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# Spatial and temporal variation of above ground biomass in tropical dome-shaped peatlands measured by Airborne LiDAR

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*Southeast Asian tropical peat swamp forests (PSF) are important for their large carbon stock storage and rich biodiversity. Reports suggested that PSF display specific surface patterns linked to hydrology which reflects on biodiversity, vegetation structure and carbon dynamics. On the other hand, excessive peat subsidence has been recorded in both degraded PSF areas and excessive drained peatlands. Therefore, the key importance of PSF to ecological processes, their resilience for forest degradation and logging highlights the need for a comprehensive forest monitoring in which LiDAR technology may play an important task.*
*Three small-footprint LiDAR transects were acquired in July 2007 and 2011 using the Riegl LMS-Q560 system. Each transect encompasses an ecological peat dome gradient ranging from the river system to the peat dome. The three transects faced in the past different forest degradation intensities. The transects are located at the Sabangau National Forest (one site) and the Mawas Reserve (two sites) in Central Kalimantan, Indonesia. Our main objectives were to map changes in the vertical structure of the PSF (canopy height), to relate different height metrics, and Above Ground Biomass (AGB), and from these maps to identify both sources and sinks of carbon across the three-peat dome-shaped gradients. AGB values were related to in-situ field measurements.*

*The spatial patterns of biomass changes matched expected patterns given the distribution of PSF physiognomies and previous forest disturbance history. Pairwise comparisons showed that the canopy top height changes are coincident with expected changes based on the different PSF physiognomies. Undisturbed PSF showed similar canopy heights between the period of 2007 and 2011, while degraded PSF had net gain in average of up 2m. As a result, the AGB map (derived at 1ha sample plots) showed most of the PSF as a carbon sink, with widely scattered and isolated areas as neutral (no net biomass change) and sinks caused by both dieback effects and current logging activities.*

*The quantification of the AGB changes and the sensitivity of LiDAR to characterize the vertical structure of the PSF may help further development under the Reducing Emissions from Deforestation and Degradation (REDD+) mechanism.*

Keywords: Peat Swamp Forest, Peat Dome Slope, self-regulation mechanism, LiDAR, airborne laser scanning, change detection, REDD, Kalimantan and EMRP.

## Introduction

Peatlands originally cover more than 25 million hectares of the coastal areas of the Southeast Asia archipelago (Page et al., 2004, Page and Banks, 2007). These peatlands are basically terraces or dome-shaped dominated by trees with a surface isolated from mineral soil-influenced groundwater receiving water through precipitation only (i.e. ombrogenous peat swamp forest, henceforth PSF). PSF are of global importance for their rich biodiversity and the huge amounts of carbon stored (Sieffermann et al., 1992, Sorensen 1993, Page et al. 2002, Hirano et al. 2007).

In recent years the PSF have increasingly been drained, logged, and converted to farm land and oil palm and acacia plantations (Boehm and Siegert, 2004, Miettinen and Liew, 2010). The awareness of the consequent greenhouse gas emissions, from biomass reduction by deforestation and forest logging and not last peat subsidence by oxidation and compaction has created strong political support for reducing these emissions in the framework of the reducing emissions from deforestation and degradation (REDD) protocols (Gibbs et al., 2007). Efforts have been made in this regard by decreasing the rate of deforestation and forest degradation and by rewetting and reforesting selected areas of Indonesia (Jaenicke et al., 2008, Page et al., 2009).

In undisturbed peat swamp domes, the vegetation and associated surface relief used to function as hydrological 'self-regulation' mechanisms that secured permanent water saturation and might made the domes exceptionally resilient against climate change (Dommain et al. 2010, 2011). Typical for this self-regulation phenomenon is the concentric arrangement of PSF physiognomies and micro-relief patterns conditioned by the arrangement of hummocks and aerial roots (Anderson 1983, Joosten 1993, Dommain et al., 2010, Boehm et al., 2010). Modelling results (Couwenberg and Joosten 2005) show how in the centre of a dome, weather conditions favour the establishment of more permeable elements that readily permit water flow to the edges (Bakker, 1992). Whereas towards the margins, drier conditions favour less permeable elements that limits lateral runoff (Takahashi and Yonetani, 1997). The vegetation itself and relief patterns that generate these hydrological feedback mechanisms on a landscape level are on the local level also conditioned by surface topographic variables such as dome slope due to slight changes in altitude from the river system to the peat dome plateau (Page et al., 1999, Couwenberg and Joosten 1999, 2005, Boehm et al., 2010, 2013). The dome slope may also drive changes in the vertical structure and spatial arrangement of the vegetation in a peat dome due to a coupled stressing effect by water saturation and exposure to weather conditions. However, the relationship between the vegetation height and topographical variables such as the dome slope has not yet been confirmed by remotely sensed observations in such tropical PSF environments.

Remotely sensed measurements proved already to be a useful tool in such endangered environments for several applications, and not last, serving as a tool for the policy and management of natural resources (Boehm and Siegert, 2004, Korpela et al., 2009, Miettinen and Liew, 2010). However, a good single sensor to retrieve both vertical structure of the forest and ground surface is the Light Detection and Ranging (LiDAR) system whose performance overcomes both optical and microwave sensor retrievals, respectively (Hajnsek et al. 2009, Boehm et al., 2010, 2013, Asner et al., 2012).

Although limited on the spatial coverage and temporal acquisition interval due to its relative acquisition cost, compared to other remotely sensed systems, airborne LiDAR measurements based on transects with a considerable swath, and acquired from the river system to the peat dome plateau are still representative for ecological studies.

## Materials and Methods

### *Study area description*

The study area encompasses four LiDAR transects in three test sites located in Central Kalimantan, Indonesia (Fig. 1). They represent different peat dome relief shape and intensities of past forest log. Mawas encompass two test sites and is located at the northeast part of block E of the Ex-Mega Rice Project (EMRP) (Figs. 1a, 1b) between river Kapuas and towards river Barito, whereas 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) and is located inside the Sabangau National Park (SNP) (Fig. 1c). Sabangau and Mawas km238 (south of equator) transects were partially damaged by peat fires during the El Niño Southern Oscillation weather effect in 1997 (Page et al., 2002, Usup et al., 2004).

The three selected test sites are relatively flat. According to Shepherd et al. (1997) and Page et al. (1999) the peat thickness of Sabangau test site varies from 0 to 12m. Estimates conducted by Jaenicke et al. (2008) using GIS techniques showed that the peat thickness varies from 0 to 18m at Mawas sites. The climate of the entire study area following the Köppen climate nomenclature is humid tropical rain forest (Af).

The monsoon occurs between November and April and the average annual rainfall and air temperature are 2500mm and 25oC respectively (Usup et al., 2004). The selected LiDAR transects consist of altered primary forest patches, in which trees have been already selectively logged until the end of the 1990s. However, drainage channels at Mawas and Sabangau were not close completely and are still being used for illegal logging activities up to date. A detailed description of the vegetation species at Sabangau test site can be found in Shepherd et al. (1997). Hence, at this specific test site, vegetation species richness has been related to soil properties and peat thickness (Page et al., 1999) and gibbon density (Hamard et al., 2009).

