Assessment of leaf area index and canopy openness across four land-use systems in Jambi Province Sumatra, Indonesia

Dissertation

To obtain the MSc. degree

in the Tropical and International Forestry MSc. Program

(TIF)

at the Faculty of Forestry and Forest Sciences,

Georg-August-University Göttingen, Germany

Supervisor: Prof. Dr. Holger Kreft

Co-supervisor: Dr. Katja Rembold

Presented by

George Ofori Ankomah

Göttingen, March 2019

ABSTRACT

Leaf area index (LAI) and canopy openness (CO) are important biophysical indices, which have been widely applied in ecological studies and are estimated through various indirect methods including the LAI-2200 plant canopy analyzer or hemispherical photographs. This study aims at investigating leaf area index and canopy openness across four prominent land-use systems in Jambi province, Sumatra, Indonesia. Specifically, I aimed at comparing changes in canopy cover within a four-year period, and how LAI and CO differ with varying site conditions and how they are determined by stand structural attributes. LAI and CO for the year 2018 together with 2014 CO and stand inventoried data for the land-use systems were analysed in the statistical software R. The analyses revealed significant differences of LAI and CO for the year 2018 across the land-use system. LAI value of 5.96 m^2/m^2 in the forest plots was the highest while rubber plantation recorded the lowest value of 2.46 m^2/m^2 with an intermediate value of 5.09 m^2/m^2 for jungle rubber. In terms of CO, rubber plantation had the highest value of 14.73 % whereas jungle rubber recorded the lowest value of 3.6 % with an intermediate value of 4.14 % for forest plots. In contrast to my expectation, I did not find statistically significant differences of LAI and CO between riparian and well-drained plots although tendency of higher LAI and CO in riparian plots was observed. For instance, LAI in riparian forest plots was 6.25 m^2/m^2 whereas well-drained plots was 5.96 m^2/m^2. CO in riparian rubber plantation plots was 18.35 %. CO in well-drained rubber plantation was 14.73 %. Between 2014 and 2018, CO significantly decreased in jungle rubber and oil palm plantation.

Moreover, LAI was moderately to strongly correlated (R^2=0.45, R^2=0.74) with basal area and stem density in jungle rubber.

Assessment of canopy structure is necessary in determining influencing factors for LAI in forest ecosystems. Secondly, the duration of riparian conditions in land-use systems needs to be considered in order to fully account for patterns of change in LAI and CO.

Keywords: Leaf area index, canopy openness, land-use systems, forest (rainforest), jungle rubber, oil palm, rubber, Jambi Province, Indonesia

ZUSAMMENFASSUNG

Blattflächenindex (Leaf Area Index, LAI) und der Grad der Kronendeckung (Canopy Openness, CO) sind wichtige biophysikalische Indizes, die in ökologischen Studien weite Anwendung finden. Sie werden mit Hilfe von verschiedenen indirekten Methoden geschätzt, zum Beispiel mit Geräten wie dem LAI-2000 Plant Canopy Analyzer oder durch hemisphärische Fotos. Diese Studie untersucht LAI und CO in vier typischen Landnutzungssystemen in der Provinz Jambi der indonesischen Insel Sumatra. Sie zielt darauf ab, Veränderungen in der Kronendeckung über vier Jahre zu vergleichen sowie LAI und CO zwischen den verschiedenen Landnutzungsformen zu vergleichen und mit Strukturmerkmalen der Vegetation in Verbindung zu setzen. LAI- und CO-Werte, gemessen im Jahr 2018, sowie CO von 2014 und Strukturmerkmale der Landnutzungstypen wurden mit der statistischen Software R analysiert. Die Ergebnisse zeigten signifikante Unterschiede von LAI und CO zwischen Landnutzungsformen im Jahr 2018. LAI-Werte waren am höchsten im Wald (5.96 m^2/m^2), während Kautschukplantagen die niedrigsten (2.46 m^2/m^2) und Kautschuk-Agroforstsysteme mittlere Werte (5.09 m^2/m^2) aufwiesen. Bei CO hatten Kautschukplantagen die höchsten Werte (14.73%), wohingegen Kautschuk-Agroforst mit 3.6% die niedrigsten und Wald mittlere Werte (4.14%) zeigten. Engegen vorheriger Vermutung fand ich keine statistisch signifikanten Unterschiede von LAI und CO zwischen Flächen mit und ohne Grundwasserbeeinflussung. Allerdings waren die Werte in Grundwasser-beeinflussten Flächen tendenziell höher. Von 2014 bis 2018 nahm CO in Kautschuk-Agroforst und Ölpalmplantagen signifikant ab. LAI war mittel bis stark korreliert mit Basalfläche und Stammdichte inn Kautschuk-Agroforst, aber nicht in den anderen untersuchten Systemen. Um Faktoren zu finden, die LAI in Waldökosystemen beeinflussen, ist eine Untersuchung der Kronendachstruktur notwendig. Zudem muss die Dauer der Überflutung in wasserbeeinflussten Landnutzungssystemen berücksichtigt werden um Veränderungsmuster in LAI und CO zu verstehen.

Schlagworte: Blattflächenindex, Kronendeckung, Landnutzungsysteme, Wald, Kautschuk-Agroforstsysteme, Ölpalm, Kautschuk, Provinz Jambi, Indonesien.

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1 Introduction

1.1 Land use change and Indonesia (Sumatra)

Total rainforest area in South-east Asia is reducing due to deforestation and conversion into other land-use types especially, rubber and oil palm plantations, mining, pulp and timber (Guillaume et al., 2015; Laumonier et al., 2010a). Additional 4.3–8.5 million ha of biodiversity significant areas under threat such as protected areas of Asian forest is projected to be cultivated with rubber plantations in order to meet the expected rubber demand by 2024 (Warren- Thomas et al., 2015). oil palm was responsible for an average of 270,000 ha of forest conversion annually from 2000–2011 in major palm oil exporting countries such as Indonesia and Malaysia (Henders et al., 2015).

Between 1985 and 2007, Sumatra Island, Indonesia lost half of its natural rainforest, remaining a forest cover of 30 % (13 million ha) of the island (Laumonier et al., 2010a; Wilcove and Koh, 2010). Margono et al. (2014) reported that Indonesia has the highest deforestation rate worldwide surpassing the previously leading country, Brazil. The Island of Sumatra has the highest deforestation rates within Indonesia. Excessive logging, increasing trend of rubber and oilpalm mono-cropped plantations as well as jungle rubber agroforest systems are known to be the major drivers of the massive decline of forest cover in Sumatra, Indonesia (Margono et al., 2012; Villamor et al., 2014). A larger portion (52 %) of the total area under oil palm cultivation are owned by private enterprises whereas the remaining 48 % are owned by both, the government and small holding farmers. Greater share (85 %) of the rubber plantations are owned by small holders (Statistics Indonesia, 2015; 2016).

1.2 Relevance of leaf area index and canopy openness in land-use studies and measurement methods

Leaf area index (LAI) is defined as one sided green leaf area per unit ground surface area (Watson, 1947) which represents an essential biophysical index to describe exchange of energy, water vapour and carbon dioxide between terrestrial systems and atmosphere. Canopy openness is described as the exposed area at the canopy level that is unobstructed by branches and leaves, measured at one point when observed upwards within the canopy of a woodland system (Sang et al., 2008). Canopy closure which can be used as a proxy of canopy openness is defined as the portion within the canopy of a vegetation cover obstructed by foliage materials. Canopy openness is measured through hemispherical photographs which can give a vivid account of the total size and distribution of canopy openings (Valverd and Silvertown, 1997). Additionally, the distribution of canopy openings in a hemispherical photograph together with data on above canopy spatio-temporal pattern of photosynthetically active radiation to get a periodic light regime at a small site (Chazdon and Field, 1987).

Moreover, LAI has been commonly applied in ecological studies and serves as significant input variable in transpirational models, precipitation models and primary production models (Propastin and Erasmi, 2010; Chen et al., 1991; Johnson I. R. and Thornley J. H. M., 2006). Landsberg and Waring (1997) described the expediency of LAI in the functional process-based model, hence, LAI can be used to describe growth characteristics, canopy health and productivity of forests (Franklin et al., 1997). However, the efficiency of these models is extremely reactive to the deviation of LAI at variable spatiotemporal scales and therefore needs a precise estimation (Li, 2010).

Numerous approaches (direct and indirect methods) have been widely used to evaluate LAI values in different landscapes across biogeographical scales (Gower et al., 1999). Direct means of estimating LAI work with ground-based techniques of destructive sampling, litter fall gathering and point contact sampling to determine LAI in planimetric or gravimetric procedures (Zheng and Moskal, 2009). Jonckheere et al. (2004) reported that direct estimation approaches give correct values of LAI, whereas, several others take the opinion that the approach is very expensive, arduous, time-consuming and closely unrealistic in large areas and for small plants in limited experimental plots (Propastin and Erasmi, 2010; Zheng and Moskal, 2009; Gobron et al., 1997).

