Leaf area index in oil palm plantations under different management practices and in re-growing tree islands in Sumatra, Indonesia

Blattflächenindex in Ölpalmplantagen unter verschiedenen Bewirtschaftungspraktiken und bei der Wiederaufforstung von Bauminseln in Sumatra, Indonesien

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Para mi familia de dos y cuatro patas...
Zulema, Jhonnattan, Negrito y Momo

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List of Abbreviations

BEE	Biodiversity Enrichment Experiment
CRC	Collaborative Research Center
LAI	Leaf area index
OP	Oil palm
OPM	Oil Palm Management
PTPN VI	PT. Perkebunan Nusantara

Appendixes

Abstract

In landscapes dominated by oil palm, partial restoration and alternative management strategies to increase biodiversity and ecosystem functions are suggested. Leaf area index (LAI) assessment is critical for the analysis of canopy structure and productivity, therefore is important for testing the performance of restoration and management strategies. This study contributes to assess: (1) LAI in conventional, commercial oil palm plantations, (2) how management changes in a commercial oil palm plantation such as mechanical weeding and fertilization reduction affect LAI, (3) LAI changes across species richness levels and plots grouped by size in a tree enrichment experiment, (4) the relationship between species richness and plot size to LAI in the tree enrichment experiment, (5) how species identity and species interaction, inside tree enriched plots, influence LAI, and (6) LAI in naturally established regeneration within the oil palm landscape. Using the LAI-2200C Plant Canopy Analyzer, LAI measurements above and below canopy were made. In the commercial oil palm plantation mean LAI was 4.33 $m^2\,m^{-2}$, and after one year, plots with reduced fertilization showed similar average LAI estimates to plots with conventional management. Results in the enrichment experiment indicated that the relationship between LAI and species richness is not linear as expected and decreases when a third tree species is present in the mixture. However, LAI of 4.34 $m^2\,m^{-2}$ measured in the enriched plots, doubles the average leaf area of plots where no trees were planted (2.02 $m^2\,m^{-2}$). Analysis at plot level in the enrichment experiment found that average LAI increases with plot size ($p= 0.005$), and a positive but not significant relationship between species richness and LAI. Individual species contribution to LAI of *Parkia speciosa* and *Peronema canescens* was above the average, although the coefficient of interaction among species was slightly higher than the species identity. Large LAI values were recorded in natural tree islands (7.86 $m^2\,m^{-2}$ for the three-year old fragment) compared to tree enriched plots and plots with no trees planted. Constant LAI values across the plots managed under conventional and alternative practices, suggest that is possible to reduce fertilizer application in mature commercial plantations by 50% without affecting LAI. In the enrichment experiment light competition, canopy architecture of the OP landscape and phenotypic plasticity likely influence the non-linear trend of LAI across species richness levels. Plot size-LAI relationship might be due to a selection type effect, but in the near future the effect of species richness on LAI could become significant because of an increase of architectural complementarity in a more mature experiment. Interspecific differences may have improved the light capture of *Parkia speciosa* and *Peronema canescens*; however, the presence of palms in the mixture and the mortality effects could have influenced certain species interactions, which is reflected by the non-linear richness coefficient. The very low value of the plots with no trees compared to the three-year old natural fragment suggests that oil palm cultivation intensity is severe and LAI recovery is slow, which invite to think that artificial enrichment is needed to recover LAI in the OP landscape. Leaf area assesment across the oil palm landscape contributed to understand the impacts of different managament practices in commercial plantations. By looking at one central variable it seems possible to reduce fertilizer application, and improve LAI by planting tree islands. However, natural tree regenaration still performs better in terms on LAI compared to artificial enrichment experiments.

Key words: oil palm, leaf area index, ecosystem functions, species richness.

Zusammenfassung

In Ölpalmen-dominierten Landschaften werden Teilrestauration und alternative Managementstrategien vorgeschlagen, um Biodiversität und Ökosystemfunktionen zu steigern. Der Blattflächenindex (LAI) ist ein zentrales Mittel zur Untersuchung der Kronendachstruktur und -produktivität und ist daher wichtig, um die Leistungsfähigkeit von Restaurations- und Managementstrategien zu bewerten. Diese Studie trägt bei zum Verständnis von (1) LAI in konventionellen, kommerziellen Ölpalmplantagen, (2) der Beeinflussung des LAI durch Veränderungen im Management kommerzieller Ölpalmplantagen wie mechanisches Jäten und Düngemittelreduktion, (3) dem Verhalten von LAI gegenüber Plots von unterschiedlicher Größe und Artenreichtum in einem Baumvielfaltsexperiment, (4) dem Effekt von Artenreichtum und Plotgröße auf LAI im Baumvielfaltsexperiment, (5) wie Artenidentität und Arteninteraktion innerhalb der baumangereicherten Plots LAI beeinflussen, (6) LAI in natürlicher Baumverjüngung innerhalb der Ölpalmenlandschaft. Mittels des LAI-2200C Plant Canopy Analyer wurden LAI Messungen ober- und unterhalb des Baumkronendaches vorgenommen. In der kommerziellen Ölpalmenplantage betrug der LAI 4.33 $m^2 m^{-2}$ und nach einem Jahr zeigten Plots mit verringerter Düngung einen ähnlichen LAI-Mittelwert wie Plots unter konventionellem Management. Ergebnisse im Vielfaltsexperiment zeigten, dass der Zusammenhang zwischen LAI und Artenreichtum entgegen der Erwartungen nicht linear verläuft, sondern abnimmt, wenn eine dritte Baumart in der Mischung vorhanden ist. Jedoch ist der in den angereicherten Plots gemessene LAI von 4.34 $m^2 m^{-2}$ doppelt so groß wie in Plots, in denen keine Bäume gepflanzt wurden (2.02 $m^2 m^{-2}$). Eine Analyse auf Plotlevel im Vielfaltsexperiment zeigte, dass der mittlere LAI mit der Plotgröße zunimmt *($p=0.005$)*, sowie einen positiven, aber nicht signifikanten Zusammenhang zwischen LAI und Artenreichtum. Der Beitrag der einzelnen Arten *Parkia speciosa* und *Peronema canescens* zum LAI war überdurchschnittlich, obschon der Arten-Interaktionskoeffizient leicht höher war als die Artenidentität. Große LAI Werte wurden in natürlichen Bauminseln gemessen (7.86 $m^2 m^{-2}$ für das drei Jahre alte Fragment), verglichen mit baumangereicherten Plots und Plots mit keinen gepflanzten Bäumen. Konstante LAI Werte zwischen den natürlich und alternativ gemanagten Plots deuten darauf hin, dass es möglich ist, die Düngerverabreichung in adulten kommerziellen Plantagen um 50 % zu reduzieren ohne den LAI zu beeinflussen. Im Vielfaltsexperiment beeinflussen voraussichtlich Lichtkonkurrenz, Kronendacharchitektur der Ölpalmenlandschaft und phänotypische Plastizität den nicht-linearen Trend des LAI zwischen Artenreichtumsstufen. Ein

Zusammenhang Plotgröße-LAI entsteht vermutlich aufgrund eines Selektionstypeneffekts, doch in naher Zukunft könnte der Effekt von Artenreichtum auf LAI aufgrund einer Steigerung der architektonischen Komplementarität im fortgeschrittenen Experiment signifikant werden. Interspezifische Unterschiede haben eventuell die Lichtaufnahme von *Parkia speciosa* und *Peronema canescens* verbessert; jedoch könnten die Anwesenheit von Palmen in der Mischung und Mortalitätseffekte bestimmte Arteninterkationen beeinflusst haben, welches sich im nicht-linearen Artenreichtumskoeffizienten abbildet. Der sehr geringe Wert von baumfreien Plots verglichen mit dem dreijährigen natürlichen Fragment deutet darauf hin, dass die Bewirtschaftungsintensität hoch ist und sich der LAI nur langsam erholt, was den Schluss nahelegt, dass eine künstliche Pflanzung nötig ist, um den LAI in der Ölpalmenlandschaft wieder anzuheben. Blattflächenuntersuchungen in Ölpalmenlandschaften trugen dazu bei, die Auswirkungen verschiedener Bewirtschaftungen in kommerziellen Plantagen zu verstehen. Durch den Fokus auf eine zentrale Variable scheint es möglich, die Düngemittelgabe zu reduzieren und LAI durch Anpflanzung von Bauminseln zu verbessern. Jedoch ist der LAI unter natürliche Baumverjüngung höher als in der künstlichen Pflanzung.

Stichwörter: Ölpalme, Blattflächenindex, Ökosystemfunktionen, Artenreic

1 Introduction

1.1 Oil palm plantations and ecosystem functions

Land use such as agriculture describes how humans utilize the land, whilst land cover describes the biophysical characteristics of the land. Human activities transform land cover, and these variations directly impact ecosystem functions (Hao, et al., 2012). The term ecosystem functions was first used to describe the ecosystem processes occurring within an ecological system regardless of whether or not those processes were useful for humans; time later the term "functions of nature" was accepted to refer about work done, space provided and goods delivered to humans (Braat & De Groot, 2012). The term function at the same time describes the potential of the ecosystem to deliver a service (De Groot, et al., 2010).