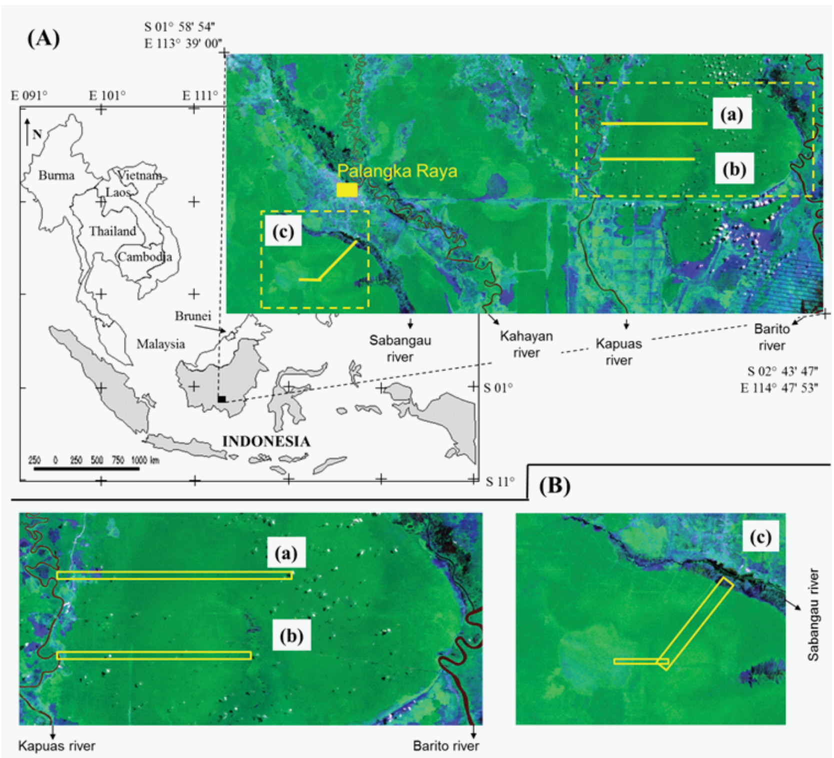


Figure 1. Location of the study area in Central Kalimantan, Indonesia (top) and location of the three selected test sites (bellow). The yellow rectangle shows the location of the Palangaka Raya

city. The solid yellow lines indicate the LiDAR transects (A). Lower part of the image indicates in order: Mawas km228 south of equator (a), Mawas km238 (b) and Sabangau (c). Each test site is indicated in more detail over the Landsat-7/ETM+ acquired on August 5, 2007 (3R4G5B).

### *LiDAR acquisition and preprocessing*

The LiDAR transects were surveyed twice by Kalteng Consultants and Milan Geoservice GmbH from August 5 to 7, 2007, and August 4 to 5, 2011, using a Laser Scanner System Riegl LMS-Q560. It was attached to a Bell 206 helicopter for the first flight and a BK117 helicopter on the second flight. The nominal height was in average 530m for both surveys. A differential global positioning system (DGPS) reference station was mounted at the airport of Palangka Raya city considering an elevation of 25.0m or 82 feet. The position and orientation of the LiDAR system on the helicopter was measured by an Inertial Navigation System (INS) and a differential GPS located on the tail boom respectively on the cockpit roof with 256Hz. A complete description of the LiDAR survey can be found in Boehm et al. (2007, 2008). Technical details of the LiDAR systems are further detailed in Table 1.

| | |
|---|---|
| Scan Angle (field of view) | ±30 degrees |
| Swath width (m) | □ 500m |
| Scan Frequency (kHz) | 66 to 100 |
| Vertical laser beam accuracy (m) | ≤ 0.15m |
| Horizontal laser beam accuracy (m) | ≤ 0.5m (both x- and y- directions) |
| Laser beam (mrad) | 0.5 (footprint up to 30cm) |
| Laser Wavelength (µm) | 1.55 (near-infrared) |
| Point density (points/m2) | 1.4* and 3.5** |
| Ground resolution (pixel size) | 0.5m for both DTM and DSM |

Note: for the flight measurements taken in *2007 and ** 2011.

Table 1. Specifications of the airborne LMS-Q560 LiDAR (Riegl) system and its data products

Ground backscattering passing through dense PSF amounted from 1% to 3% of the total laser beams. The processed laser beams were classified into ground surface and over ground classes using a terrain-adaptive bare earth algorithm for both dates. The algorithm is integrated with the Cloud Peak software (LASEdit) and in an IDL software used by company Milan and provides an unsupervised classification of the cloud points and adapts it to a hypothetical bare earth condition. The triangular irregular network (TIN) was used to construct based on a delaunay triangulation. Then a square grid of pixels was extracted for each TIN using linear interpolation for both ground and over ground layers in both acquisition dates. The classified laser representing the ground surface were converted in a digital terrain model (DTM), and the canopy surface into a digital surface model (DSM), respectively, both with a spatial resolution of 1m. The difference between DSM and DTM provided us the canopy height model (CHM).

Radiometric, geometric and off-scan line corrector (SLC) corrections were performed on a Landsat-7/ETM+ scene acquired on August 20, 2001, August 5, 2007 and June 13, 2011 (path/rows 118/61-62). It also coincides with the both LiDAR surveys. The Landsat data was then converted to the hemispherical directional reflectance factor (HDRF) using the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm, which is based on a MODTRAN4 approach for path scattered radiance, absorption, and adjacency effects. Spectral signatures extracted from the Landsat data were used for spectral characterization and support for the LiDAR analyses. Due to the strong haze and cloud coverage, the results were basically restricted to Sabangau test site.

***LiDAR Data Analysis***

1-ha sample plots (100x100m) were selected from each LiDAR transect with a regular spacing between plots of 200m for both Mawas transects (Figs. 1a,b). All Laser beams in this 1-ha sample plots were analyzed for the DSM and DTM data using the Global Mapper software. At the Sabangau transect the distance was variable taking into account the establishment of in-situ field measurements (Fig. 1c). The variation in the distance of two sample plots was necessary to avoid as much as possible the influence of the drainage channels, degraded forest patches and former railways used in the past for timber transportation. In each sample plot we accounted for different LiDAR derived CHM parameters such as the average of the trees, the maximum tree height and the dominant tree height. The last parameter was obtained using a local maximum filter algorithm and is reported to be a good indicator of the emergent forest strata in the tropics. Field measurements were performed during July and August, 2011. A total of 52 sample plots we measured with a sample plot of 10x50m (Boehm et al., 2013).

Biophysical properties of the vegetation such as the diameter at breast height (DBH) higher than 5cm were measured, and were used for the tree basal area (TBA) determination. Above ground biomass (AGB) was estimated for the Sabangau test site using the allometric equation proposed by Brown (1997) for moist forest (Eq. 1).

$$\text{AGB} = exp^{[-2.13+2.53\times\ln(DBH)]} \qquad Eq.1$$

Other AGB allometric formula for the tropics can be found in Chave et al., 2005 and Kronseder et al., 2012. Thus, total tree height and up to the first branch, crown diameter and form, trunk quality and geographical position were measured. The field measured parameters in the field were extrapolated per ha and related to the LiDAR sample plots of 1ha. Additionally, the estimation of canopy coverage (CC) and plant area index (PAI) through hemispherical photographs was performed. PAI differs from leaf area index (LAI) since it has not been corrected for the woody-to-total area ratio.