Moreover, indirect methods of LAI measurement such as with Li-cor LAI instruments and satellite sensors have been extensively employed in larger areas (Zheng and Moskal, 2009; Li, 2010) and thus, offer a prompt assessment of LAI (Chen et al., 1991). Friedl et al. (1994) and Epiphanio and Huete (1995) have revealed the importance of LAI estimations using remote sensing. However, other studies suggest that, indirect methods underestimate the LAI by 25 – 50 % (He et al., 2007; Chason et al., 1991). Gower et al. (1999), ascribed this problem to the uneven distribution of foliage in the canopy and radiation interception by woody components. Deforestation and land-use change have a strong influence on LAI and the related biophysical aspects which in turn have the potential of causing changes in atmospheric conditions within land-use types to have indirect impact on productivity and ecosystem functioning (Hardwick et al., 2015).

1.3 Study objectives and research questions

The ecological and socioeconomic functions of tropical lowland rainforest transformation systems (EFForTS) project in Jambi Province (Sumatra, Indonesia) aims to quantify the consequences of the rapid land-use change on biodiversity (Rembold & Kreft, 2015).

In context of the EFForTS project, this study seeks to investigate the biophysical (LAI, canopy openness (CO)) and stand structural (basal area (BA), stem density (SD)) parameters across the four land-use systems (forest, jungle rubber, rubber and oilpalm) in Jambi Province, compare changes in canopy cover within a four-year period as well as how LAI and CO differ with varying site conditions and how they are determined by stand structural attributes.

The following hypothesis were tested:

1. There is relatively higher leaf area index in forest and jungle rubber agroforest as compared to oil palm and rubber plantation will register the lowest value. This trend is the reverse between land-use systems in terms of canopy openness.
2. There is a substantial decrease in canopy openness in forest and jungle rubber agroforest as compared to oil palm and rubber plantations over the four-year period (2014 – 2018).
3. LAI is higher in riparian forest plot than in riparian plantation plots. The reverse will be true in terms of canopy openness for the land-use systems.

The following research questions are addressed:

1. Has the canopy openness between the land-use systems (forest, jungle rubber, monoculture rubber and oil palm plantations) changed over the four-year period (2014 – 2018)?
2. How do LAI and canopy openness data of the same year (2018) in different land-use systems correlate?
3. What are the influencing site factors (stand attributes) affecting the LAI and canopy openness estimations across the different land-use systems?

2.0 Materials and methods

2.1 Study area

The study was carried out in context of the EFForTS project in Jambi Province (Sumatra, Indonesia) from March to mid-June, 2018 (Fig. 1) (Drescher et al., 2016).

The vicinity of Jambi covers a land size of 50 160 km^2 extending from the Barisan highland region in the west through wide-ranging lowlands towards the southern Malacca Strait in the east (Badan, 2014). Acrisols constitute the dominant soil type in Jambi province(Allen et al., 2015). The climatic condition in Jambi's lowlands is tropical humid with the highest rainfall seasons around March and December. The dry period starts from July to August with an average yearly temperature of 26.7 ºC (Drescher et al., 2016). The growing demographic structure and demand for arable land in Jambi resulted in persistent reduction of rainforest cover through accelerated land-use changes. The rainforest cover in the hilly areas of Jambi province was only 30 % in 2013, out of which 55 % had been transformed into arable land and 10 % degraded land projected to be utilised for monoculture plantations (Drescher et al., 2016).

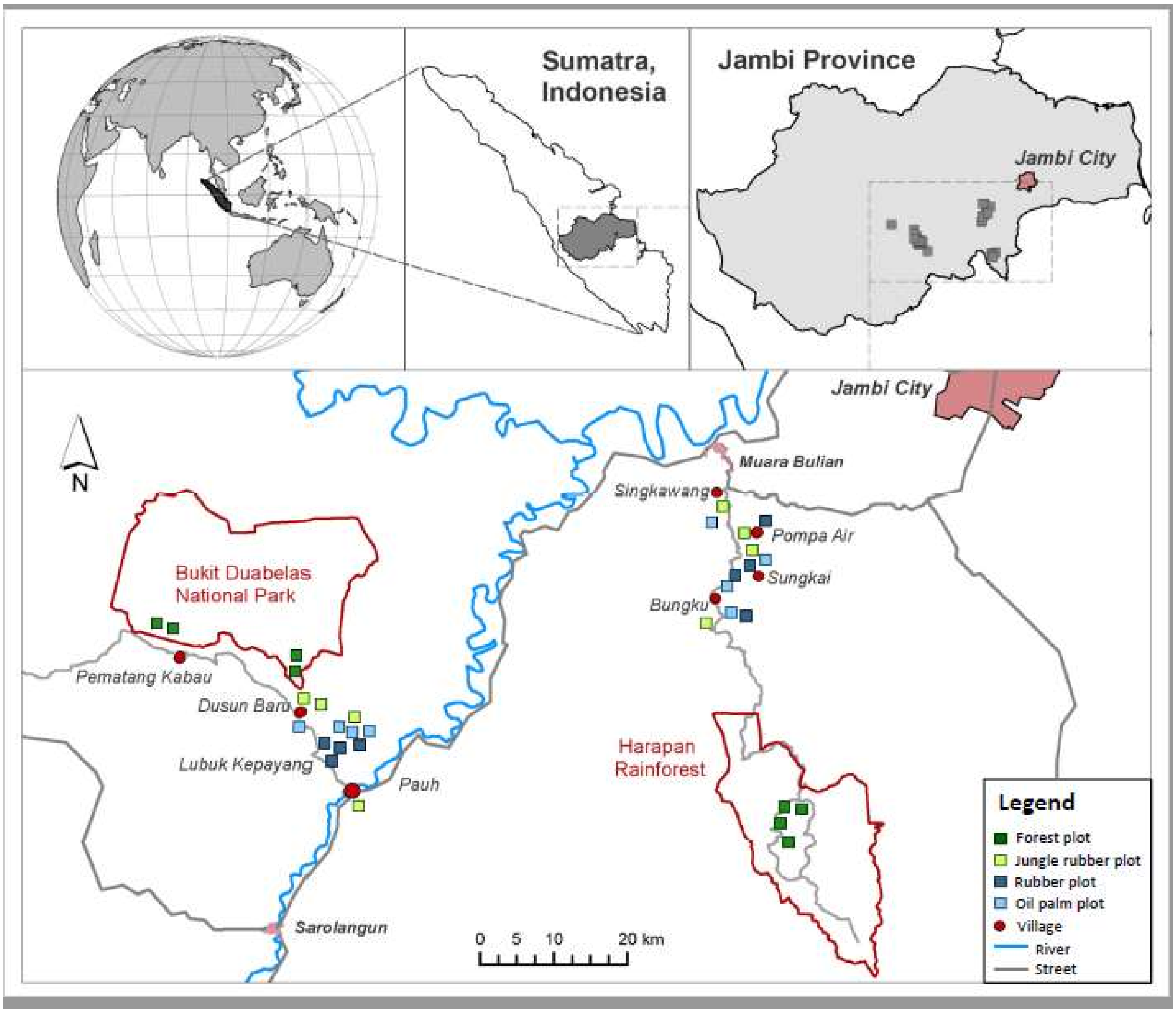

Figure 1. Location of EFForTS study sites in Sumatra and Jambi Province with the distribution of the 32 well-drained plots near Bukit Duabelas National Park and Harapan rainforest (Rembold et al., 2017)**.**

2.2 Field sampling

Forty-four core plots of 50 x 50 m dimension (Fig. 2a) had been established by the EFForTS project across two different landscapes and in four different land-use systems. Each core plot contains five subplots measuring 5 x 5 m which are unevenly laid at specific locations. 12 core plots cover riparian sites in the Harapan landscape with four plots each in rainforest, rubber and oil palm plantations. The remaining 32 core plots were established on well-drained soils distributed across two landscapes with eight plots in each of the four land-use systems (Drescher et al., 2016). Rainforest plots represent primary degraded forest with indication of selective logging and non-timber forest product extraction as categorized by (Margono et al., 2014). Jungle rubber plots are agroforest system with rubber trees planted in a selectively logged rainforest (Gouyon et al., 1993). Rubber and oil palm plots represent rubber and oil palm monoculture plantations with varying ages of 13 and 22 years as well as 14 and 21 years respectively as of 2018. Four of the forest plots were damaged by fire and storm after canopy openness was measured in 2014. These plots represent disturbed plots whereas the remaining upland forest plots constitute undisturbed plots. All core plots are provided with a meteorological station which records air temperature, relative air humidity soil temperature and soil moisture (Drescher et al., 2016). Data on tree diameter at breast height (DBH) and height were already available from a previous survey for all plots in March, 2014 (Kotowska et al., 2015).