Oil palm (OP) crop is widely distributed in the tropics, between 2003 and 2012 the area occupied by oil palms expanded by over 80%, which increased the awareness about the effects of OP over forest and biodiversity loss (Corley & Tinker, 2016). OP plantations present reduced ecosystem functioning compared to forest. The main impacts are on gas regulation, water regulation, habitat functions and information functions. Nevertheless, none other oil crop can compete with OP in terms of yield per hectare (Corley & Tinker, 2016), and in terms of biomass production, food and raw materials, ecosystem functioning shows a net increase (Dislich, et al., 2017).

The OP demand is predicted to increase, by 2050 is likely to reach 120-156 Mt y^{-1} meaning that 12 to 28 million hectares of palm must be planted (Corley & Tinker, 2016). Keeping this in mind is mandatory task to (1) protect the tropical forest remnants, (2) implement better management practices, and (3) include biodiversity conservation into the management strategies (Teuscher, et al., 2015). In landscapes already dominated by oil palm, restoration strategies to increase ecosystem functions are suggested (Gérard, 2016). Planting native trees islands may increase ecosystem functions and services (Lamb, et al., 2005), which are beneficial to OP plantations in terms of pollination, biological pest control and soil fertility (Foster, et al., 2011). However, is not yet clear how to implement new strategies towards the recognition of biodiversity, economic and livelihood needs in the tropical landscape (Koh, et al., 2009).

1.2 Restoration of ecosystem functions

Changes in management practices may help to maintain some of the ecosystem functions at forest level, although is not clear how the environmental conditions and plantation age influence ecosystem functions (Dislich, et al., 2017). Permanent agroforestry systems with OP-trees mixtures have performed satisfactorily; for example, OP-cacao did not affect OP yield and even showed higher yields for cacao (Egbe & Adenikinju, 1990). In Indonesia native tree species *Aquilaria malaquesis* and *Shorea* sp demonstrated to grow properly under OP (Muryunika, 2015). Nevertheless, knowledge gaps related to ecosystem functions restoration in OP dominated landscape require further research towards a better understanding about the costs and trade-offs of an OP agroforestry system.

Indonesia is a special case of study due to the importance and dominance of OP plantations. In 2015 the total land area allocated for OP plantations reached 10.6 million hectares (USDA, 2016), most of this land is located in Borneo and Sumatra Islands (Nugroho, 2018). From 2006 onwards Indonesia became the main world producer (Corley & Tinker, 2016), and in 2016 the country produced 34 500 kt of OP, which means 58% of the global market (POA, 2017). In addition, Indonesia is the third country with the largest area of tropical forest, which accounts for 91 million hectares (FAO, 2015).

The Collaborative Research Center (CRC) 990 project “Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems”, aims to provide scientific knowledge to protect and enhance the ecological functions of tropical forests and agricultural transformation systems at landscape scale, whilst human welfare is improved. The project takes place in Jambi Province in Sumatra, Indonesia, where OP plantations are part of the transformation systems under study. A wide number of issues are assessed within the project including biodiversity, soil fertility, water, greenhouse gas fluxes; besides economic, social, cultural and political features related to rainforest transformation (Collaborative Research Center, 2016).

1.3 Leaf area index and ecosystem functions

Leaf area index (LAI) is defined as the projected area of leaves over a unit of land (m^2 m^{-2}), thereby one unit of LAI is equivalent to 10 000 m^2 of leaf area per hectare (Waring & Running, 2007). Reliable estimations of LAI are critical for numerous studies of atmosphere–vegetation interaction, and are very often a basic parameter for the analysis of canopy structure (Arias, et al., 2007). Changes in LAI by drought, defoliation, storm, and management practices show effects in yield (Bréda, 2003).

Oil palm presents less dense canopies and lower LAI compared to forest, this fact results in warmer and drier microclimate (Dislich, et al., 2017) (Meijide, et al., 2018). According to Hardwick et al. (2015) in OP plantations the average maximum air temperature is up to 6.5 ˚C warmer than in old growth forest and up to 4 ˚C warmer than logged forest. The warming effect is more dramatic in young plantations (Luskin & Potts, 2011), due to lower LAI. Impacts on microclimate could be mitigated by sequential replanting of palms to favor different age plantation (Luskin & Potts, 2011); and even more, by implementing agroforestry OP-tree systems.

In OP plantations LAI depends on the average area of individual fronds, number of fronds, number of palms per hectare, and management practices (Noor & Harun, 2004). According to Henson and Chai (1998), there is a tendency for LAI to present cyclic changes due to fronds pruning during harvesting. Depending on the age, LAI in oil palm plantations can range between 0.69- 4.05 (Awal, et al., 2010b). With this in mind, the experiments currently running in the collaborative research project may have an influence in the LAI performance of the OP transformation system under study.

1.4 Leaf area index assessment in the CRC990 project

The study presented in this thesis document is a contribution to the main research collaborative project. LAI assessment in OP plantations under different management practices and restoration strategies, intend to provide reliable information regarding changes and differences in terms of the study variable. As previously mentioned LAI is critical variable, since it works as input to model biosphere-atmosphere interactions and canopy structure. LAI strongly influences photosynthesis, evapotranspiration and CO_2 uptake processes (Bonan, 1993) (Gower, et al., 1999).

Leaf area index assessment is divided into direct and indirect measurements. Direct LAI measurements require destructive sampling and are considerably labour intensive and costly (Beets, et al., 2011). However, direct methods are the most reliable in order to determine true leaf area (Awal & Wen, 2008a). Indirect methods include litter traps, allometric models and optical devices (Asner, et al., 2003). Among the indirect methods optical devices are preferred, because LAI measurements can be made in short time. For example, instruments like LAI-2000 and LAI-2200C from LI-COR quantify the sky brightness in the blue band using five concentric rings centered at zenith angles of 7˚, 22˚, 38˚, 52˚ and 68˚ (Pearse, et al., 2016). In this study LAI-2200C was used to evaluate the changes on foliage cover among different oil palm plantations under different management and experimental conditions.

The methodology and results presented in this study supports the research activities in the (1) climate tower located in PT. Perkebunan Nusantara (PTPN VI), (2) Oil Palm Management (OPM) experiment in PTPN VI, (3) Biodiversity Enrichment Experiment (BEE) in the OP plantation PT. Humusindo. Additionally, naturally established tree islands inside an OP landscape were considered relevant study sites as reference systems.

The climate tower project located in PTPN VI monitors the continuous fluxes of carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), and nitrous oxide (N_2O) to assess the greenhouse gas and energy balance in OP plantations. In particular N_2O emissions are of special interest, due to significant amounts of nitrogen fertilizer commonly applied in commercial OP plantations (Collaborative Research Center, 2016).

The OPM experiment located in the state owned plantation PTPN VI was established in 2017, in response to the current management practices that carry nutrient losses that directly affect ground water quality (Kurniawan, 2016). The goal is to evaluate management alternatives in terms of fertilizer and herbicide use, seeking to reduce the negative impacts and increase the environmental services (Collaborative Research Center, 2016).

Biodiversity Enrichment Experiment (BEE) in oil palm plantations is a landscape design project to evaluate the impact of agroforestry over biodiversity. In this way, tree islands of different sizes mixing native species and oil palms, at different tree diversity levels, were established in 2013. Within this project continuous research about ecological and socio-economic impacts take place in order to validate its effectiveness in oil palm landscapes (Teuscher, et al., 2016).

Naturally established islands are patches of secondary forest, probably abandoned land, at different successional stages. According to the local villagers these fragments can be classified by age: 3, >10, 30 years old. Natural regeneration of secondary forest plays an important role in land reforestation; some estimates suggest that one out of six to seven hectares in the tropics has been reclaimed by secondary forest (Wright, 2005). In the tropics secondary forest can reach maximum values of LAI within few years (<5) (Uhl, 1987a) (Saldarriaga & Luxmoore, 1991), which indicate a strong light competition during early stages (van Breugel, 2007). Secondary forest fragments are interesting study sites because are able to restore in short time some of the structural and functional aspects present in old growth forest (Guariguata & Ostertag, 2001) (Lugo, 2002), thereby can restore ecosystem functions and provide environmental services (Grau, et al., 2003).