Peat surface slope was obtained by calculating the difference of DTM values between two sample plots and their respective distance. In the slope determination, the averaged DTM value was used in order to minimize the inclusion of signals from the understory vegetation, tree trunks and branches lying on the ground. These analyses were conducted for both surveys (e.g. 2007 and 2011). The tree height variations were computed for each test site and related to dome slope through the use of linear regression. Roughness was obtained taking into account the difference between the highest and the slowest ground points and were representative of the hummocks and hollows variation.

The resilience of the PSF was analyzed through the peat subsidence and forest regrowth. Forest regrowth was obtained following with the subtraction of the bi-temporal CHM (i.e. CHM2011 minus CHM2007). The peat surface subsidence was determinate with the subtraction of the bi-temporal DTM (i.e. DTM2011 minus DTM2007). The results were also employed for the peat dome characterization and related to previous forest log/degradation and Landsat signatures. Ortho-Photos taken by a Hasselblad camera acquired during the second LiDAR survey and in-situ photos were used to show demonstrate the current scenario of the peat domes. Results of forest regrowth and subsidence were afterwards related to peat roughness, dome slope and also each other, and finally discussed for each test site.

A flowchart of the methodology involving LiDAR data processing is shown in Figure 2. Estimation of the amount of carbon release to the atmosphere was not taken into account due to the unavailability of local bulk density measurements as well as uncertainties of factors such as the percentual of oxidation, compaction and lixiviation. Such analyses required specific modelling and are beyond the scope of this investigation.

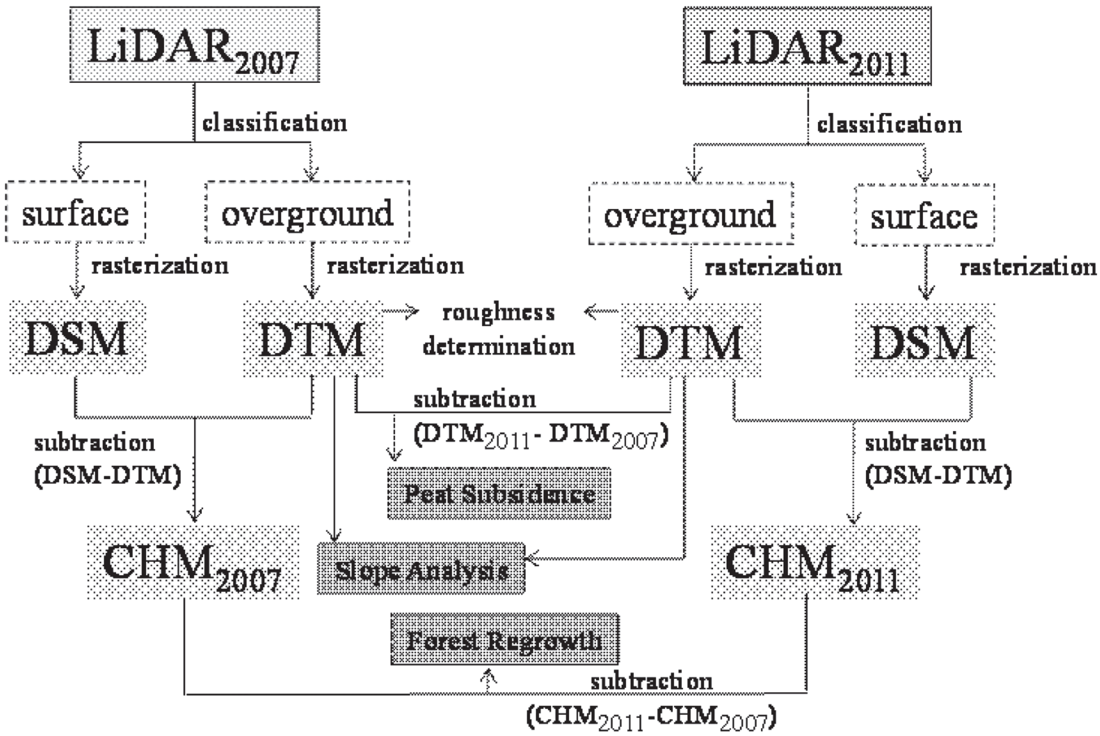


Figure 2. Schematic diagram of the LiDAR data processing flow applied to this study.

## Results and Discussion

### *LiDAR derived parameters*

The peat surface of the selected transects, represented by the LiDAR derived DTM, show from the river system to the near-horizontal dome plateau an increasing surface gradient of up to 15m (Table 2a, Fig. 3). The selected transects are characterized by a considerable topographic heterogeneity with a roughness ranging in average from 0.68m at Mawas km228 to 0.94m at Sabangau transect (Table 2a). Roughness is a good indicative of the ground heterogeneity between hummocks and hollows. Trees are usually growing on hummocks of root material and litter in this particular ecosystem (Yonebayashi et al., 1997, Brady et al., 2007, Page et al., 1999). Although the DTM was restricted to a low number of laser beams passing through dense canopy in both surveys (i.e. up to 3% of the total beams), the temporal roughness variability between surveys was up to 10% (Table 2a). A summary of the geomorphological characteristics extracted from the LiDAR derived parameters for the selected test sites is shown in Table 2a.

| Test Site's Name | Mawas | | Mawas | | Sabangau | |
|---|---|---|---|---|---|---|
| UTM Latitude | km 228 | | km 238 | | km 256 / km266 | |
| **LiDAR derived DTM parameters** | | | | | | |
| | 2007 | 2011 | 2007 | 2011 | 2007 | 2011 |
| River level (m) | 17.8 | 17.8 | 17.1 | 17.1 | 15.5 | 15.5 |
| **Altitude of the peat dome (m)** | **32** | **32** | **29** | **29** | **26/31** | **26/31** |
| Max. slope (m/km) | 2.41 | 2.90 | 1.41 | 1.57 | 1.71 | 1.76 |
| Average slope (m/km) | 0.62±0.57 | 0.63±0.60 | 0.61±0.37 | 0.55±0.41 | 0.73±0.43 | 0.72±0.42 |
| Hummocks roughness (m) | 0.73±0.33 | 1.16±0.22 | 1.42±0.53 | 1.12±0.38 | 0.94±0.15 | 0.93±0.20 |
| Nominal transect length (km) | 23 | | 23 | | 12/17* | |
| **LiDAR derived CHM parameters** | | | | | | |
| | 2007 | 2011 | 2007 | 2011 | 2007 | 2011 |
| Dominant tree height (m) | 21.8±2.3 | 24.6±1.6 | 18.8±2.5 | 19.1±2.4 | 21.3±2.2 | 24.7±1.8 |
| Averaged tree height (m) | 13.5±1.8 | 16.1±1.5 | 10.9±1.6 | 13.1±1.6 | 13.5±2.1 | 16.3±1.6 |
| Maximum tree height (m) | 28.3±3.5 | 32.1±3.4 | 25.6±3.9 | 27.4±3.9 | 28.5±2.9 | 29.7±2.4 |
| Number of sample plots | 75 | | 91 | | 52 | |
| Past activity log** | slight | | heavy/moderated | | moderated | |

Note: * Sabangau test site is a mosaic of two transects (see Fig. 1c). ** based on the visual interpretation and spectral signatures analysis of Landsat images.

Table 2. Averaged LiDAR derived DTM and CHM parameters for the selected transects in Central Kalimantan, Indonesia.