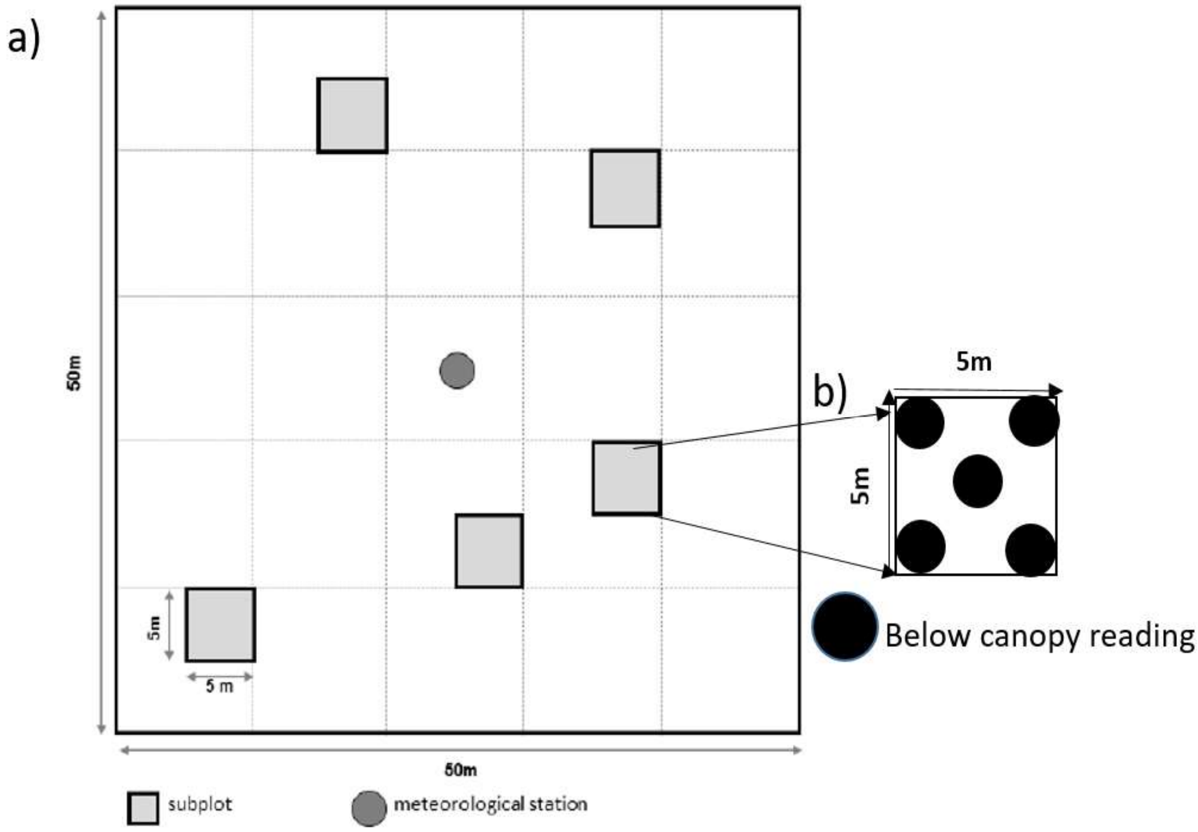

Figure 2. a) Plot design and b) locations for below canopy reading measurements within each subplot (modified after Drescher et al., 2016).

2.2.1 Leaf area index data collection and processing

LAI measurements were taken in May till mid-June 2018 at five positions in all five subplots (Fig. 2b) established within each of the 44 core plots (1100 measurements in total) using the Licor LAI-2200TC plant canopy analyzer. This device is equipped with a console developed with advanced setup options for data collection and storage. There are two wands with cables which can be connected to the console when in use with built-in fish-eye optical sensors calculating interception of blue light at 5 zenith angles from above and below canopy readings. Sensors contain optical filters which restrict sensed radiation of wavelengths below 490 nm, in order to minimize scattered radiations from the foliage (Welles and Norman, 1991). Canopy data captured by the Sensors are synchronized into the large storage system of the control unit (console) for later universal serial bus (USB) data transfer into the instrument's software windows FV2200 package installed on a computer for further processing. The device is an improved successor model of the LAI-2000 and therefore regarded as a standard instrument for indirect LAI estimation under diffused sky conditions (Bréda, 2003). Moreover, the LAI-2200 is uniquely designed to perform light scattering correction to improve accuracy even under direct sunlight though measurements under obscured sun give best results (LI-COR, Inc., 2017).

LAI data were obtained from above and below canopy readings taken simultaneously in each subplot with two wands. All measurements were taken with view cap-free wands under diffused sky conditions. Optical sensors were covered and packed into its protective case at the slightest detection of precipitation to avoid any potential optical damage to the sensors and other sensitive parts of the device. Wands were always orientated towards the magnetic north with the use of a compass (LI-COR, Inc., 2017). The above canopy readings were captured by mounting a 10-second autolog wand (reference sensor) facing the sky on a 2 m sturdy tripod with an accurate leveling bubble. This was positioned in nearby open areas to the core plots of at least 200 m x 200 m range with surrounding vegetation height less than 3.5 m to ensure unobstructed optical sensor's view of the sky across a wide azimuth (Pearse et al., 2016). Below canopy readings in each plot were taken concurrently with that of the reference sensor at five positions within each subplot to obtain accurate measurement of canopy transmission (LI-COR, Inc., 2017). However, due to technical challenges under field conditions, above and below canopy readings for six plots (BF1, HF4, HFr1, HFr2, HFr4 and HRr2) were taken at different times of the day. Final data accuracy improved significantly after a thorough data cleaning process. The distance between designated reference sensor locations (open areas) and core plots for below canopy readings was less than 1 km to ensure uniform sky brightness between the two-sensor locations for canopy measurements. Saved plot canopy readings were imported into the FV2200 software package (version 2.1.1, LI-COR Biosciences Inc., Lincoln, NE, USA) to compute the LAI values with a closure of the two outer rings to account for any potential scattering effects, which could affect data accuracy. LAI values for Subplots were averaged out for the respective core plots.

LAI data from the study were subjected to rigorous cleaning process by observing trends of error and their potential sources to enable easy identification and fixing of incorrect data. Canopy reading time mismatch was identified during the data error monitoring process for six core plots and optical sensor ring sensitivity for the plots were tested graphically to generate linear regression functions to correct for the anomaly by recalculating the light time for the above canopy readings to match with that of below canopy. LAI values were recomputed with the calculated time for each of the five optical sensor rings to ensure data consistency (Table 6). Final LAI values (Table 7) for statistical analysis for all core plots were recalculated using the FV2200 software with a closure of two outer rings for each plot. Data cleaning was carried out using 2016 version of Microsoft excel software.

2.2.2 Hemispheric photograph acquisition and processing

Hemispherical photographs were taken in March and April 2014 from 32 positions within each of the 32 well-drained plots including the five subplots by using a Canon EOS 700D SLR Camera (Canon Inc., Ōta city, Japan) and SIGMA 4.5 mm F2.8 EX DC circular Fisheye lens (Sigma Corp., Ronkonkoma, USA) (Drescher et al., 2016). In April and May, 2018 hemispherical photographs were taken in the same 32 plots with an additional 12 riparian plots distributed across three of the four land-use systems making a total of 44 plots, by using a Nikon D5100 AF-S DX NIKKOR 18-55 mm f/3.5-5.6G VR Camera and the same lens type used in 2014. Hemispherical photograph acquisition method for both years followed recommendations from Beckschäfer et al. (2013). Photographs were taken at 1.2 m above ground using a tripod with a bubble level slotted into a flash socket to vertically align the camera towards the magnetic north without the interference of understory vegetation to the lens' field of view (González et al., 2011). Photograph histograms in the camera's exposure compensation function as well as basic camera settings like programmed auto, International Organisation for Standardization (ISO = 400) and matrix metering were appropriately adjusted to avoid overexposure and with strict adherence to the recommendations of Beckschäfer et al. (2013). The 'highlight clipping warning' function in the play back mode was additionally used to decrease over exposure by capturing quite a number of incorrect photographs until warning light disappeared as an indication of correct exposure to take the best hemispherical photographs (Fig. 3a) for each subplot. Photographs were taken under uniform overcast sky conditions with strict avoidance of direct sunlight and water to the lens (Weiss et al., 2004). Hemispherical photographs were stored in JPG image format (3984 x 2656 pixels resolution) as grey values between the TIFF and JPG format were found not to be different (Frazer et al., 2001).

2.0 Materials and methods

Canopy openness data for hemispherical photos captured in both 2014 and 2018 were derived through the ImageJ software with mask_01.tif and the Hemispherical_2.0 macro plugins respectively. The macros work by applying a 'minimum' thresholding algorithm identified to achieve higher accuracies in ImageJ software (Glatthorn and Beckschäfer, 2014). The number, area and the fraction of gaps are calculated from the thresholded photographs (Fig. 3b) and displayed in a table of results by the plugins (Beckschäfer, 2015).

