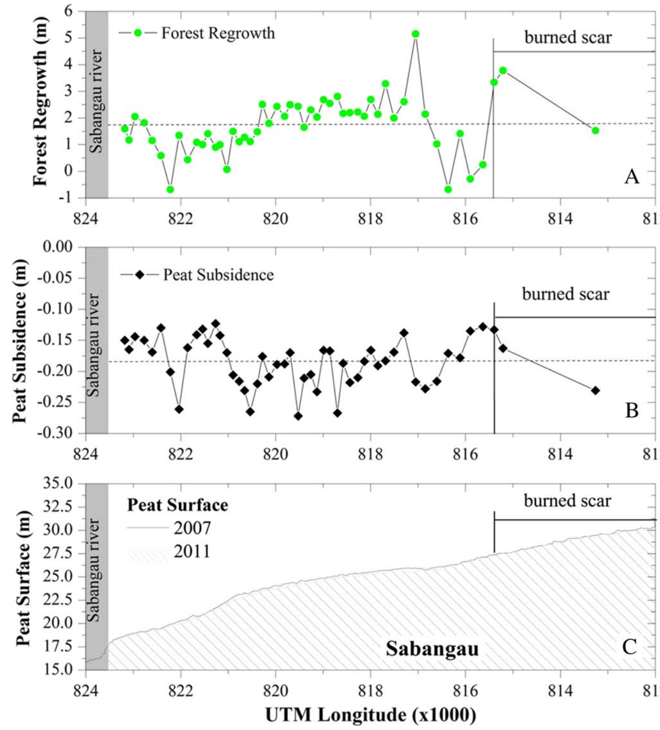

Fig. 10. LiDAR survey 2007 and 2011 of CIMTROP transect using 52 plots each 1 ha. Forest regrowth is in avg. 1.86 m $+/1$ m, peat subsidence in avg. 0.18 m ±0.04 m for 4 years and peat roughness in avg. per ha 0.84 m ±0.17 m; y-values in m and x-values in km of UTM zone 49.

TABLE II
TEST SITE CIMTROP-TRANSECT. AVERAGE LIDAR DATA FOR 52 PLOT EACH 1 ha FROM DTM AND CHM PARAMETERS OF 2005 SURVEY

River level (m)	15.5
Altitude of the peat dome (m)	26/31
Nominal transect length (km)	12/21
Maximum slope (m·km^{-1})	1.7
Hummocks roughness (m·ha^{-1})	0.84±0.17
Dominant tree height (m)	21.9±2.8
Averaged tree height (m)	13.9±2.8
Maximum tree height (m)	30±5.7
Number of sample plots	52
Past logging activity up to end 1997	Moderated

roughness of this 52 peat samples is 0.84 m ± 0.17 m per ha. Further peat land and PSF values are shown in Table II.

V. CONCLUSION

A LiDAR survey was performed by helicopter over PSF and opened peat land in Central Kalimantan, Indonesia during two time periods in 2007 and in 2011. Parallel ground field measurements were done in 2011 to collect from the PSF parameters as DBH-, tree height- and LAI-values. We evaluated carbon changes of this tropical lowland ombrogenous PSF: averaged forest regrowth of 1.9 m and averaged peat subsidence of 18 cm were measured over the interval of 4 years. Additionally we estimated the AGB for 2011 of the study area Sabangau CIMTROP transect. We found an AGB value of over 300 Mg $\cdot$ ha^{-1} at a forest area with the highest peat slope of 1.7 m $\cdot$ km^{-1}.

It is not completely clear if the remaining PSF in the Sabangau National Park is a carbon source or sink. The forest regrowth and the peat subsidence for the study area may yet in balance if no logging occurs. The opened peat land in this part of Central Kalimantan with its drainage and subsidence is now becoming a carbon source supported by fires during the dry period across all 4 years. More investigations are necessary in the future.

ACKNOWLEDGMENT

The LiDAR data was kindly provided for research purposes from Kalteng Consultants. The LiDAR survey 2011 was strongly supported by Ehime University, Japan, and the authors thank Prof. Dr. Tatsuo Sweda for his encouraging assistance. The CIMTROP team is kindly acknowledged for both logistic and field survey support at the NPSFL. Landsat scenes were provided from the U.S. Geological Survey (USGS).

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