At the Sabangau transect for example, buttressed and stilt tree roots grow out from the base of the trunk sometimes as high as 2m above the hummocks. The harsh nature of the peat soil reported by Page et al. (1999) at this site from the river system to the peat dome plateau may increase the area of these superficial roots in which inorganic nutrients can be better uptake absorbed from the soil. Thus, trees that grow in such swamp condition have developed also adaptations that allow them to enhance gas exchange from pneumatophores roots during long wet periods (Richter 1984, Bruenig 1990).

Additionally, spreading plank buttresses and dense stilt roots also help keeping indirectly the superficial water saturation by limiting the water percolation across the peat floor through physical barriers such as litter, vegetation and depressions (Herwitz 1988). The water level remains therefore at the uppermost layer of the peat floor for the most of the year implying on a continuous saturation of the water table (Anderson, 1964, Hooijer 2005). This might bring an arrangement of plant communities in mounds (not inundated) and non-mounds (under frequent water saturation) according to their flood tolerance including innumerous pneumatophores and knee roots in non-mounds at specific slope conditions. Hence, large hummocks benefit from the establishment of buttresses and stilt root trees. They have usually many mounds around the base of each tree trunk due to the root architecture supporting aboveground organs raising the peat surface around the buttresses and stilt roots trees (Shimamura and Mimose, 2005, 2007).

Mounds are especially prevalent around huge buttresses and stilt root trees, which form an emergent stratum of the forest (Shimamura and Mimose, 2005). The emergent stratum of the PSF, represented by the CHM dominant tree height, tends to increase from the river system to the steepest part of dome and then to decrease towards to the peat dome plateau (Figs. 3a, 3b). An exception was observed at Sabangau towards to the dome plateau due to the burned scar which leads to lower trees according to the burning severity (Fig. 3c). Tree height increases in average for the selected transects up to 5m if the peat dome slope increases more than 1.3m/km indicating a clear dependence on the dome slope (Figs. 3, 4).

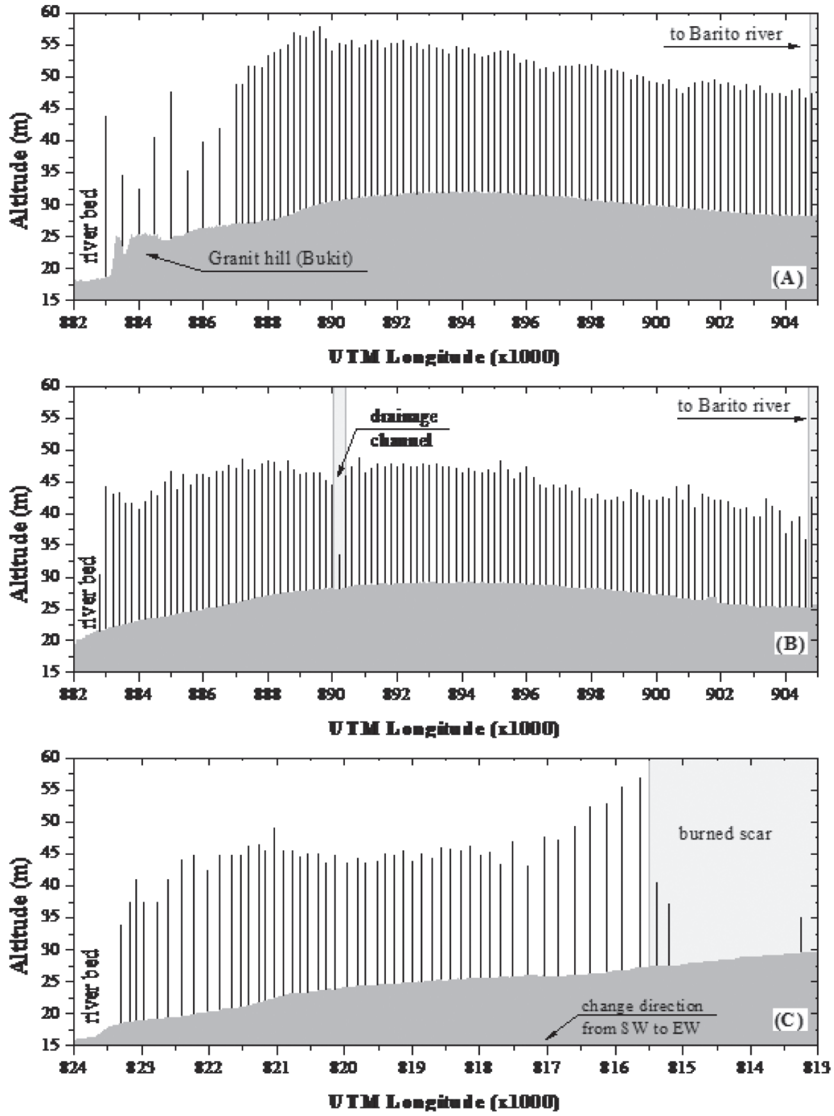


Figure 3. LiDAR derived digital terrain model (DTM) profiles and LiDAR derived canopy height model (CHM) parameter dominant tree height overlaid over the DTM for Mawas km228 south of equator (A), Mawas km238 (B) and Sabangau km256 (C). Results are based on LiDAR measurements acquired in 2007. Each vertical bar is a 1-ha sample plot. Transects have different lengths and vertical scales. Refer to Figure 1 and Table 2 for the selected test sites description.

The averaged tree height varied widely over the selected transects (Figs. 3, 4). This might be due to different intensities of past log intervention to the forest that may explain part of the heterogeneity in the roughness (Table 2a, Fig. 3) and the variations of tree height among the selected transects (Fig. 4, Table 2b). While Mawas km228 has faced less intervention by forest logging, Sabangau and Mawas km238 had experience strong intervention by selective logging through different concession companies until 1997 (Boehm and Siegert, 2004). In such forest logging practices, the large trees are harvested what directly implies on large gaps in the canopy besides the damage of neighbours' trees that further causes a drastic loss in the amount of organic matter inputs. Thus, harvesting practices also includes the construction of small railways and channels to bring the logs out from the forest. These leads to significant changes of the peat floor heterogeneity and their eco-hydrological function. The forest disturbances are still visible on the LiDAR derived products (i.e. CHM and DTM) as well as based on the visual interpretation (Fig. 1) and the spectral analysis of the Landsat scenes (results not shown).