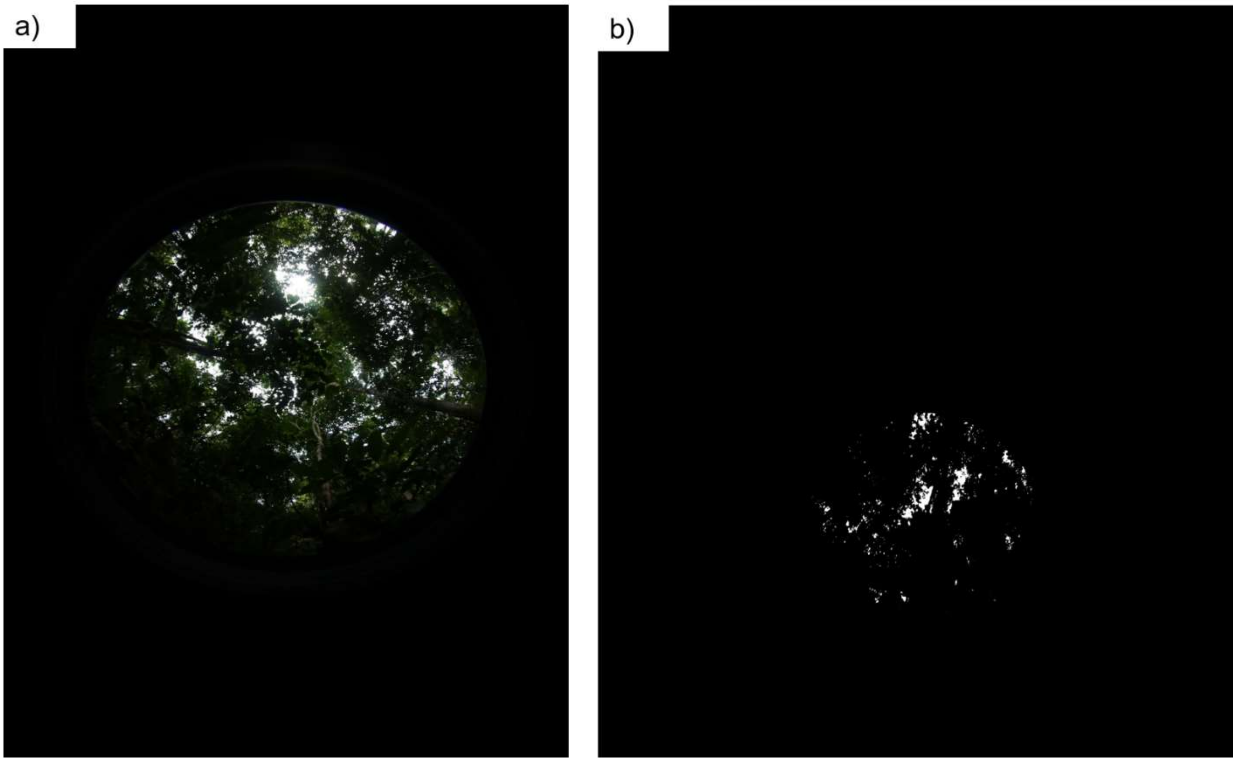

Figure 3. **(a)** Hemispherical photograph taken from subplot A of plot HFr1 with its **(b)** thresholded photograph after the ImageJ software processing.

2.3 Statistical analysis

Initial analysis commenced with investigation of normality for all parameters against land-use type, namely: leaf area index (LAI) canopy openness (CO) (for 2014 and 2018), stem density (SD) and basal area (BA) (2013/2014) using Shapiro-Wilk. Normality of CO data for 2014/2018 allowed for the assessment of variance homogeneity among the four land-use systems using Levene's test and indication of variability in systems was concretized with Tukey HSD post hoc test (Table 2). However, non-normality of LAI, SD and BA also endorsed the use of Kruskal Wallis rank test and evidence of significant differences in land use types was specified with Dunn's post hoc test (Table 1). Similar test of normality for LAI and CO (2018) against site conditions in land-use types was further carried out and non-normality of both parameters permitted Kruskal Wallis rank/Dunn's post hoc test to reveal the significant statistical differences among the varying site conditions (Table 3).

Significant differences in canopy openness between the two estimated years (2014 & 2018) across land-use systems were also verified using Wilcoxon signed rank test and statistical significant differences were only observed in Jungle rubber and Oil palm plantations (Table 4).

Linear regression models per Land use for LAI and CO against stand structural parameters (SD and BA) with LAI and CO as dependent variables (Fig. 8) were explored to examine relationships existing between the grouped biophysical parameters using the 'lm' package in R (Douglas et al., 2015). All statistical analyses were conducted using R-statistical environment (R Core Team, 2018).

3.0 Results

3.1 Comparative assessment of biophysical measures across different land-use systems

All the two biophysical parameters, leaf area index (LAI) and canopy openness (CO) showed significant differences across the four land-use systems (Fig. 4). Results from basal area (BA) and stem density (SD) were already published (see Rembold et al., 2017).

LAI in forest (5.96 m^2/m^2) and jungle rubber (5.09 m^2/m^2) was significantly higher than in oil palm (3.37 m^2/m^2) and rubber (2.46 m^2/m^2) plantations (Fig. 4a). Contrary to the LAI results across the land-use systems, rubber (14.73 %) and oil palm (11.81 %) plantations had significantly higher CO values than in forest (4.14 %) and jungle rubber (3.86 %) (Fig. 4b).

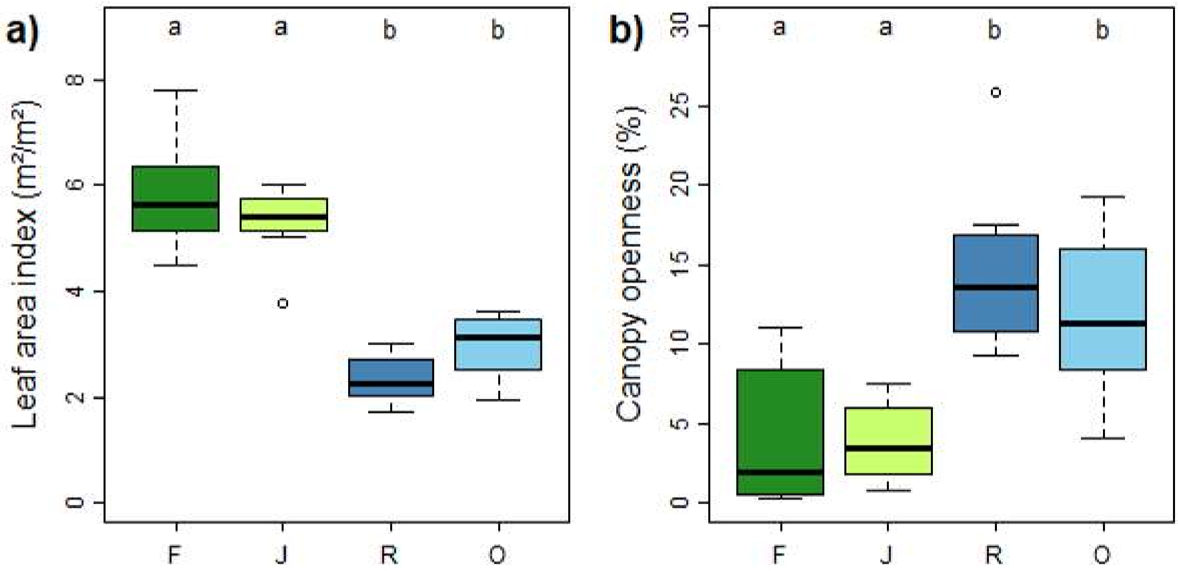

Figure 4. Boxplot for two biophysical parameters: (a) leaf area index and **(b)** canopy openness for the year 2018 across four land-use systems: Deep green boxplots represent forest (F), light green for jungle rubber (J), deep blue for rubber (R) plantation and light blue for oil palm (O) plantation in Jambi province, Sumatra-Indonesia. Different letters in plots indicate significant statistical differences of parameters at 5 % probability level between systems and same letters show no significant differences. Leaf area index by Kruskal Wallis test produced results as follows: (test statistics= 19.09, p-value <0.001) and ANOVA was significant for canopy openness (p-value <0.001, F-value= 22.85).

3.2 Varying site conditions impact on leaf area index and canopy openness estimations

Forest and jungle rubber were significantly different from rubber and oil palm plantations in terms of LAI and CO (Fig. 5).