LAI literature available is limited to the study of oil palm plantations under normal conditions and traditional management practices, the experiments running in the collaborative research project set the scene to better understand LAI changes when management practices and restoration strategies are implemented. Specifically, this study aims to assess: (1) LAI in conventional, commercial oil palm plantations, (2) how management changes in a commercial oil palm plantation such as mechanical weeding and fertilization reduction affect LAI, (3) changes of LAI across species richness levels and plots grouped by size in the tree enrichment experiment (4) the relationship between species richness and plot size to LAI in the tree enrichment experiment, (5) how species identity and species interaction, inside tree enriched plots, influence on LAI, (6) LAI in naturally established regeneration within the oil palm landscape.

2 Materials and Methods

2.1 Study sites description

Study sites for LAI assessment are located in Jambi Province in Sumatra-Indonesia. The total area of the province is 50 million hectares (Stolle, et al., 2003), and according to Drescher et al. (2016) in Jambi Province more than 590 000 hectares of oil palm are being cultivated, with 30% of tropical forest cover mainly located in mountain areas.

PT. Perkebunan Nusantara (PTPN VI) (1°41'35.0"S, 103°23'29.0"E, 76 m a.s.l) is a state owned company that operates approximately ninety thousand hectares of oil palm. LAI measurements were taken in the Batanghari unit that covers 2 186 hectares, here palms are planted in triangular array, with 8 m horizontal distance in between which results in 156 palms per hectare (Fan, et al., 2015) (Collaborative Research Center, 2016). This unit is intensively managed with high levels of fertilizer (Meijide, et al., 2017). Soil type is dominated by highly weathered loam Acrisols (Allen, et al., 2015). Data collection in PTPN VI was done (1) surrounding the climate tower and (2) in the Oil Palm Management (OPM) experiment (Figure 1).

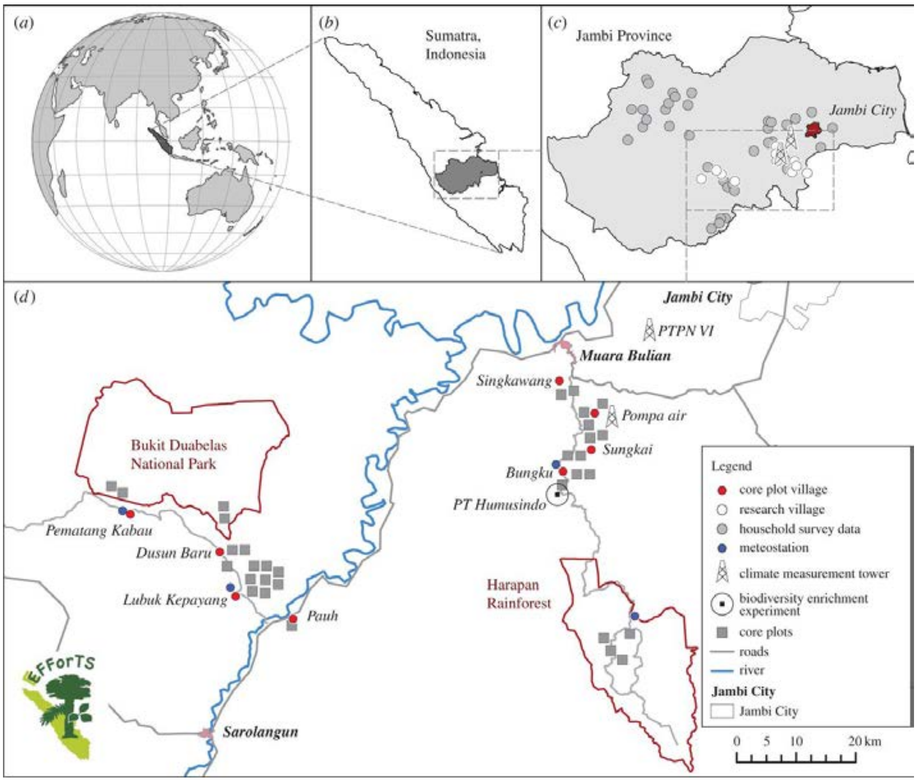

Figure 1. *Map of the study area. (d) PTPN VI located between Jambi city and Muara Bulian, PT Humusindo located south Bungku core plot village (Drescher, et al., 2016).*

Experimental plots around climate tower were randomly established during May 2018. Twelve plots of 5 m side size and four plots of 40 m side size were temporally marked. Plots locations are presented in Appendix 1.

The OPM design is a 2 x 2 factorial experiment that comprises 16 experimental plots of 50 x 50 m (0.25 hectares) with 4 different management treatments, each one repeated 4 times (Collaborative Research Center, 2016). Treatments are (1) CH: conventional fertilization and herbicide spraying, (2) CW: conventional fertilization and mechanical weeding, (3) RH: reduced fertilization and herbicide spraying, (4) RW: reduced fertilization and mechanical weeding. Inside each experimental plot 5 subplots of 5 m side were settled (Figure 2). According to the design, inside each plot ca. 39 palms are located. Those plots under conventional treatment are fertilized two times a year with 2 kg N (urea) per palm or 78 kg N (urea) per plot; on the other hand plots under reduced fertilization are treated with 1 kg (urea) per palm. Weeding cycles are done 4 times per year; herbicide spraying is done with 1 500 ml ha^{-1} y^{-1} (Collaborative Research Center, 2016).

LAI measurements were quantified on each of the subplots, which accounts for 80 total readings.

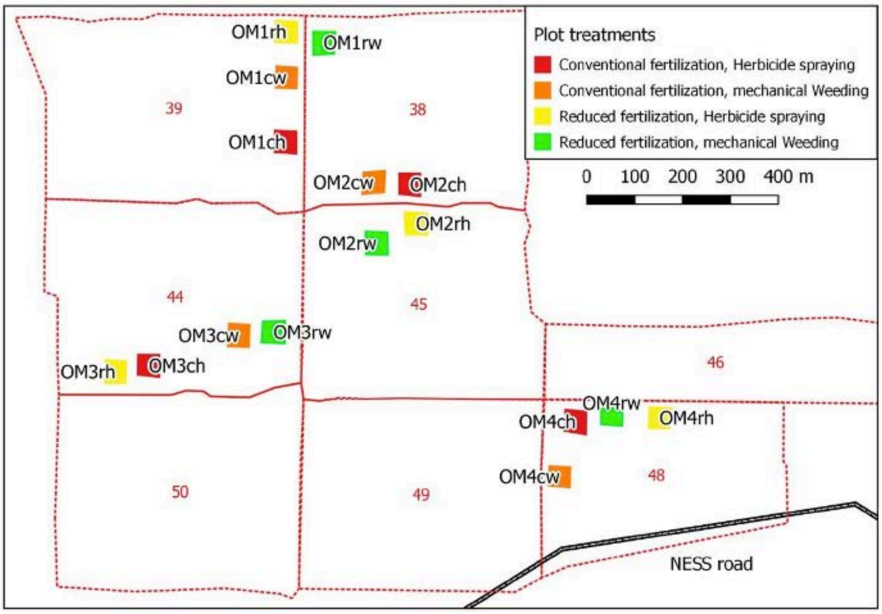

Figure 2. *Experimental design applied to the Oil Palm Management experiment at PTPN VI. The experiment comprises 16 experimental plots of 50 x 50 m with 4 different management treatments; each management treatment is repeated 4 times (Collaborative Research Center, 2016).*

PT. Humusindo Makmur Sejati (S 01°54'39.5" E 103°16'00.1", 47 m a.s.l) is a OP plantation located near Bungku village (Figure 1). The plantation covers ca. 300 hectares, here palms are planted in 9 x 9 m triangular grid resulting in ca. 143 oil palms per hectare. Soil type is dominated by highly weathered loam Acrisols (Allen, et al., 2015).

The biodiversity enrichment experiment (BEE) is based on tree islands of side size 5, 10, 20, and 40 m, planted with six different tree species combinations within the oil palms. Tree species are *Parkia speciosa, Archidendron pauciflorum, Durio zibethinus, Dyera polyphylla, Peronema canescens, Shorea leprosula*; between the plots, no repetition of species composition was permitted (Teuscher, et al., 2016). To improve light availability 40% of palms were removed, except for the control plots and the 5 m side size plots (Teuscher, et al., 2016). The experiment comprises 13 plots for each side size and 4 control plots of side size 10 m, inside the control plots no experimental intervention was applied and plots are managed as usual. Six species richness levels (R=0,1,2,3,5,6), according to the tree species alive at the time of the data collection in each plot, are identified on the entire experimental matrix; 5 plots in level zero (no trees planted, in the case of one plot all trees died), 29 plots in 1evel 1, 8 plots in level 2, 7 plots in level 3, 2 plots in level 5, and 1 plot in level 6 (Teuscher, et al., 2016). Experimental plots receive special management treatment, which includes suspending herbicide, pesticide and fertilizer application; besides, weeding was stopped after two years of tree planting (Teuscher, et al., 2016). Total counting of measurements in the enrichment experiment were 56 plots. With the aim to have at least one control plot of each size, two plots, one of 20 m and one of 40 m side size, were established by extending the plot area of one of the 10 m control plots (Plot 54).