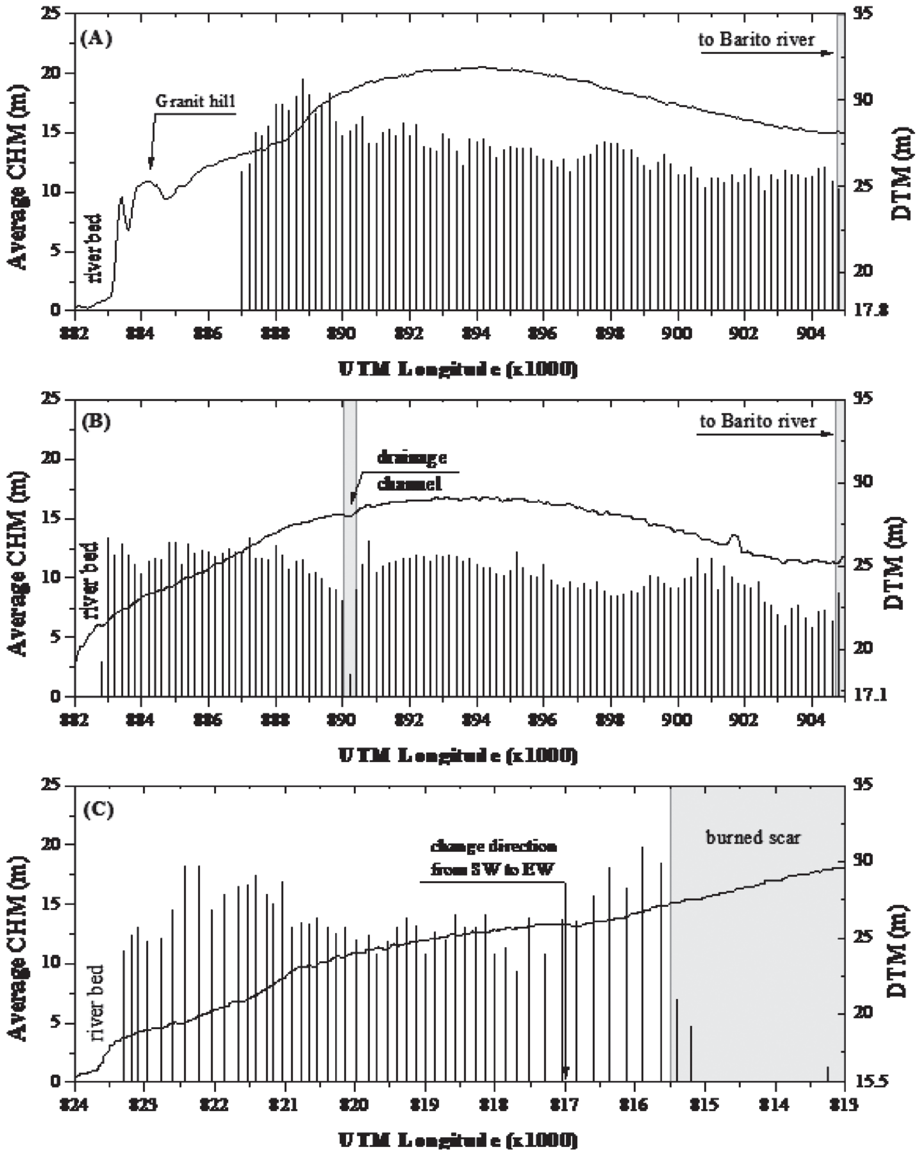


Figure 4. LiDAR derived digital terrain model (DTM) profile and separately LiDAR derived canopy height model (CHM; average tree height) for Mawas km228 (A), Mawas km238 (B) and Sabangau (C). Refer to Figure 1 and Table 2 for the test site description. Results are based on LiDAR measurements acquired in August 5-7, 2007. Each vertical bar is a 1-ha sample plot.

***Relationship between tree height and peat dome slope***

Linear regression (Fig. 5a) shows that a large part of the forest height at Mawas km228 can be explained by dome slope (up to 80%). Whereas at Mawas km238 and Sabangau this relationship is lower (up to 40%, Figs. 5b, 5c). Thus, the dome slope (Boehm et al., 2010, 2013) tends to explain better the dominant tree height than maximum and averaged tree height (Table 3, Fig. 5).

The extraction of certain commercial species through selective logging and the clear cut of small patches in the forest for hunting practices (Harrison et al., 2011) brought gaps on the canopy layer mainly at the Mawas km238 and Sabangau transects. As a result, faster peat decomposition is noticed due to a reduction on the organic matter supply and an increase on the peat floor surface temperature (Jauhiainen et al., 2005, Ali et al., 2006, Ludang et al., 2007). A homogeneity of the forest canopy is then observed due to the reduction of dominant trees (Figs. 4, 5), consequently also diversity, followed by the establishment of certain pioneer species as a response to increasing offer of light and less competition effects. This may explain the similarity of the different forest attributes in the statistical analysis for the logged transects such as in Mawas km238 and Sabangau transects (Table 3). Thus, these transect show a higher reflectance in NIR and lower reflectance in red than Mawas km228 (results not shown). This indicates higher biomass production, and therefore, more evidences of the secondary stage status of the PSF at Mawas km238 and Sabangau transects (Liesenberg et al., 2010).

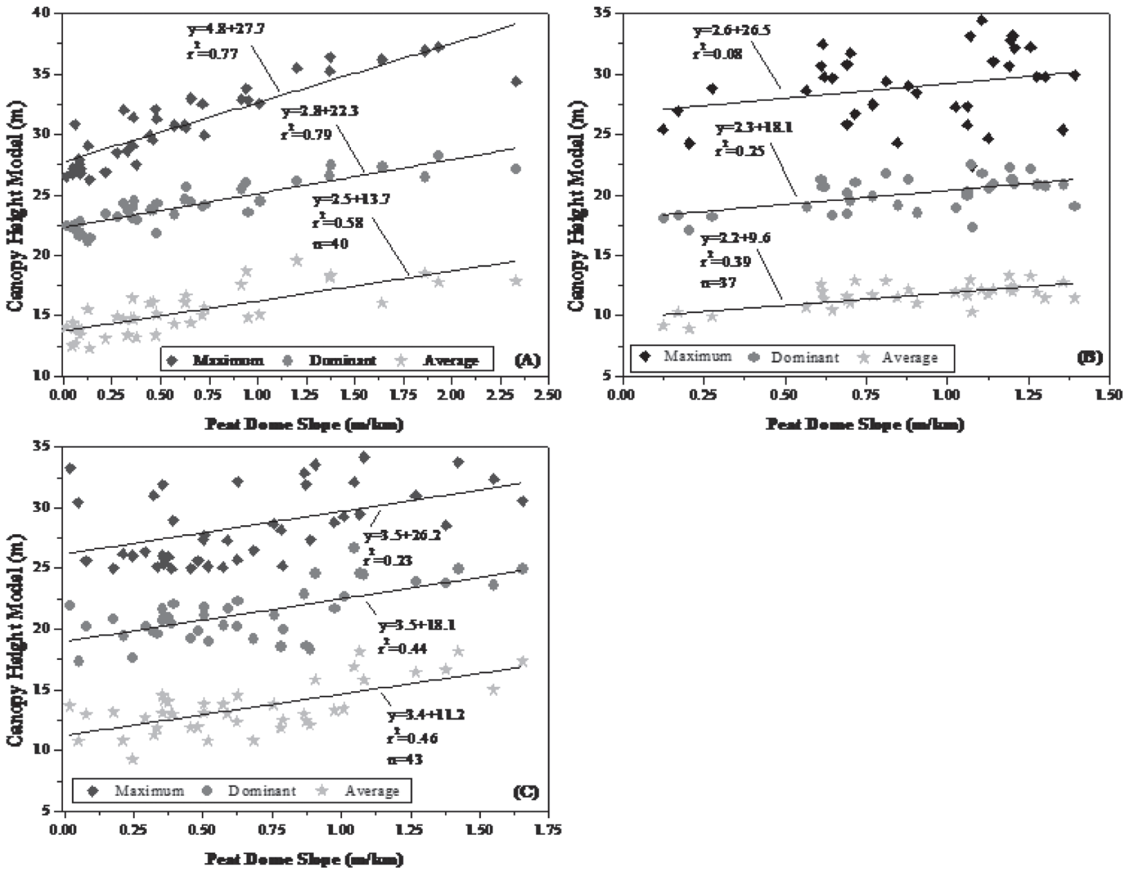


Figure 5. Linear regression models considering peat dome slope versus CHM parameters (i.e. averaged tree height, dominant tree height and maximum tree height) for Mawas km228 south of equator (A), Mawas km238 (B) and Sabangau (C). Refer to Figure 1 and Table 2 for the selected test sites description. Each point represents a 1-ha sample plot. Results are based on the LiDAR acquisition from August 5 to 7, 2007.