There was no significant difference of LAI and CO between riparian and well-drained plots in all the land-use systems. In spite of this overall observed outcome, tendency of higher LAI and CO in riparian plots was observed. LAI in forest riparian plots was higher than plantation plots (Fig. 5a). CO in riparian plantation plots was higher than forest plots (Fig. 5b). This presupposes that riparian conditions are likely to cause more openness in plantation plots than under well-drained conditions. Much in the same way, riparian conditions are likely to favour higher LAI within forest plots and vice versa in plantation plots.

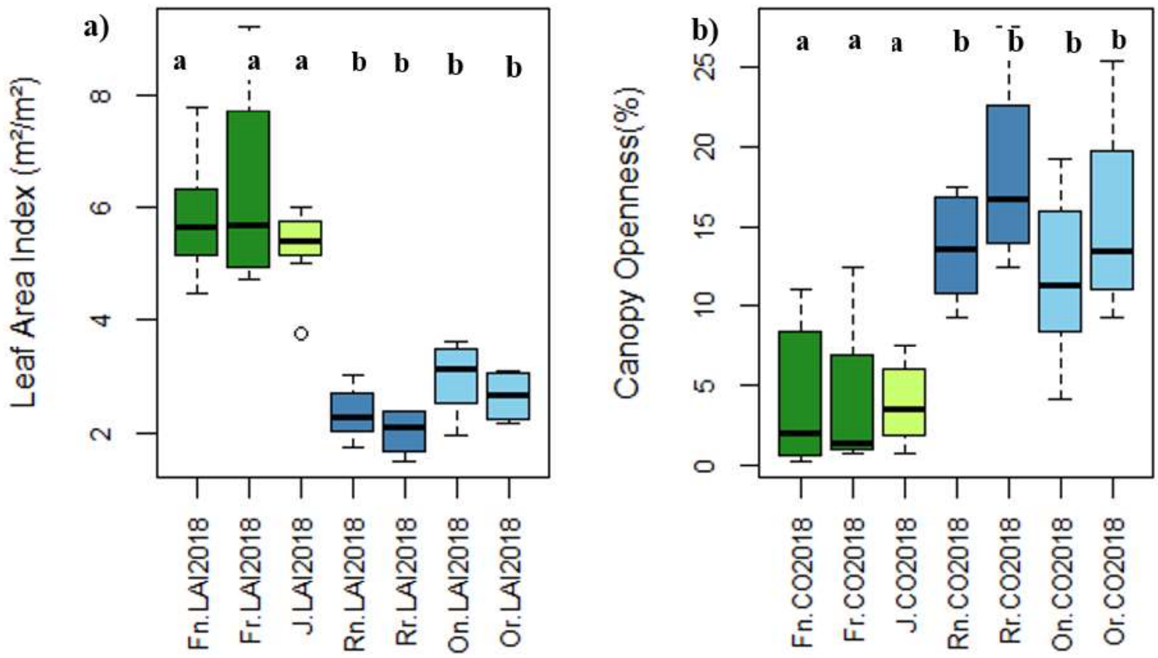

Figure 5. Boxplot of (**a**) leaf area index and (**b**) canopy openness estimated in 2018 among different land-use systems under varying site conditions. LAI2018 and CO2018 represents Leaf area index and canopy openness respectively measured in 2018. Colour description of land-use systems; deep green boxplots represent well-drained and riparian forest plots (Fn & Fr), light green boxplots represent jungle rubber well-drained plots (J), deep blue boxplot represent well-drained and riparian rubber plantation plots (Rn & Rr) and light blue boxplots represent well-drained and riparian oil palm plantation plots (On & Or). Kruskal Wallis/Dunn's post hoc test expressed statistical significant differences of leaf area index at different site conditions as

follows: (test statistic = 34.43, P-value <0.001) whereas ANOVA/Tukey HSD post hoc test produced similar results for canopy openness (test statistics = 26.81, P-value <0.001). Same letters are assigned if differences between well-drained and riparian plots of the same land-use are not statistically significant.

3.3 Canopy openness change assessment for four land-use types over a four-year period (2014 – 2018)

Wilcoxon signed rank test revealed marked differences between specific land-use systems as canopy openness change within the four-year period. Out of the four systems which were considered for the canopy openness change assessment, obtained results revealed negative values as statistically significant (P-value = 0.023) changes (Fig. 6b) in canopy openness for oil palm plantation and jungle rubber land-use systems out of which oil palm registered the highest change (Fig. 6b). This signifies a positive indication of canopy closure within the systems in question within the period under review (2014 - 2018). Conversely, rubber plantation explicitly demonstrated further canopy openness within the four-year period though statistically insignificant (p-values=0.64, 0.84 respectively) while that of forest was quite variable which suggests that quite a number of forest plots are under various stages of recovery (Fig. 6b).

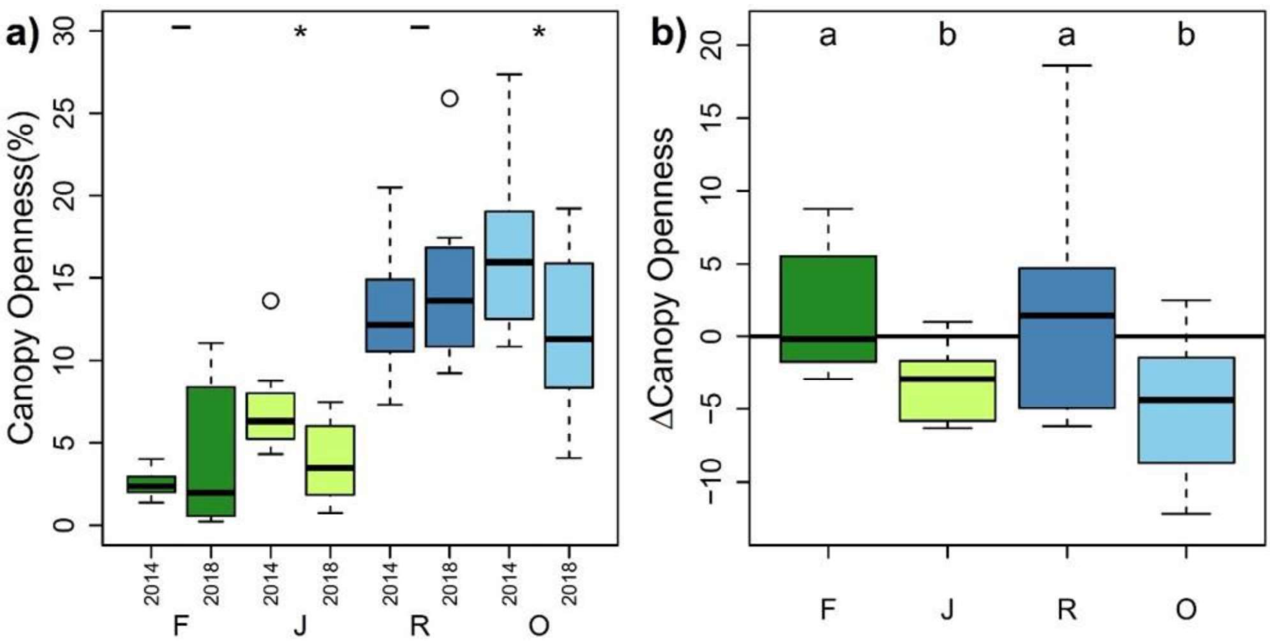

Figure 6. a) Comparison of canopy openness measured in 2014 and 2018 for four land-use systems in Jambi province. Deep green boxplots represent forest (F), light green boxplots represent jungle rubber (J), deep blue boxplots represents rubber plantation (R) and light blue boxplots represents oil palm plantation (O). Sign '*' shows land-use systems with significant statistical differences of canopy openness between 2014 and 2018. Sign '-' shows land-use systems without significant statistical

change in canopy openness. Wilcoxon signed rank test was statistically significant for jungle rubber and oil palm with same results ($V = 34$, p-value = 0.023). **b)** Change in canopy openness between 2014 and 2018 (Δ Canopy Openness) within each land-use system. Letter 'b' is assigned to land-use systems with significant statistical changes in canopy openness over the four year period. Letter 'a' is assigned to land-use systems without significant canopy openness change over the same period.

3.4 Canopy openness change assessment between disturbed and undisturbed forest plots.

Eight well-drained forest plots out of which three (BF3, BF4, HF1) were disturbed by fire and another one (BF2) disturbed by storm were put together after canopy openness estimation in 2014. Canopy openness for these plots (disturbed and undisturbed) were reassessed after four years in 2018 to examine the change in canopy openness within the period between the two plot types (Fig. 7). Kruskal Wallis and Wilcoxon signed rank tests revealed no significant change in canopy openness between the two plot types over the four-year period (Fig. 7) although reduction in canopy openness was observed in disturbed forest plots. This is a positive indication of forest recovery after disturbance.