Naturally established tree islands are located around the enrichment experiment (PT. Humusindo), but still inside the dominant oil palm landscape (NP1: 01.93˚ S - 103.264˚ E, NP2: 01.93˚ S - 103.250˚ E, NP3: 01.95˚ S - 103.257 E, Figure 3). According to the local villagers the NP1 tree island is around 30 years old, NP2 is more than 10 years and NP3 around 3 years old. Locations of the naturally established islands centers are presented in Appendix 2.

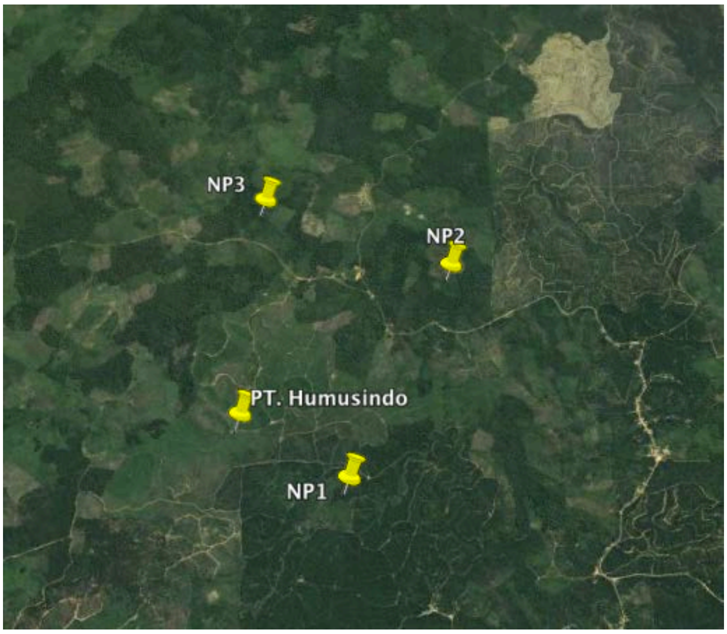

Figure 3*. Naturally established regeneration islands are located around the enrichment experiment. According to local villagers NP1 fragment is 30 years old, NP2 is more than 10 years and NP3 is 3 years old (Google Earth , s.f).*

2.2 Instrumentation

The LAI-2200C Plant Canopy Analyzer (LI-COR, Biosciences Inc., Lincoln, NE, USA, 2014) calculates LAI from readings made above and below canopy; these are used to determine canopy light interception at five angles. Data collected is fitted to a model of radiative transfer inside vegetative canopies to compute LAI, mean tilt angle, and canopy gap fraction. LAI-2200C instrument, in contrast with the last versions, accounts for clumping in heterogeneous canopies, and supported by the FV2200 2.1 software (LI-COR, Biosciences Inc., Lincoln, NE, USA, 2014) provides a mechanism for scattering corrections (LI-COR, 2015).

2.3 Sampling technique

Data collection was done with one unique sensor to take above and below canopy readings. Above canopy reference readings were sampled at the beginning of each cycle of measurements (one cycle = one plot) in the closest open road near the plots. To avoid the influence of palm leaves near the roads, the 45˚ fish-eye lens was used (LI-COR, 2015). All measurements were taken at 1.3 m height, avoiding partly cloudy skies, and holding the sensor parallel to the ground with the help of the bubble level.

The number of measurements taken by plot depended mainly on the plot size. The following considerations were considered prior to design the sampling technique. (1) The entire landscape is dominated by a monoculture of OP planted in a triangular grid separated 8 to 9 m one from another, (2) when the study plot is small, 90˚ view cap is used to make readings in each corner facing the plot (LI-COR, 2015) (see Figure 4), (3) for row crops with heterogeneous canopy, the 45˚ view cap is used to take measurements inside the plots, (4) *Row crops* technique, recommended by the Instruction Manual, suggests readings for diagonal transects in pairs: one transect with the sensor looking to the north, and the other looking to the west (see Figure 5). In summary, the experimental design is composed by the techniques advised for small plots and row crops with heterogeneous canopies. The final LAI value is one unique average number per plot computed by the console.

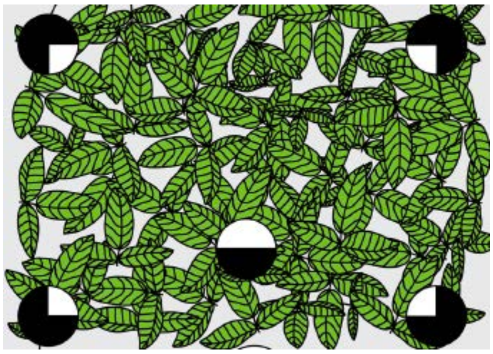

Figure 4*. LAI measurement design for small plots, 90˚ view cap was used in each corner to make readings looking into the plots. This technique was applied for 5 m and 10 m side size plots in the OPM experiment, BEE, and temporal plots around the climate site (LI-COR, 2015).*

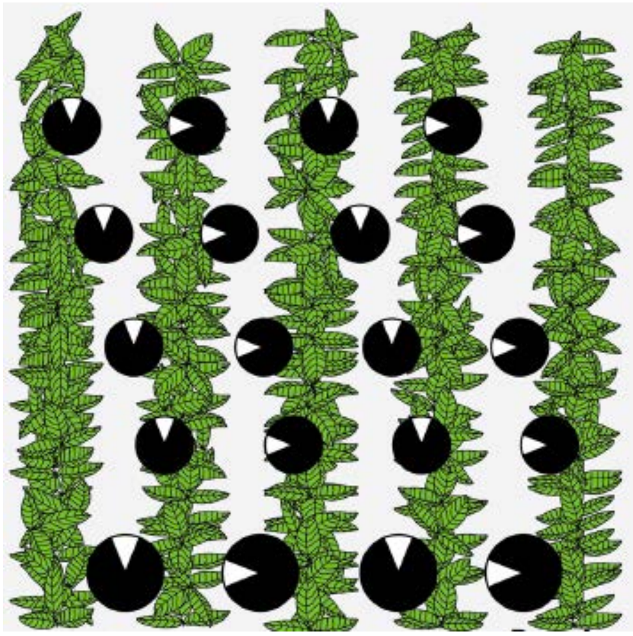

Figure 5. *LAI reading design using the row crops with heterogeneous canopies technique. Diagonal transects readings, one transect with the sensor looking to the north and the other transect with the sensor looking to the west. This technique was applied to the 20 m and 40 m side size plots in the BEE, and temporal plots around the climate tower (LI-COR, 2015).*

The minimum number of measurements for each plot size in order to cover the entire area was calculated using the following formula (LI-COR, 2015).

$$A = f\pi H^2 \quad (1)$$

Where A is the ground area represented by the sample, f is the view fraction and H is the canopy height. The reference height for the oil palm plantation was 7 m, and the view fractions applied were 0.125 and 0.25 for the 45° and 90° view caps respectively. One LAI reading done with the view fraction of 0.25 represents 38 m^2, which means that an area of 152 m^2 is covered when four corners are measured. Considering this, with only one measurement is possible to cover the entire area inside the 5 m side size plots, and four readings to cover the 10 m side size plots. However, LAI readings were taken in the four corners of 5 and 10 m side plots. When readings are made with the 0.125 view fraction the area covered is 19 m^2; then all the additional LAI readings taken inside the 20 m and 40 m side size plots were calculated accounting this coverage factor. As a result of this, a total of 12 readings for the 20 m plots and 76 readings for the 40 m plots were taken inside. Additionally, LAI readings with the 90° cap at each corner looking into the plots (Figure 6 and Figure 7). Readings were adjusted according to the presence of oil palms and trees to keep the sensor view free of obstructing objects such as very close leaves, branches, or stems.

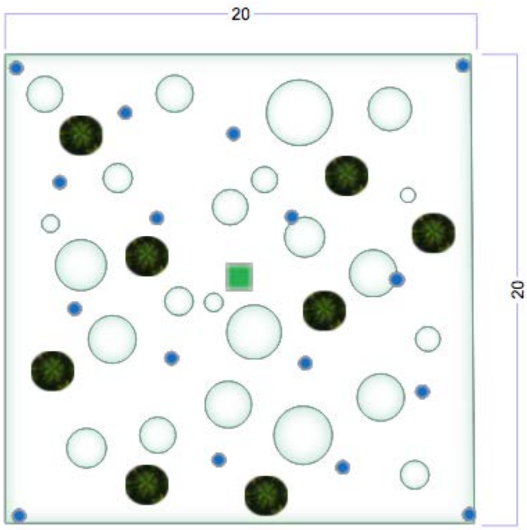

Figure 6. *LAI data collection design for the plots of 20 m side size in the enrichment experiment. Blue points show the LAI readings (N=16), Twelve readings made inside the plots with the 45° view cap and one reading made in each corner with the 90 ° view cap. Diagonal transects readings technique: one transect with the sensor looking to the west and the other transect with the sensor looking to the north. Readings along the plot center (green square) were made with the cap opening pointing to the center. The measurements always started at the first South-East diagonal with the sensor looking to the west, second diagonal to the north, third diagonal to the west and so*

on. Distance between diagonals is 6 m, distance between the readings in the first diagonal (South-East corner) is 2.6 m, second diagonal is 4.1 m, same distances apply for the first and second diagonals starting from the North-West corner. Readings along the center diagonal line are 5m apart from the center point. Black and green circles represent the presence of OP and trees inside the plots, but do not reflect the real spatial distribution.