| | **Mawas km 228** | | **Mawas km 238** | | **Sabangau** | |
|---|---|---|---|---|---|---|
| | 2007 | 2011 | 2007 | 2011 | 2007 | 2011 |
| CHM (maximum) | 0.77* | 0.80* | 0.08 | 0.08 | 0.31* | 0.30* |
| CHM (dominant) | 0.79* | 0.81* | 0.25* | 0.25* | 0.40* | 0.39* |
| CHM (average) | 0.58* | 0.52* | 0.39* | 0.39* | 0.29* | 0.30* |
| Accumulated subsidence | 0.07 | 0.06 | 0.08 | 0.14 | 0.15 | 0.20* |
| Accumulated forest regrowth | 0.08 | 0.07 | 0.01 | 0.13 | 0.06 | 0.28* |

Note: * p<0.000

Table 3. Coefficient of determination (r2) obtained from the linear regression results of peat dome slope versus maximum, dominant and average CHM. Peat dome slope versus accumulated subsidence and forest regrowth.

Changes in tree height may also coincide, at least partially, with surface roughness that acts as small water and nutrient reservoirs. In certain conditions, the supply of mineral nutrients as well as the strategy of cycling and uptaking nutrients efficiently by symbiotic associations and aerial roots (e.g. balance between peat accumulation and peat degradation) is observed in such environments (Tawaraya et al., 2003, Nishimua et al., 2007). However, there was no statistical evidence of the roughness variations according to slope changes (Table 3) most probably due to the multiple interventions into the forest that and the relative low point density at the peat surface. The driest part of the peat dome should occur on the near-horizontal plateau where the soil supply of nutrients becomes progressively more limited since they are more susceptible to runoff to the edges (Anderson 1983, Bruenig 1990, Yamada 1997, Page et al. 1999). The PSF at the steepest dome slope (Boehm et al., 2010, 2013) where the highest trees were observed (Table 3, Figs. 4, 5) is characterized by three to four well-structured canopy layers. Trees have in general stilt and buttresses roots (up to 1/3 of the trees with DBH>15cm) and the peat surface besides large hummocks is also dominated by pneumatophores and knee roots. The understory layer is rich with seedlings and the peat thickness is also higher (Page et al., 1999). Sedges and ferns are more common in large gaps and also in the understory layer towards to the peat dome plateau where the tree height and CC becomes smaller.

Water table fluctuations are larger in high dome slope conditions (i.e. >1m/km) besides nutrient availability driving trees to grow to substantial height (Anderson 1983, Esterle and Ferm 1994, Page et al., 1999). This substantial height also subjects the trees to wind stress (Figs. 4, 5) which further stimulates the expansion of stilt and buttresses roots (Anderson 1983, Richter 1984, Yamada 1997). In addition, the large crowns observed at this part of the dome favor a stronger stem flow that due to the stilt and buttress roots prevents erosion and promote rewetting of their own root system (Herwitz 1988). Hence, it also may favor competitive advantage for other neighbor species (Crook et al. 1997, Shimamura et al. 2006).

The tree height variability was also verified at the Sabangau transect with field measurements (Fig. 6) that similar trends observed by the CHMs (Figs. 4, 5). The agreement with the CHM dominant tree height for the main transect was moderated ($r2=0.51$, $p<0.000$) due to differences between the plots sizes measured in the field twenty times smaller than those from LiDAR used in this investigation. At this site, large TBA (i.e. from 44 to 70 m2·ha-1) and AGB (i.e. from 197 to 360 Mg·ha-1; Fig. 6) variations were also found at the steepest part of the dome. The results also corroborate with the high PAI and canopy coverage values at this peat dome interval (results not shown).

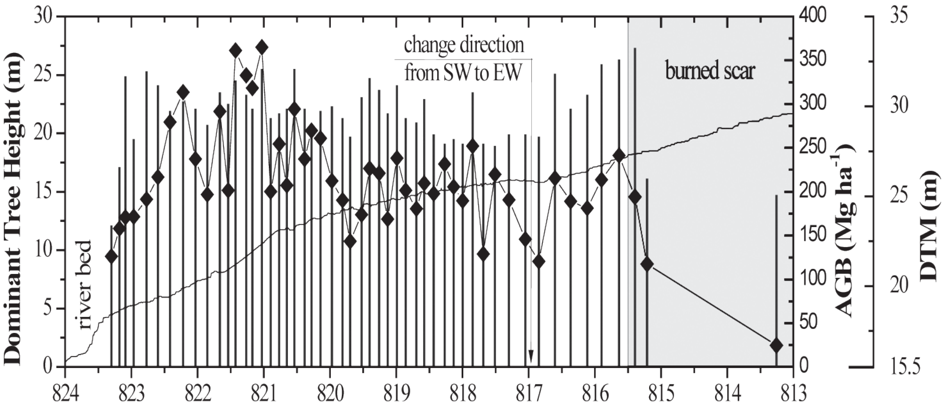


Figure 6. Above ground biomass (AGB) based on Brown (1997). Field measured dominant tree height at the Sabangau test site. High AGB values are found at the highest slope between km 821.5 and km 821. Arrow indicate the change direction of the transect. Refer to Figure 1 for the selected test site description.

### *Change detection analysis using bi-temporal LiDAR analysis*

The aerobic decomposition process of the peat floor in undisturbed PSF is generally faster than the anaerobic decomposition of the bellower peat soil layers (Brady 1997, Chimner and Ewel 2005, Couwenberg et al. 2010). However, long periods of extreme low precipitation can lead to a temporary drought of the peat floor (Wösten et al., 2008). Coupled with forest logging practices and drainage, a subsidence of the peat is therefore favored.

An accumulated subsidence varying from 0.15 to 0.50m (Table 4, Fig. 7) was noticed in the selected transects for the four years period (i.e. from 2007 to 2011). The highest average subsidence was found at Mawas km238 (Table 4, Fig. 7b). Whereas at Mawas km228 and Sabangau the lowest average subsidence values (Table 4, Figs. 7a, 7c). Hence, highest values were commonly found close to drainage channels (Figs. 7a, 7b). At Mawas km238 and Sabangau several small channels are still present and were not completely closed. The channels were dug, usually 1-2m wide and 1m deep with variable length for the transportation by floating to the main rivers and then to sawmills. The subsidence pattern corroborates with previous findings conducted converted PSF into oil palm and Acacia spp. plantations (Hooijer et al., 2012). Hooijer et al. (2013) findings of subsidence in Block A of EMRP are much lower than our findings, private communication 2013.