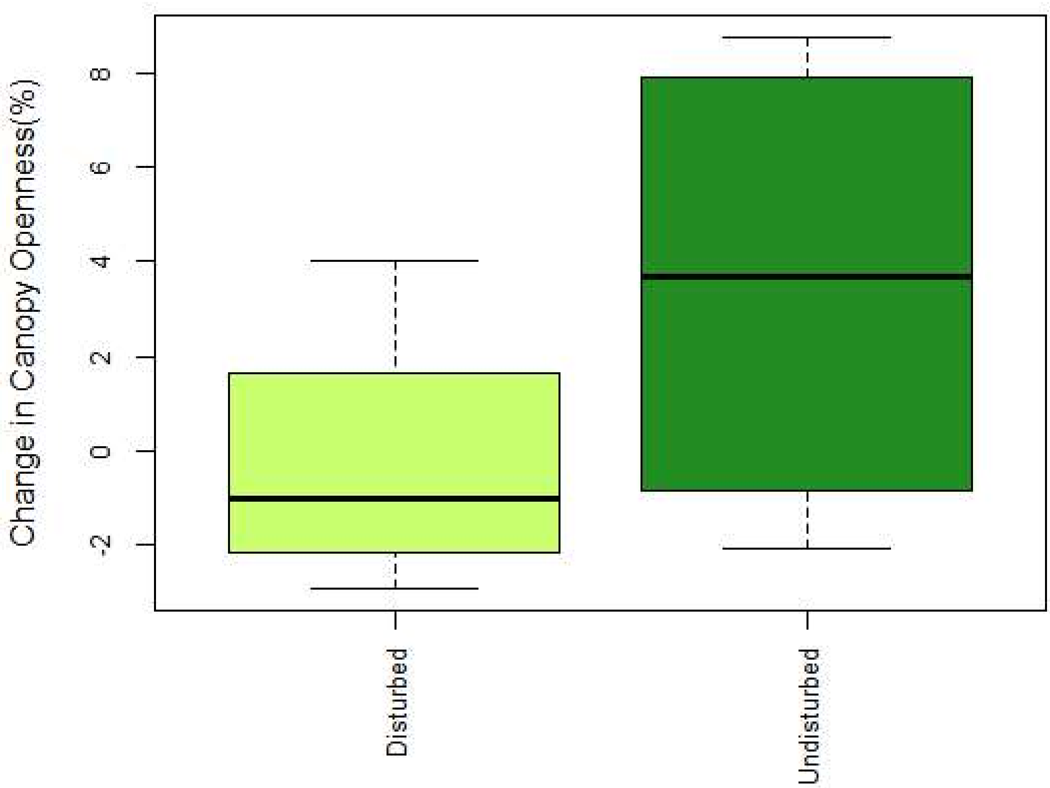

Figure 7. Assessment of canopy openness change between disturbed and undisturbed forest plots in Jambi province. Disturbed plots are BF2, BF3, BF4 and HF1 which are represented with a light green plot whereas the undisturbed plots include BF1, HF2, HF3 and HF4 and are represented with a deep green boxplot. Kruskal Wallis/Dunn's post hoc as well as Wilcoxon's signed rank tests at 5 % probability levels between the two plot types were respectively not significant (test statistics = 1.333, p-value = 0.248; test statistics= 0, p-value = 0.125).

3.5 Relationship between biophysical parameters and stand structural attributes

Leaf area index was observed to have a moderate negative correlation with basal area (p-value=0.04) in jungle rubber agroforest (Fig. 8b). Leaf area index again had a strong negative correlation (p-value=0.004) with stem density in jungle rubber (Fig. 8b). No statistically significant correlation was detected between canopy openness and stand variables in the various land-use systems (Fig. 8c and 8d).

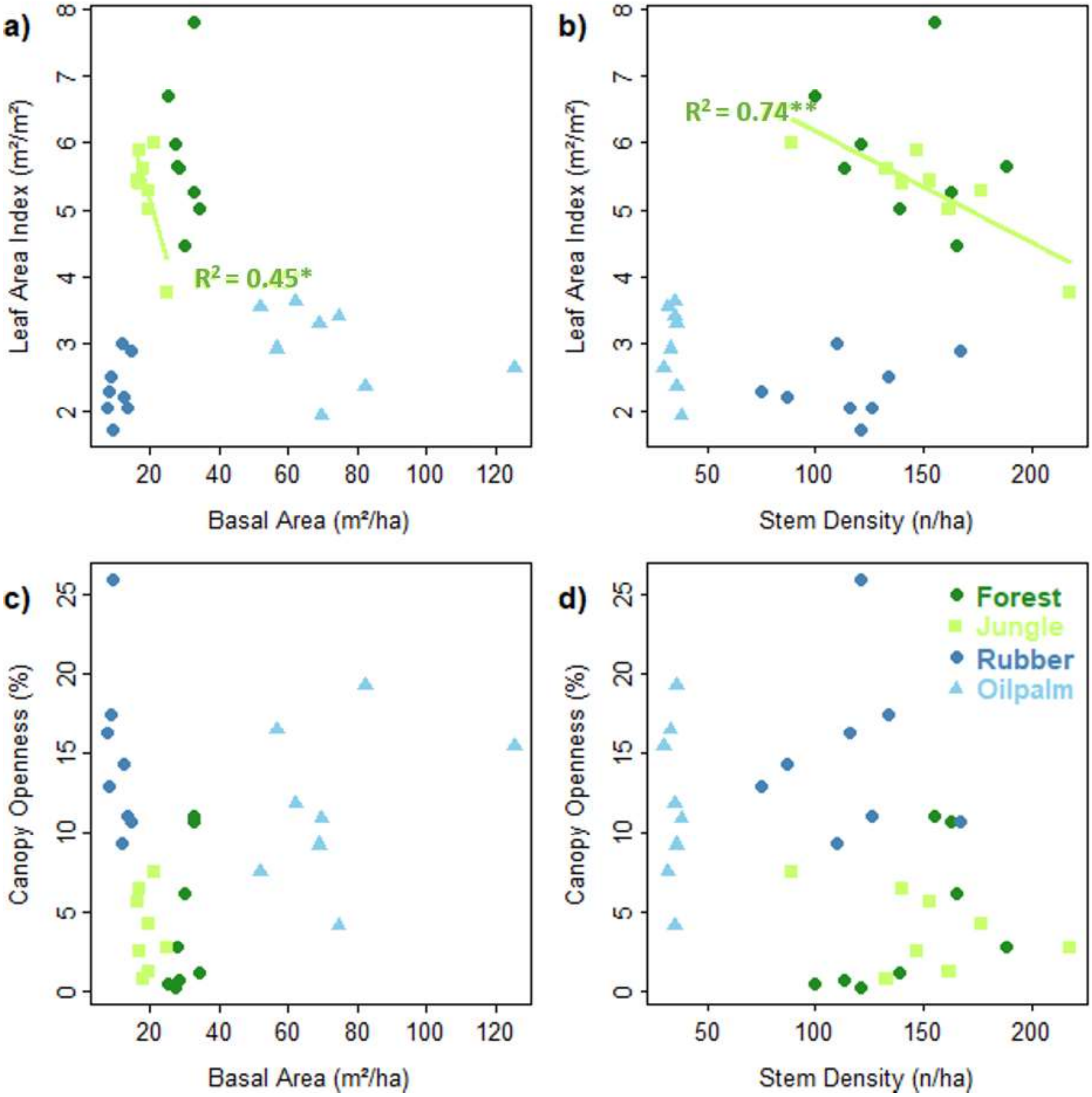

Figure 8. Leaf area index, canopy openness and stand structural attributes' (basal area (BA) and stem density (SD)) relationships. Colours of land-use systems could be interpreted as used in the legend. The regression line in the color of the according land-use system (jungle rubber) shows a correlation between LAI and BA/SD of this system. The absence of a line in Fig. c) and d) means that no correlation could be determined between CO and BA/SD in all the land-use systems.

3.0 Results

4.0 Discussions

4.1 Leaf area index and canopy openness results from the four land-use systems

Generally, LAI estimation from a land-use system is influenced by wide range of factors including leaf position and spatial variations in canopy structure (LI-COR, Inc., 2017).

The higher LAI value in the forest plots could be explained as due to the presence of three-layered (strata) canopy architecture described by (Bourgeron, 1983). This vertically arranged canopy strata absorbed or scattered most of the radiated light coming to the forest floor preventing them from reaching the sensor's view of the measuring device. Jungle rubber recorded an intermediate LAI value due to the presence of fairly open to dense canopy as a result of the leaf shedding nature of the rubber component and management practices such as brushing and cutting of lianas on young rubber trees. Some of the canopy strata which occur in forest may be absent in jungle rubber even if they exist, may not be well-developed to better perform this function as compared to old-growth or primary forest due to previous degradation or disturbance. Monoculture plantations such as rubber and oil palm of the same planting year usually have equal canopy heights at fixed positions determined by their fixed planting distances and are prone to have open canopies due to lack of strata as compared to forest and jungle rubber which consist of unevenly distributed different plant species.