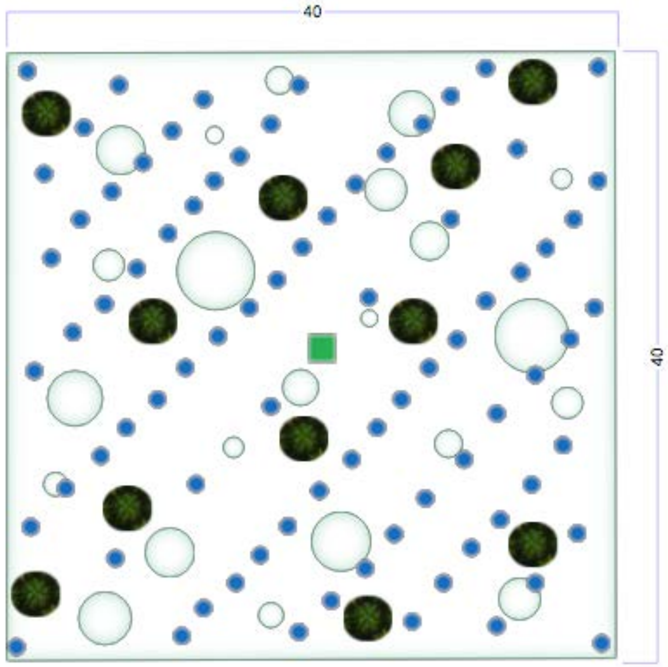

***Figure 7**. LAI data collection design for the plots of 40 m side size in the enrichment experiment and temporal plots around the climate tower. Blue points show the LAI readings (N=80), Seventy six readings made inside the plots with the 45° view cap and one reading made in each corner with the 90 ° view cap. Diagonal transects readings technique: one transect with the sensor looking to the west and the other transect with the sensor looking to the north. The measurements always started at the first South – East diagonal with the sensor looking to the west, second diagonal to the north, third diagonal looking to the west and so on. Readings along the plot center (green square) were made with the cap opening pointing to the center. Distance between diagonals is 7.6 m, distance between the readings in the first diagonal (South-East corner) is 3.6 m, second diagonal is 4.3 m, third diagonal is 3.6 m, and fourth diagonal is 2.5 m. Same distances apply for the first, second, third and fourth diagonals starting from the North-West corner. Readings along the center diagonal line are 5m apart from the center point and between them. Black and green circles represent the presence of OP and trees inside the plots, but do not reflect the real spatial distribution.*

Leaf area index readings in the naturally established tree islands were taken in four transects starting in the center and following every cardinal direction. Every two meters LAI was registered using the 45° view cap pointing to the west, until reach the border between the natural island and the oil palm plantation. A total number of three naturally established islands were assessed, which means 12 transects.

2.4 Statistical analysis

The data stored in the LAI-2200C was processed using the FV2200 2.1 software. Two adjustments were applied to each LAI value, scattering correction and omission of the four outer rings (Castro-Izaguirre, et al., 2016). Due to the site conditions, it was not possible to find an adequately clearing area near the plots to take the above reference readings; to cope with this, the field of view was restricted to the first ring from zenith (Dufrene & Breda, 1995) (Moser, et al., 2007). The final LAI value was computed by the FV2200 2.1 software, which means one single average value per plot. In addition, is possible to visualize minimum, maximum and standard deviation values per plot, besides every single reading to follow the experimental design step by step.

The statistical software chosen for the analysis was *RStudio*. Mean LAI and standard deviation values were calculated for (1) plots around the climatic tower, (2) OPM experiment plots, (3) biodiversity enrichment plots (4) naturally established islands NP1-NP3.

Data distribution for plots in the conventional plantation, BEE and naturally established islands is represented in box plots. A box plot displays a summary of the data set with 5 numbers, the bottom of the box represent the first quartile (Q_1) and the top represent the third quartile (Q_3), within these two values 50% of the data is accumulated (Dawson, 2011). The horizontal line that crosses the box shows the median, which is the middle number of a set of ordered data; the vertical lines or whiskers extend from the Q_1 to the minimum value of the observed variable and from the Q_3 to the maximum value of the observed variable (Dawson, 2011). The box plots also indicate the outliers, values that greatly differ from the values in a data set, and the mean is depicted in a diamond shape vector inside the boxes.

Significant differences between plots in the conventional plantation under intensive managament, and BEE were tested using the non-parametric Kruskal-Wallis test and Dunn test as post hoc analysis with Bonferroni correction. Kruskal-Wallis test is the non-parametric equivalent of the one-way analysis of variance (ANOVA) and is applied to compare three or more unrelated samples, when data is not normally distributed (Corder & Foreman, 2009); moreover, is applicable to different sample size groups (Field, et al., 2012). Kruskal-Wallis test does not show which pairs of samples are significantly different, for these a post hoc analysis is needed. Dunn test is the adequate procedure after Kruskal-Wallis test (Dinno, 2015). Bonferroni correction is recommended when performing multiple sample comparisons to correct for the Type I error inflation (Corder & Foreman, 2009).

Linear mixed models (LMM) are an extension of linear models, which consider both fixed and random effects, and are specially used when there is non-independence in the data (UCLA, 2018). Such a model was used to describe the relationship between LAI and the independent variables plot size and species richness levels, both associated with individual experimental units (Plot.ID) for the BEE. Considering this, all measurements taken inside the BEE plots were accounted as input. Linear mixed model can be described as (Pinherio & Bates, 2004):

$$y_{im} = \beta_{00} + \beta_1 x_{im} + b_{0m} + \varepsilon_{im} \quad (2)$$

For the study case here, y_{im} corresponds to LAI for observation i and group m, β_{00} and $\beta_1 x_{im}$ are the fixed effects, plot size and species richness levels, b_{0m} is the random effect Plot.ID, and ε_{im} the observation error.

Using *RStudio* homoscedasticity violation was solved by transforming LAI values according to the optimum *boxcox* ( ) function, the response variable by the power of 0.33 was the best transformation (Appendix 3 and Appendix 4). According to the sampling design for LAI, the number of readings augments with the plot size, thus the model considers a potential increase of variance. Then to make up for this the weighting function *varIdent* ( ) was applied using the variable Plot.ID, because this is the level at which measurements were taken. It is important to clarify that the mixed model output depends on the settings pre defined by the researcher.

The LMM was additionally used to test the interaction between plot size and species richness; however, the model outcome indicated that such interaction is not significant (Appendix 5 and Appendix 6).

A linear model method for biodiversity-ecosystem functioning experiments was applied in the BEE; the model estimates the impact of individual species on LAI when the contribution of each individual tree species in the mixture is unknown (Bell, et al., 2009). To apply this model the average LAI value per plot was used. For each plot in the enrichment experiment presence and absence of the planted tree species was marked. The least squares model is described as:

$$y = \beta_0 + \beta_{LR}x_{LR} + \beta_{NLR}x_{NLR} + \left(\sum_i^S \beta_i x_i\right) + \beta_Q x_Q + \beta_M x_M + e \qquad (3)$$

Where y is the response variable LAI, β_0 is the intercept, β_{LR} is the effect of linear richness on LAI when is treated as a continuous variable, x_{LR} codes for the particular level of species richness, $\beta_{NLR}x_{NLR}$ is the nonlinear species richness treated as categorical variable. The term $\sum_i^S \beta_i x_i$ codes for the overall effect of species identities on LAI, β_i is the effect of i species and $x_i$codes for the presence and absence of i species. The β_Q term is the effect of the particular partitioned species pool and x_Q codes for the partitioned species pool. The BEE design considers four partitions that differ in plot size (5 x 5 m, 10 x 10 m, 20 x 20 m, 40 x 40 m), each partition is divided into 5 blocks, one per tree diversity level, within each of these blocks each species is randomly selected from the species pool without replacement (Teuscher, et al., 2016). The β_M term accounts for the effect of the species mixture, x_M codes for the particular mixture. The e term codes for random errors.

The linear model method for biodiversity-ecosystem functioning as presented in the equation (3) depicts the impact of the tree species over LAI relative to the average species (Bell, et al., 2009). A positive coefficient explains an above-average contribution to LAI. Nonlinear species richness coefficients indicate the relevance associated with the interaction among species, to plot this result the sum of squares (variance) was used (Bell, et al., 2009) (Fan, et al., 2015).