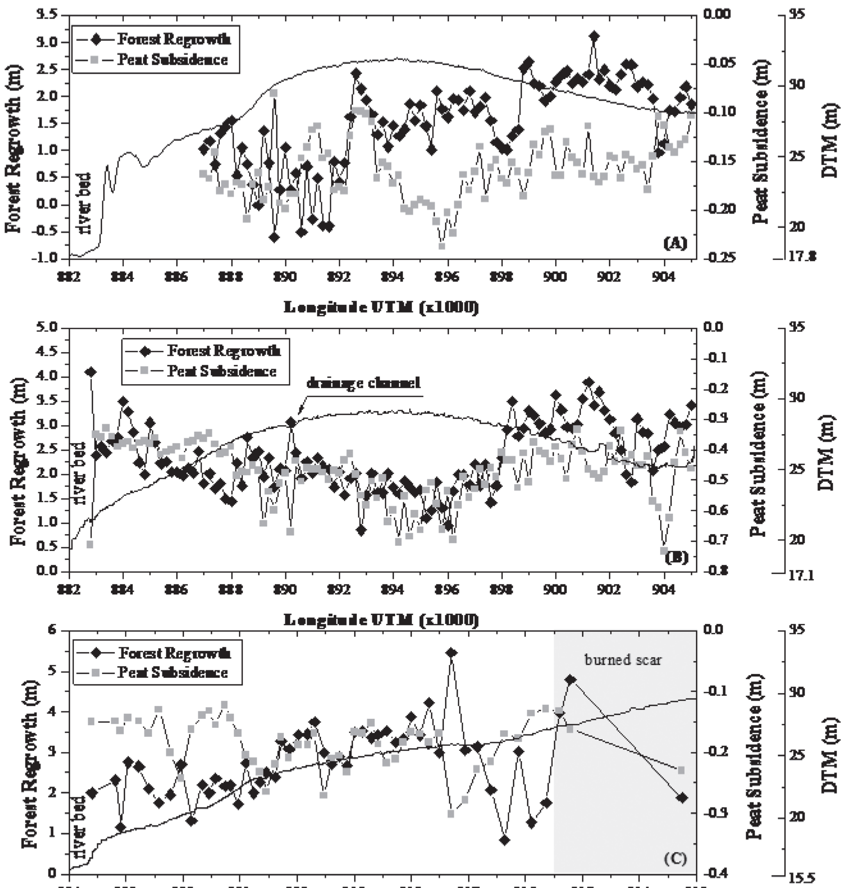


Figure 7. Average forest regrowth and peat surface subsidence for Mawas km228 (A), Mawas km238 (B) and Sabangau (C). Results are based on LiDAR measurements acquired in 2011 and 2007. Transects have different lengths and vertical scales. The arrow indicates the changed direction of the Sabangau transect from the SW to the EW direction. Refer to Figure 1 and Table 4 for the selected test sites description.

| *Test site's name* | Mawas | Mawas | Sabangau |
|---|---|---|---|
| *UTM latitude* | km 228 | km 238 | km 256 |
| Average forest regrowth (m) | 1.5±1.5 | 2.1±0.6 | 3.1±0.75 |
| Peat subsidence (m) | 0.16±0.03 | 0.50±0.1 | 0.18±0.04 |

Table 4. Averaged LiDAR change detection results in the time frame from August 2007 to August 2011 (4 years) for the selected three transects in Central Kalimantan.

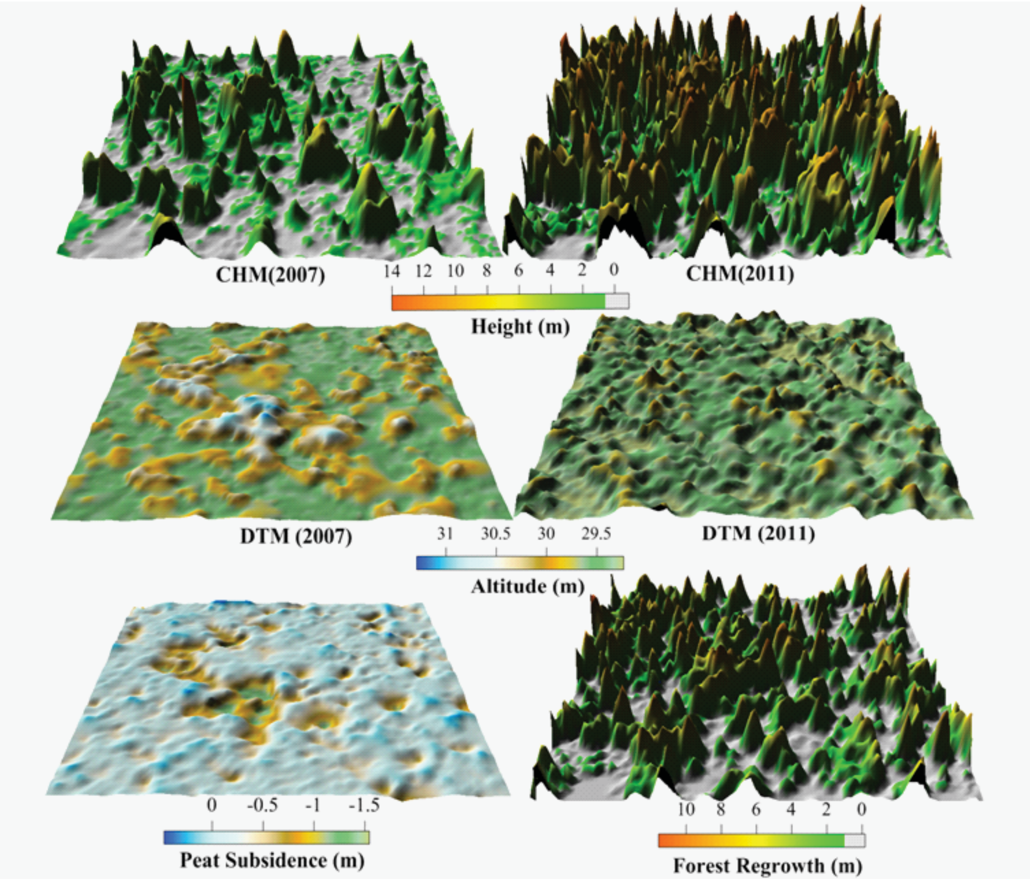


Figure 8. DTM and CHM of a sample plot for 2007 and 2011 located at a burned scar area inside the Sabangau National. Subsidence 2007 and 2011, left; regrowth 2007 and 2011, right.

Hooijer et al. (2012) reported that the subsidence rate is higher at initial stage of peat drainage and it decreases with time. The drainage of the peat cause a lowering of the water table that lead to subsidence by compaction due to peat shrinkage since peat is mostly composed by water (up to 80%, cf. Yule et al., 2010). After, oxidation may become the main contributor once the peat bulk density (mass of peat soil per unit volume) has reached certain saturation threshold. Large accumulated subsidence values were found at the dome plateau at Mawas km238 (Fig. 7b) where a drainage channel is present. Relationships between peat dome slope versus subsidence and forest regrowth could be established only at Sabangau site. At this site, low regrowth and low subsidence could be associated at steepest slope with certain uncertainty (Table 3).

However, the subsidence values for the selected transect (Table 4, Fig. 7) are higher than those observed by Jauhiainen et al. (2012) and Hooijer et al. (2012) analyzing degraded peatlands of Sumatra that were converted into oil palm and Acacia spp. plantations. Although peat characteristics and disturbance history might differ among sites, the changes reported here may also be influenced by the residual error caused by the lower point density and possible classification errors besides a vertical accuracy of 0.15m from the LiDAR system in both surveys. It is also important to mention that the four years period analyzed with LiDAR data did not encompass the period in which the drainage channels were constructed neither the forest log had started. However, the results showed a strong influence of forest disturbance on subsidence.