On the other hand, rubber registered the highest canopy openness value probably due to its deciduous nature when it undergoes seasonal dry and cold stresses by transferring nutrients from matured leaves to other parts of the plant and into the soil as an adaptation mechanism during stress periods (Frontiers, 2016).

4.2 Varying site conditions' effect on leaf area index and canopy openness measurements

It was hypothesized that LAI will be higher in riparian forest plots than in riparian plantation plots whereas CO will be higher in riparian plantation plots than in the counterpart plots as well as forest plots.

LAI increment in forest riparian plots more than the well-drained forest plots might probably be due to rapid understory plant species growth and population increase during the flood depth reduction period to close up canopy gaps. Floral species' survival and growth under riparian conditions are influenced by factors such as depth, duration, timing, frequency of flooding, most importantly the degree (partial or full) of plants' submergence (Van Eck et al., 2006). A research conducted during flooding period in amazon forest to ascertain the effects of flooding on canopy dynamics revealed that understory tree growth was rapid during the flooding period to fill most of the canopy gaps that previously existed before the flooding (Schleuning et al., 2008). It further showed that understory plants are unable to compete well with emergent plant species for water and only take advantage during the inundation to enjoy enough water for fast growth. Depending on the duration and depth of the flooding event as well as the degree of plant species' submergence in flood, can influence formation of dense understory canopies to increase the LAI during such conditions. This may account for the insignificant increase in LAI within the riparian forest plots.

On the other hand, the moderate increase of CO within the riparian plantation plots could be an expression or indication of waterlogged stress in rubber and oil palm plants. Riparian or waterlogged conditions in rubber and oil palm plantations create waterlogged stress through reduced oxygen content (anoxic condition) thus suffocating the plants to significantly reduce their water uptake capacities under prolonged flooding conditions (Zhao et al., 2014). This condition results in leaf shrinkage in oil palm and shedding in rubber as adaptation mechanism which opens up canopies within the plantations (Yan et al., 2015).

Moreover, the flood intolerant nature of oil palm could possibly result in plant death through root rot within two weeks of inundation, suffocation or saline conditions (Mantel et al., 2007).

This may account for the slight increase in CO within the riparian plantation plots.

4.3 Canopy openness change assessment between land-use systems over four-year period (2014 – 2018).

The positive significant change in canopy openness observed in oil palm plantation plots over the four-year period could be assigned to rapid growth coupled with oil palms' evergreen nature as possible factors for the significant CO reduction over the period. Regular management practices in oil palm plantation plots such as application of weedicide and fronds pruning as was observed during the field study could stimulate continuous growth under favourable climatic conditions. Growth in oil palm leads to expansion/spread of top fronds which overlap with neighbouring oil palm plants and this together with its evergreen (not deciduous) nature rapidly closes canopy gaps in plantations (Corley and Tinker, 2003). This explains why the significant CO decrease occurred in oil palm rather than rubber (deciduous even under proper management) and forest (gradual tree growth due to close canopies and competition).

The significant decrease in canopy openness thus fast recovery process confirmed by the results in Jungle rubber within the four-year period could be ascribed to rapid succession which is very common in previously disturbed ecosystems but faster under conducive environment for floral species regrowth (Chazdon, 2003). For instance, heavily disturbed sites or forest ecosystems such as uncontrolled pasture or oil pollution can inhibit seed propagation success and regrowth of some pioneer species such as *cecropia* (Aide et al., 1995). Natural regeneration of diverse species and density of understory species are greatly influenced by overstory species due to resource competition (Powers et al., 1997). Based on the extent of damage to the soil and favorable climatic conditions, seeds of fast-growing pioneer species with short life span may colonize and die for shade bearing species to remain under the understory canopy. Large deciduous tree species grow on top of the understory to enhance fast recovery within the shortest possible time (Hassan and West, 1986). This recovery mechanism might have taken place in jungle rubber agroforest at a faster rate due to available resources and conducive climatic conditions within the period. The same process explains why a certain degree of recovery although statistically insignificant was observed in the disturbed forest plots.

4.4 Basal area and stem density relationship with LAI in jungle rubber agroforest

It has been shown that dense understory layer of canopy height ranging from 5 – 150 cm in secondary forests yields higher leaf area index than LAI obtained from a forest stand with canopy height > 150 cm (Feldpausch et al., 2005). One general reason accounting for the moderate to strong relationships between LAI and stand structural attributes (BA and SD) in jungle rubber could be attributed to the existence of dominant shrub population in jungle rubber as the results (BA and SD) suggest. It was observed from the results that jungle rubber recorded the highest stem density of trees with a basal area below 40 m^2/ha which could be an indication of dominant shrub presence to have significant influence on the LAI results from the land-use system (jungle rubber). However, the negative nature of the correlations also means that canopies of the dominant shrub in jungle rubber was fairly open in a manner that restricted higher LAI record. This accounts for the observed moderate to strong negative correlations between LAI and stand structural attributes (BA & SD) in jungle rubber.

5.0 Conclusion and recommendations

Possible explanations for the differences in LAI and CO across the land-use systems are the existence of different canopy strata in forest as a key factor for influencing higher LAI record in forest as compared to jungle rubber, oil palm and rubber monoculture plantations whiles the reverse is respectively true for the CO data. The potential effect of riparian and well-drained conditions in forest and plantations plots on the tendency of higher LAI and CO record in riparian plots was explained as follows; reduced flood depths in forest as observed in the study area, stimulated rapid understory plant growth to fill canopy openings for a higher LAI record in the riparian forest plots. Additionally, riparian conditions create waterlogged stress in rubber and oil palm plantations as a result of suffocation to reduce their water uptake capacities. This condition triggers leaf shrinkage in oil palm and leaf shedding in rubber to open up canopies for higher CO record in plantation plots. The significant canopy closure demonstrated in oil palm plantation between 2014 and 2018 across the different land-use systems was also assessed and rapid growth induced by regular management practices coupled with oil palms' evergreen (not deciduous) nature resulted in the significant CO decrease over the period. However, the significant canopy closure in jungle rubber was also attributed to rapid succession processes that might have occurred within the period under favourable conditions to close previous canopy gaps. Finally, the possible reason for the moderate to strong relationships existing between LAI and stand structural attributes (BA and SD) as shown in jungle rubber was given as a result of the dominant shrub population suggested by the SD and BA in the system to form fairly open understory canopies in a manner that restricted higher LAI record over the period.

Suggestions to improve LAI and CO assessment are highlighted below:

In view of canopy structure variation's significant effect on LAI estimation in forest ecosystems, incorporating its assessment in field LAI data collection will be of prime importance to confirm its influence on the obtained LAI data. Secondly, the duration of riparian conditions in land-use systems needs to be considered in order to fully account for patterns of change in LAI and CO.

Finally, to determine realistic relationships between biophysical and stand structural parameters, it is important that data for assessment are either collected in the same year or the difference in data collection date for the parameters is not more than two years.

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7.0 Appendix

Table 1. Comparative assessment of biophysical parameter and stand structural parameters in different land-use systems using Kruskal Wallis /Dunn´s post hoc test. H is Kruskal Wallis test statistic; Mean values of biophysical and stand structural parameter(s) are row per land-use system significant at $p < 0.05$.

Parameters	**Land-use systems**				**Statistics**	
	Forest	**Jungle r.**	**Rubber**	**Oil palm**	**H**	**P-value**
Leaf area index (m^2/m^2)	5.96	5.09	2.46	3.37	23.80	<0.001
Basal area (m^2/ha)	29.96	19.39	10.91	74.03[1]	29.09	<0.001
Stem density (n/ha)	143.00	152.38	117.00	34.38	19.97	<0.001

[1]Calculated based on diameter including persistent frond bases.

3.0 Results

Table 2. Comparative assessment of change in canopy openness between 2014 and 2018 across four land uses using ANOVA/Tukey honest significant difference post hoc test. F is ANOVA test statistic, significant at $P < 0.05$, mean values of canopy openness (%) are row per land-use system.

Canopy Openness (%)	**Land-use systems**				**Statistics**	
	Forest	**Jungle r.**	**Rubber**	**Oil palm**	**F**	**P-value**
Canopy openness (2018)	4.14	3.86	14.73	11.81	11.97	<0.001
Canopy openness (2014)	2.51	7.14	12.89	16.60	22.85	<0.001

Table 3. Comparative assessment of leaf area index and canopy openness in land-use systems estimated in 2018 at varying sites using Kruskal Wallis /Dunn´s post hoc test. H is Kruskal Wallis test statistics, significant at $P < 0.05$, Fn represents forest at well-drained site, Fr represents forest at riparian site, J represents jungle rubber at well-drained site, Rn represents rubber plantation at well-drained site, Rr represents rubber plantation at riparian site, On represent oil palm plantation at well-drained site and Or represents oilpalm plantation at riparian site. Mean values of leaf area index and canopy openness are in row per each site condition.