3 Results

3.1 Leaf area index in conventional OP plantation

3.1.1 Conventional oil palm plantation

In the plots established around the climate tower (N=16), exposed to an intensive management, the mean LAI value was 4.33 ± 1.32 $m^2 m^{-2}$.

3.1.2 OPM experiment

Average LAI values measured in the different management treatments were CH (N=20): 2.38 ± 1.31 $m^2 m^{-2}$, CW (N=20): 2.50 ± 1.09 $m^2 m^{-2}$, RH (N=20): 2.67 ± 1.44 $m^2 m^{-2}$ and RW (N=20): 2.37 ± 1.13 $m^2 m^{-2}$. The analysis of significance did not show any statistically significant *($p<0.05$)* differences of the mean between the different management treatments CH, CW, RH and RW.

3.2 Leaf area index in the enrichment experiment

3.2.1 LAI changes across the enriched plots

Mean LAI inside the re-growing tree islands, where native tree species were planted R>0 (N=47), was 4.34 ± 2.36 $m^2 m^{-2}$. LAI inside plots with no tree species planted, R=0 (N=5), was 2.02 ± 0.6 $m^2 m^{-2}$. The difference between R=0 and R>0 was not significant *($p<0.05$)*. Average LAI for control plots (N=7) was 3.13 ± 1.73. Significant difference $p = 0.0416$ was found when compared plots where no tree species were planted R=0 (2.02 ± 0.6 $m^2 m^{-2}$) and plots where two different tree species were planted R=2 (5.61 ± 1.02 $m^2 m^{-2}$).

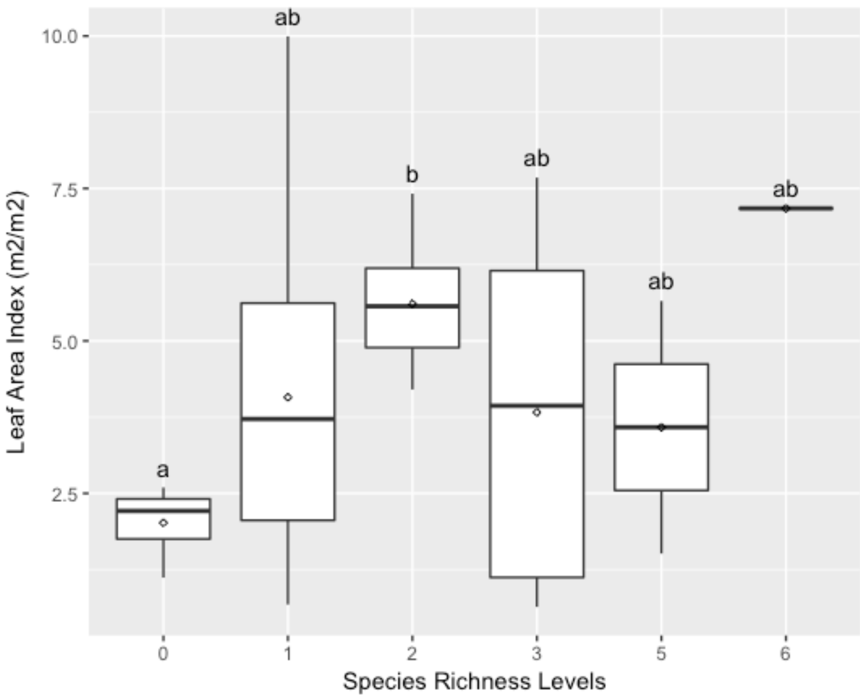

Figure 8. *Comparison of leaf area index between plots with different species richness levels. R=0 (N=5), R=1 (N=29), R=2 (N=8), R=3 (N= 7), R=5 (N=2), R=6 (N=1). Significant difference p=0.0416 is found between R=0 and R=2 plots.*

Leaf area index changes across plots grouped by size (Figure 9) for the enrichment experiment, were statistically significant $p= 0.0077$ when compared 5 m (2.04 ± 1.38 m^2 m^{-2}) and 10 m (4.86 ± 2.75 m^2 m^{-2}) side plots. Likewise $p= 0.0084$, for 5 m (2.04 ± 1.38 m^2 m^{-2}) and 20 m (4.61 ± 1.87 m^2 m^{-2}) side plots. Comparison between plots of 5 m (2.04 ± 1.38 m^2 m^{-2}) and 40 m (4.98 ± 2.04 $m^2 m^{-2}$) side, also presented significant differences $p= 0.0021$.

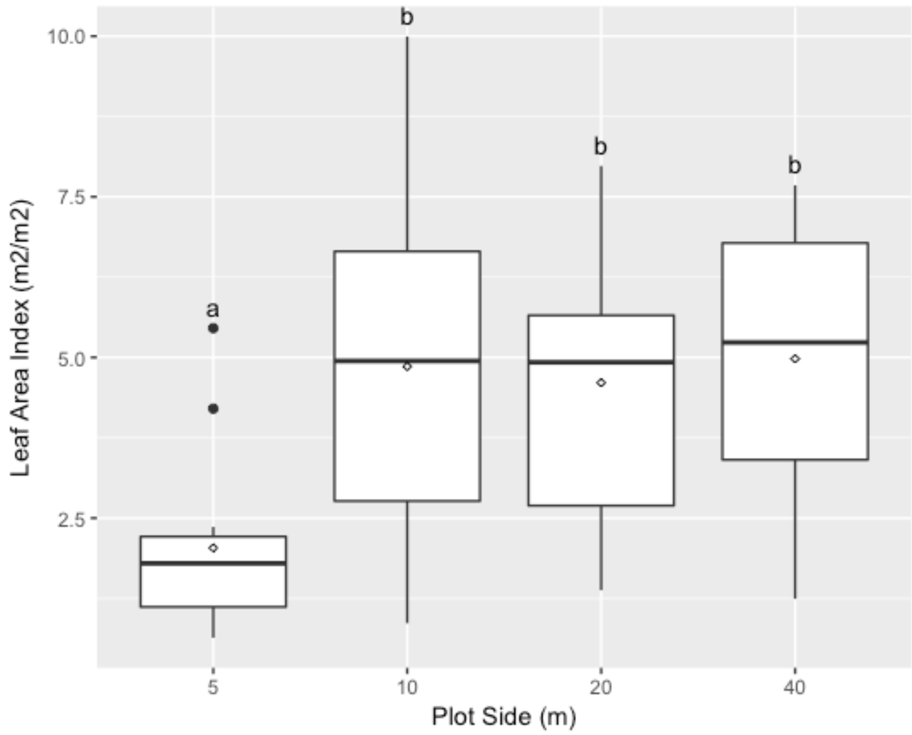

Figure 9. *Comparison of leaf area index between plots of 5 m, 10 m, 20 m, and 40 m in the enrichment experiment. Significant differences are present between the 5 m side plots and the 10, 20 and 40 m.*

3.2.2 Plot size and species richness relationship to LAI

The linear mixed model showed significantly positive plot size-LAI relationship in the BEE (Figure 10, Table 1, $p = 0.005$). Tree species richness-LAI relationship was positive but not significant (Figure 11).

Table 1. *Summary of mixed model analysis of LAI in the tree enriched plots in P.T Humusindo. Species richness (R) and plot size side are the fixed effects and Plot.ID is the random effect.*

Biodiversity Enrichment Experiment LAI				
Fixed effect	Estimate	SE	*F*	*P*
Plot Size	0.007	0.002	8.4	0.005
R levels (0-6)	0.034	0.030	1.23	0.271

Note: Fixed effects were fitted in the same sequence as indicated in the table, plot size effect on LAI is significant at *p=0.005*. F indicates F-ratios and the P is the P-value of the significance test. SD is the standard error of the estimate.

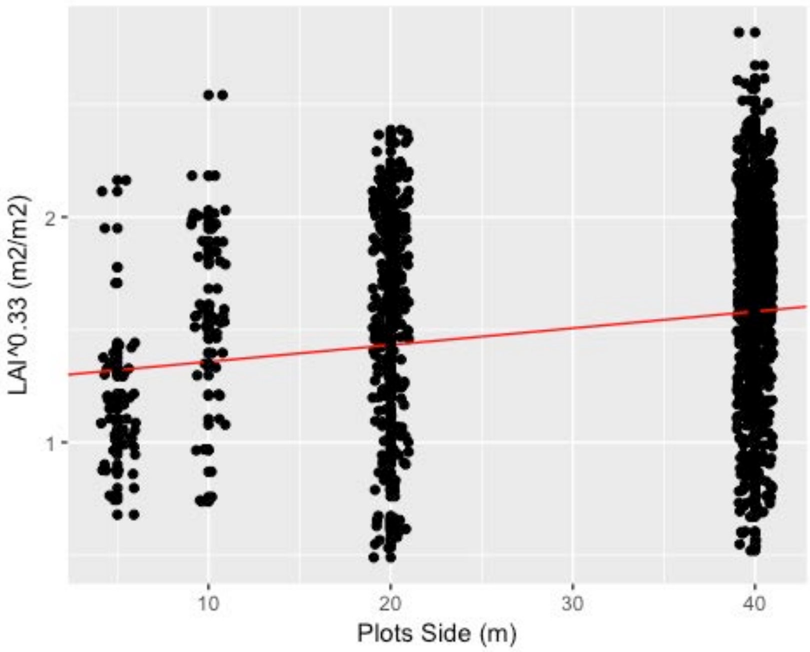

Figure 10. *Predicted fitted lines from the linear mixed model. Fixed effects are species richness (R) and plot size side, random effect is Plot.ID. Significant positive relation is found for the plot size*

and LAI (p=0.005). The y axis shows LAI estimates corrected by the power of 0.33 due to homoscedasticity violation.