The forest regrowth varies from 1.5m to 3.1m during the four years period (Table 4). Mawas km228 showed the lowest forest regrowth due to the more pristine nature of the PSF. Whereas Mawas km238 and Sabangau accounted for the highest regrowth rates showing a high resilience of the PSF. Although the regrowth analysis is restricted to few sample plots, there were areas in with negative regrowth due to the deforestation of small patches (results not shown). At Sabangau partial toppling of trees were often observe during the field survey. This may be related by wind storms coupled with drainage of the peat and could be one reason for the reduced regrowth and small negative differences at the CHM at Mawas km228 (Fig. 7a). Thus, artifacts due to differences in the point density in both surveys cannot be neglected. Finally, there was no relationship between forest regrowth and peat subsidence.

Fig. 8 shows the bi-temporal DTM and CHM for a sample plot located at the burned scar at Sabangau transect (cf. Figs. 1, 3, 4, 6). Forest regrowth at this site depends both on the characteristics of the ecosystem and specifically on the fire intensity and its recurrence (Hoscilo et al., 2011). Few isolated trees and several small bushes, most probably sedges and ferns bogs that are found in such environments, can be interpreted from the CHM in 2007 (Fig. 9a) indicating a widespread tree dieback by fires during the El Niño event in 1997 (Page et al., 2002, Usup et al., 2004). At the Landsat image acquired in August 20, 2001 this burned site showed high red and low NIR values due to the large proportions of non-photosynthetic proportions of vegetation. Fire recurrences were also reported in Kalimantan in 2002, 2004, 2006 and 2009, however were not evident at Sabangau test site by analysing the Landsat images. The red response tends to decrease from August 20, 2001 to August 5, 2007 and then to June 13, 2011 while NIR increase as more photosynthetic proportions of vegetation is present (Liesenberg et al., 2010).

A relative regrowth of the PSF is noticed after a four years period acquisition between the LiDAR surveys (Fig. 7). Several hollows are observed at the bi-temporal DTMs (Fig. 8) and still remain uncovered by vegetation. This is most probably due to strong fire intensity that builds pools where the water is frequently accumulated over the year limiting therefore the vegetation regrowth. The spatial distribution of the hollows can be identified by a subset of the aerial Ortho-photos and in-situ photos (Fig. 9). The area also registers the lowest AGB, TBA, CC and PAI.

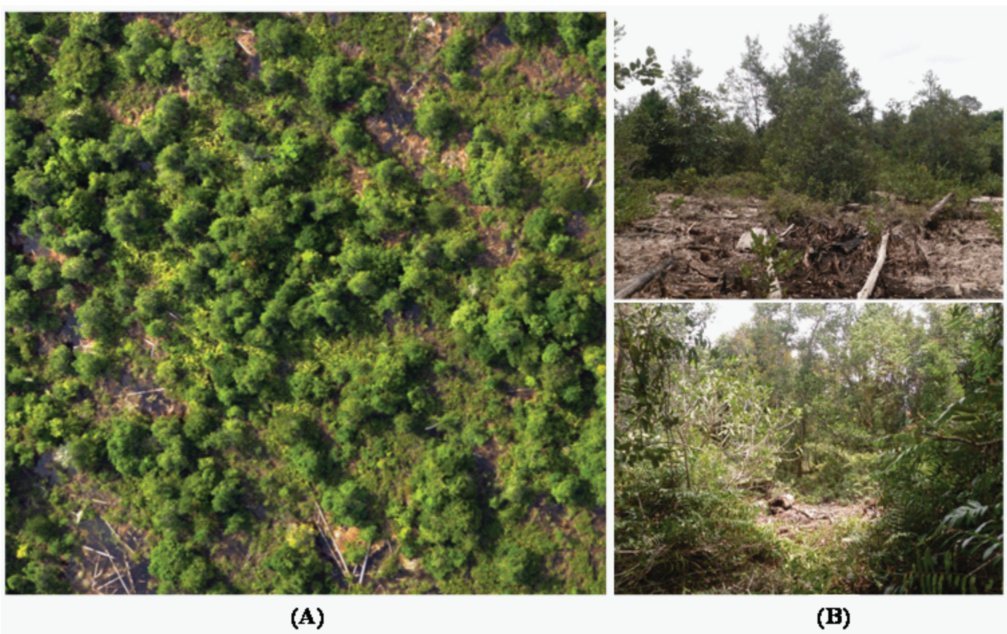

Figure 9. Ortho-photo from a Hasselblad camera showing the proportions of green and non-photosynthetic vegetation within a burned scar area at the Sabangau National Park (A). In-situ ground photos of the same regeneration area (B).

***Implications for the Ecology and Management of Peatlands***

The most striking observation from this study is that tree canopy height appears to be closely related to peat dome slope in less disturbed PSF. Undisturbed PSF with limited or no damage are rare in Southeast Asia (Miettinen and Liew, 2010). The role of conservation units in this endangered environment is of extreme importance as reported by Hoscilo et al. (2011). The PSF degradation by drainage, forest logging and hunting affects not only the tree structure diversity, its function and the litter accumulation on the peat surface that provides hydrological regulation under natural conditions. It also affects the interdependence of trees; water table level and peat floor itself due to the lack of surface resistance (cf. Yale 2010, Dommain et al., 2010).

The analysis hereby should be understood as a case study and should highlight in which degree canopy tree height might be related with peat dome slope achieved from remote sensing techniques using airborne LiDAR data. While results would certainly differ in detail for other tropical peatland sites due to peat dome characteristics (Anderson 1983, Brady 1997) and previous land use disturbance history, the results highlighted here are of general importance for further management of this endangered ecosystem. The effectiveness of conservation units in endangered PSF could be evaluated with LiDAR measurements.

With frequent LiDAR measurements, critical areas could be rapidly being identified and adequately protected enabling counteractions of restoration and management. Thus, forest policy could undertake counteractions in areas where illegal forest logging and hunting are still being practice, as for example at Mawas km238 and Sabangau transects. This is valid mainly in steep dome slope areas since they represent an important hydrological function to the peat dome.

**Conclusive Remarks**

A clear dependence between peat dome slope and tree height with was confirmed with LiDAR data. With increasing peat dome slope at the selected transects, the relation between CHM height got closer. However, it was strongly dependent on the previous degradation history.

Accumulated peat subsidence varies significantly ranging in average from 0.15 to 0.50m. Highest values were found close to drainage channels, at the peat dome plateau and previous burned areas. PSF showed high resilience in degraded PSF by forest log. Forest regrowth varies from 1.5 to 3.1m during the four years period.

The results lead to the conclusion that degraded PSF might result in dramatic changes to the eco-hydrological function of the peat domes requiring management counteractions in this endangered ecosystem. The effect of forest logging activities on PSF environments and their effects on climate change should also be investigated and confirm whether this disturbance may increase the flux of $CO2$. Since peat swamp degradation may enhance peat respiration more than net primary production, more and more areas will become carbon sources rather than carbon sinks, which may have an impact on climate change.

Understanding tree height variations associated with slope gradients is important once we consider that the last remnants of PSF are located in Kalimantan that is suffering high rates of deforestation. In the coming years, as indicated by political support for REDD long-term monitoring of the peat domes will be crucial to quantify changes in carbon stocks of the peat swamp forest, and to evaluate forest growth response to climate and land use change in which LiDAR measurements can play an important task.

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