Parameters	**Site conditions in land use**							**Statistics**	
	Fn	**Fr**	**J**	**Rn**	**Rr**	**On**	**Or**	**H**	**P-value**
Leaf area index (m^2/m^2)	5.96	6.25	5.28	2.34	1.98	2.82	2.58	34.43	<0.001
Canopy openness (%)	4.14	3.91	3.86	14.73	18.35	11.81	15.43	26.81	<0.001

Table 4. A comparative analysis of change in canopy openness between 2014 and 2018 using Wilcoxon signed rank test. V is Wilcoxon signed rank test statistic, * significant at $p < 0.05$. Mean values of canopy openness (%) are in row with median values in parentheses. Wilcoxon signed rank test was statistically significant for jungle rubber and oil palm with same results (V = 34, p-value = 0.023).

Land-use systems	**Canopy openness (%) estimation year**		**Statistics**	
	2014	**2018**	**V**	**P-value**
Forest	2.51 (2.36)	4.14 (1.96)	14	0.640
Jungle rubber	7.14 (6.32)	3.86 (3.49)	34	0.023*
Rubber	12.89 (12.17)	14.73 (13.62)	16	0.844
Oil palm	16.67 (15.98)	11.81 (11.30)	34	0.023*

Table 5. Values shown are adjusted coefficients of determination (adjusted R2) of linear regression models with leaf area index and canopy openness as dependent variables versus stand structural parameters (stem density and basal area); P-values in parentheses. Statistically significant relationships at $p < 0.05$ are shown in bold face.

Land-use systems	**Biophysical and stand structural parameters' relations**			
	Leaf area index		**Canopy openness**	
	Stem density (n/ha)	**Basal area (m^2/ha)**	**Stem density (n/ha)**	**Basal area (m^2/ha)**
Forest	-0.087 (0.531)	-0.135 (0.695)	0.224 (0.133)	0.226 (0.131)
Jungle rubber	0.736 (**0.004**)	0.452 (**0.040**)	0.059 (0.276)	-0.156 (0.822)
Rubber	-0.053 (0.452)	0.049 (0.288)	-0.166 (0.961)	0.192 (0.154)
Oil palm	-0.057 (0.460)	0.015 (0.333)	-0.145 (0.746)	-0.034 (0.414)

Table 6. Details of the corrected leaf area index from canopy measurement time mismatch for six core plots. Time for above canopy measurement (x), light intensity of the sensor ring(y) and Coefficient of determination (R2).

Above canopy measurement Plot identity	Sensor ring identity	Generated linear regression equations	R^2-values	Field leaf area index (m^2/m^2)	Corrected leaf area index (m^2/m^2)
BF1A	R07	y = 0.058x + 20.302	0,48	3.77	5.92
	R023	y = 0.0477x + 62.185	0,64		
	R038	y = 0.0257x + 72.38	0,81		
	R053	y = 0.0125x + 38.668	0,90		
	R068	y = 0.0073x + 24.362	0,87		
HF4A	R07	y = 0.0023x + 208	0.34	6.14	8.09
	R023	y = -0.0458x + 249.85	0.99		
	R038	y = -0.0852x + 300.33	1.00		
	R053	y = -0.1133x + 389.51	1.00		
	R068	y = -0.0761x + 218.66	0.98		
HFr4A	R07	y = 0.0023x + 208	0.34	7.68	9.62
	R023	y = -0.0458x + 249.85	0.99		
	R038	y = -0.0852x + 300.33	1.00		
	R053	y = -0.1133x + 389.51	1.00		
	R068	y = -0.0761x + 218.66	0.98		
HFR1A	R07	y = 0.0656x + 342.13	0.90	5.37	5.34
	R023	y = 0.0857x + 371.39	0.88		
	R038	y = 0.5445x + 455.69	0.86		
	R053	y = 2.3243x + 7167.1	0.85		
	R068	y = 0.724x + 430.22	0.82		
HFR2A	R07	y = -0.139x + 160.34	0.97	4.75	4.92
	R023	y = -0.084x + 180.76	0.70		
	R038	y = -0.02x + 217.24	0.23		
	R053	y = 0.068x + 270.34	0.57		
	R068	y = 0.13x + 295.1	0.82		
HRr2A	R07	y = 0.1812x + 525.82	0.94	1.65	2.35
	R023	y = 0.18x + 556.91	0.92		
	R038	y = 0.2045x + 537.24	0.94		
	R053	y = 0.2188x + 398.52	0.96		
	R068	y = 0.1456x + 215.13	0.88		

Table 7. Study data for leaf area index (LAI), canopy openness (CO), and tree basal area (BA) from 44 EFForTS core plots, distributed over well-drained and riparian sites. All data with the exception of BA (2014) were collected in 2018.

Well-drained sites				Riparian sites		
Plot	LAI (m^2/m^2)	CO (%)	BA (m^2/ha)	Plot	LAI (m^2/m^2)	CO (%)
Forest						
BF1	5.92	0.22	27.50	HFr1	5.34	12.39
BF2	6.48	0.45	25.44	HFr2	4.92	1.32
BF3	5.97	0.67	28.44	HFr3	5.11	1.22
BF4	4.85	1.17	34.57	HFr4	9.62	0.72
HF1	4.87	6.13	30.07			
HF2	5.64	2.75	28.13			
HF3	5.88	10.62	32.84			
HF4	8.09	11.08	32.70			
Jungle rubber						
BJ3	3.44	2.74	25.18			
BJ4	5.37	4.24	19.77			
BJ5	5.20	1.19	19.70			
BJ6	5.66	0.75	18.23			
HJ1	6.00	7.46	21.14			
HJ2	5.12	6.45	17.24			
HJ3	6.28	2.46	17.20			
HJ4	5.17	5.61	16.62			
Rubber plantation						

BR1	2.61	17.45	13.44	HRr1	2.35	12.39
BR2	1.99	16.28	8.69	HRr2	2.35	15.63
BR3	1.68	25.90	7.78	HRr3	1.78	17.76
BR4	2.20	14.33	9.39	HRr4	1.43	27.62
HR1	2.29	12.91	12.74			
HR2	3.30	9.25	8.43			
HR3	2.67	10.62	11.88			
HR4	2.02	11.08	14.90			
Oil palm plantation						
Well-drained						
BO2	2.17	15.39	125.41	HOr1	3.14	12.79
BO3	3.58	4.10	74.70	HOr2	2.79	14.17
BO4	2.29	19.23	82.21	HOr3	2.10	25.43
BO5	2.64	16.46	56.60	HOr4	2.29	9.34
HO1	2.73	11.76	62.28			
HO2	2.13	10.85	69.80			
HO3	3.41	9.19	69.18			
HO4	3.63	7.49	52.10			

DECLARATION

I do declare that, except for the references to other people's work which have been cited, this work submitted as a thesis to the Department of Biodiversity, Macroecology and Biogeography, Georg-August University, Göttingen, for the degree of Master of Science in Tropical and International Forestry is the result of my own investigation and has not been ever presented for the award of any degree.

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George Ofori Ankomah

ACKNOWLEDGEMENT

To God be the glory for seeing me through this academic ladder successfully. May his name be praised!

I am indeed grateful to my supervisor, Prof. Dr. Holger Kreft for his wonderful guidance, enlightenment and helpful feedback at every phase of the thesis.

I am also thankful to my co-supervisor, Dr. Katja Rembold for her timely support and encouragement throughout the research work.

I also owe sincere thanks to my field research Indonesian counterpart supervisor, Dr. Sri S. Tjitrosoedirdjo for her love and care to ensure field work was in progress without hindrances.

I also extend my sincere thanks to Mr. Fabian Brambach for his tireless technical support right from the field research through the analyses till completion of the work, God bless you.

I am indeed grateful to the secretariat of DAAD for their invaluable support in diverse ways firstly, in making my postgraduate educational dream in Germany to see light of the day and tirelessly supported me financially in making my field research dream in Indonesia be a reality. May the financial sources of your benevolence be like a river under a protected forest which flows irrespective of seasonal changes.

My field research for this work in Jambi, Indonesia would not have been possible to be conducted to meet the planned schedule without the selfless dedication of the B06 field team in Jambi, Mr. Edo Mauliarta, Mr. Ihksan and Mr. Ojan, not forgetting the friendly reception and the outstanding administrative support services rendered by the entire staff of the Collaborative Research Centre (CRC 990) in Jambi and Bogor, Megawati Syafni, Rizky Febrianty, Yuking, Satriyo to mention a few. I am indeed grateful for your support.

To, my lovely family in Ghana, it was through your prayers, and happy conversations that motivated me to work assiduously in my MSc studies.