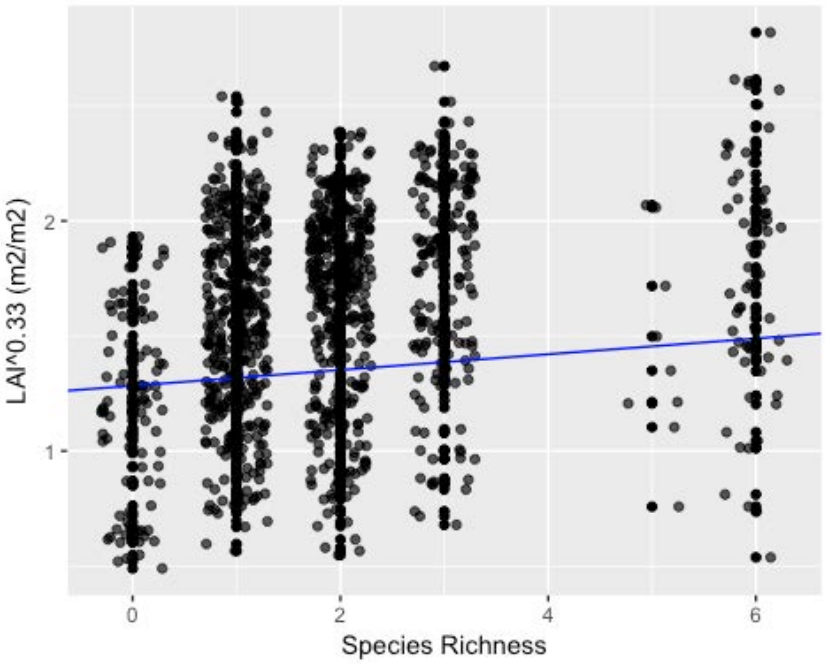

Figure 11. *Predicted fitted lines from the linear mixed model. Fixed effects are species richness (R) and plot size side, random effect is Plot.ID. Species richness shows a positive effect over the LAI however the relation is not significant (p=0.271). The y axis shows LAI estimates corrected by the power of 0.33 due to homoscedasticity violation.*

3.2.3 Species identity and species interaction effect on LAI

Results for the linear model method for biodiversity-ecosystem functioning in the BEE presented positive coefficients for *Parkia speciosa* and *Peronema canescens*, meaning that *Parkia speciosa* and *Peronema canescens* have an above-average contribution to LAI (Figure 12).

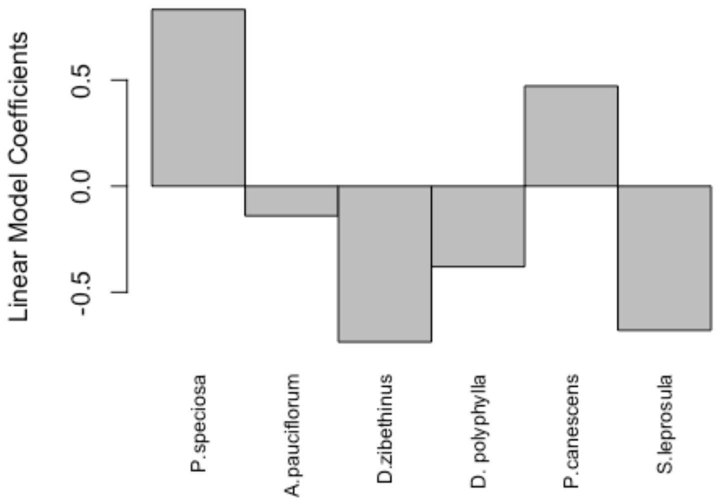

Figure 12. *Linear model method for biodiversity-ecosystem functioning coefficients for individual species planted in the BEE. The model shows positive coefficients for Parkia speciosa and Peronema canescens, which mean that both species individually perform above the average species in terms of LAI.*

Interaction among species exhibited a slightly stronger influence on LAI compared to species identity. The sum of squares for species identity was 21.12 and for the nonlinear richness 36.21, Figure 13.

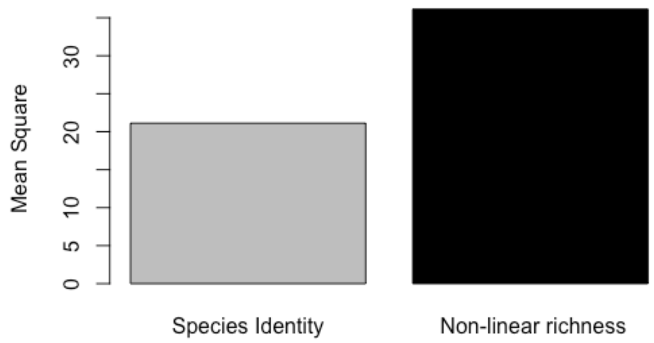

Figure 13. *Contribution of species identity and nonlinear species richness on LAI. The model shows that the interaction among the species is higher compared to species identity.*

3.3 Leaf area index in naturally established tree islands

The average LAI values in the naturally established tree islands inside the oil palm landscape for the NP1: 30 years old island was 8.85 ± 0.9 m^2 m^{-2}, NP2: >10 years old island was 9.20 ± 2.19 m^2 m^{-2} and for the NP3: 3 years old island was 7.86 ± 2.3 m^2 m^{-2}.

3.4 Leaf area index across treatments in the oil palm landscape

Data distribution for plots under conventional management, OPM experiment, BEE and naturally established islands is presented in Figure 14, maximum, minimum, mean and median leaf area values are depicted. Higher average LAI values were measured in the naturally established islands compared to enriched plots R>0, OPM plots, and plots under conventional management around the climate tower. The highest mean LAI value across the oil palm landscape was measured for the >10 years old natural tree island (9.20 ± 2.19 m^2 m^{-2}).

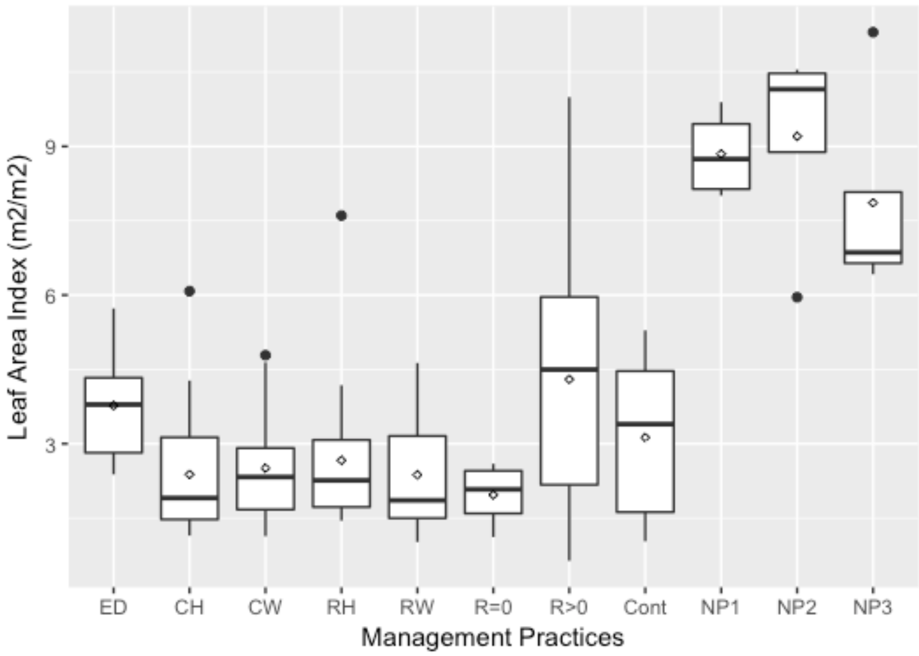

Figure 14. *Data set summary for ED (N=16): Plots around climate tower, CH (N=20): Plots under conventional fertilization and herbicide spraying, CW (N=20): Conventional fertilization and mechanical weeding, RH (N=20): Reduced fertilization and herbicide spraying, RW (N=20): Reduced fertilization and mechanical weeding. R=0 (N=5): tree enrichment experiment plots with*

species richness zero, R>0 (N=47): tree enrichment experiment plots with species richness between 1-6. Cont (N=7): control plots in the enrichment experiment. Naturally established regeneration (N=3): NP1, NP2, NP3. In terms of LAI naturally established islands reach higher values compared to tree enriched plots.

4 Discussion

Oil palm expansion represent an important threat to ecosystems and biodiversity, whereby it is a main task to develop better production systems for reducing the adverse effects (Koh, et al., 2009). The management practices evaluated in this study are a good starting in order to find a better way to sustain economic and livelihood needs, but at the same time recognize the importance to maintain and enhance ecosystem functions. Leaf area index (LAI) is a variable that enable to study the effect of different management strategies in oil palm plantations. For example, just by looking LAI in the oil palm management experiment located in a mature plantation is likely to reduce urea application by 50%. Likewise, LAI assessment showed that is possible to increase leaf area by planting trees inside an oil palm plantation, and presumably is needed in order to restore LAI in abandoned land previously used by OP. There are opportunities to develop better OP plantations and boost ecosystem functions restoration, perhaps by combining different management strategies in the same area like intensive management, agroforestry systems or enriched tree systems, and forest at different successional stages. Once the “Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems” project comes to end, a wider panorama about the partial ecosystem functions restoration dynamics and potential benefits, might encourage plantation holders to shift towards a new approach of landscape design.

4.1 Leaf area index (LAI) sampling technique

The sampling technique adopted for the study proved to be effective in order to determine LAI; nevertheless, future studies should consider specific sampling technique according to every study design, or one unified technique applicable for all treatments. For the specific case of this study and due to site conditions, only the first ring was used to produce reliable LAI estimates. Nonetheless, rings restrictions imply that only those leaves distributed in the upper part of the canopy were accounted, this may have introduced an error on the LAI estimates in the small and non-homogeneous plots (Cutini, et al., 1998). Therefore, low leaves from small individuals were not recorded and the LAI effect of these individuals could have been missed (Peng, et al., 2017).

The use of two sensors for data collection is recommended for further research, this will make possible to place one sensor in an appropriate clear area for continuous readings above canopy to improve the transmittance from each sensor ring (LI-COR, 2015) (Pearse, et al., 2017). Additional improvements in the sampling technique must consider keeping the same orientation of the view cap for the above and below canopy readings. So, when applying the *Row Crops* technique for heterogeneous canopies that implies changing the orientation in every diagonal transect, the above canopy sensor must be also adapted to this situation and change the view cap orientation. This consideration is furthermore applicable for the LAI recording in small plots, where measurements were made from the corners and pointing to the plot center.

4.2 Leaf area index in conventional managed plantation

Leaf area index mean estimated in the intensively managed plantation located around the climate tower site was 4.33 $m^2 m^{-2}$, similar LAI of 3.64 $m^2 m^{-2}$ was found in a former study in the same plantation (Fan, et al., 2015). Oil palms around the climate tower are 16 years old which means leaves already reached their maximum size and peak LAI (Gerritsma & Soebagyo, 1999), this explains why the estimates are similar. However, LAI value reported in this study is slightly higher in comparison to the value reported by Fan et al. (2015), which might be explained by the differences between the sampling techniques. The study here presented employed an optical device for the leaf area estimations, and the study carried by Fan et al. (2015) sampled leaf area of individual phytomers and scaled the values up. Besides, differences of pruning at the time of measurement might have influenced LAI values. The maximum LAI in OP plantations typically ranges from 4 to 6 $m^2 m^{-2}$ depending on pruning (Squire & Corley, 1987), fertiliser use (Breure, 1985) (Corley & Monk, 1972) and general agronomic management (Woittietz, et al., 2017). The typical values reported in literature are comparable to the mean value of 4.33 $m^2 m^{-2}$ measured in this study around the climate tower site.

4.3 Leaf area index in alternatively management experiment

The oil palm management experiment results indicate that implementing management strategies such as reduced fertilization combined with mechanical weeding or herbicide spraying, do not significantly differ in terms of LAI from management practices where conventional fertilization, mechanical weeding and herbicide spraying are implemented. Mean LAI values among the four different treatments are very similar ranging from 2.37 $m^2 m^{-2}$ to 2.67 $m^2 m^{-2}$.

The management experiment findings up to now are not conclusive because the experiment was established one year ago, therefore probably it will take longer until leaf area responds to the treatment. Nonetheless, results to date encourage thinking that is possible to reduce by 50% the amount of urea (kg N) used per palm without apparently affecting LAI. Usually managers tend to add large excess of urea in the soil as a safety measure, which tends to unbalance the fertilization process (Corley & Tinker, 2016). Frequently OP shows a good response to N as long as LAI is below 5 (von Uexkull & Fairhurst, 1991). The fact that all treatments exhibit similar LAI values may suggest that N is present in excessive amounts in the soil, hence reduced fertilizer conducts to similar LAI responses. The amount of nitrogen released to the atmosphere due to the excess of urea can be extremely large depending on the weather conditions (Corley & Tinker, 2016), besides significant amounts of the greenhouse gas nitrous oxide (N_2O) are released in plantations located in areas with high water tables (Aulakh, et al., 1992).

Results suggest mechanical weeding as appropriate for weed control in mature plantations. However the yield response of mature plantations to various weed populations is unknown (Woittietz, et al., 2017), which encourages future research in this area. According to Dilipkumar et al. (2017) chemical weed control in OP plantations may not be sustainable because of few varieties of herbicides. Several studies advise to establish an integrated weed management, depending on the growth stage of the palms, these practices encompass chemical, cultural, mechanical, and biological approaches, including herbicides, hand weeding, mulch, high planting density, livestock grazing, cultivation of cover crops, and mechanical slashing (Chung, 2013).

4.4 Leaf area index in tree enriched islands

4.4.1 Changes of mean LAI across species richness levels and plots size

In the tree enrichment experiment higher LAI estimations and variability was expected for plots with more species present in the mixture. However, changes on LAI across the different species richness levels is not linear as expected and decreases after a third tree species is added to the mixture. A reference study developed in a subtropical forest recorded LAI increment with tree species richness in the fifth year of stand establishment, in this study particularly large LAI increase occurred when doubling species richness from 1 to 2 and smaller gains when more species were added (Peng, et al., 2017). Differences among the enrichment experiment and the reference study are likely explained by light competition, between OP and planted trees, as canopy start to close (Li, et al., 2014). Before trees were planted in the enrichment experiment, 40% of palms were removed on each plot bigger than 5 m side; nonetheless, the structure and canopy architecture of remaining palms strongly influence LAI and may have affected survival rates and growth of planted trees after more than two species were planted. Nevertheless this alone cannot explain the LAI-species richness trend, because on the single plot with six tree species mixture the mean LAI is the highest among all levels. It is well known that phenotypic plasticity in plants in response to light availability including shifts in biomass allocation and crown architecture, could modify its light capture efficiency (Sterck & Bongers, 2001) (Valladares, et al., 2007) (Sapijanskas, et al., 2014). Hence, apart from competition, it is likely that some trees on the richness levels of three, four and five, did not grow in height and may have experienced some morphological changes. But as mentioned, LAI sampling technique adopted could have missed low leaves from small individuals, which could have conducted to underestimation of LAI across richness levels. It is relevant to point out that the average leaf area in all enriched plots with native tree species (4.34 ± 2.36 $m^2\ m^{-2}$) double mean LAI of plots where no trees were planted (2.02 ± 0.6 $m^2\ m^{-2}$), and present higher variability. Besides, all species mixtures categorized by species richness levels from 1-6 present higher mean LAI values compared to oil palm plots. Which suggests that partial removal of oil palms with the aim to plant native trees positively affect leaf area development.

Average leaf area change across the plot size categories (5, 10, 20 and 40 m) was large when plot side increased from 5 m to 10 m, afterwards mean LAI did not change with side increment. This trend was expected owing the fact that palms on the 5 m side size plots were not removed and planted trees were not able to grow well. The consistent findings across all plots, grouped by size, indicate that average LAI per plot is independent of the original species pool, and the estimates may have been influenced by the presence of some particular species (Peng, et al., 2017).

4.4.2 Plot size and species richness relationship to LAI

Plot size significant effect *(p=0.005)* on leaf area may have been driven by good performance of tree species repeatedly encountered on bigger plots where more measurements were taken and more extreme LAI values were detected (Appendix 7). Probably plot size-LAI relationship responds to a selection type effect explained by demographic processes that altered the abundance of individual species, likely leading to a dominance of some traits at plot level (Peng, et al., 2017). Moreover, the sampling design favors tall individuals, including palms, which were recorded more times on bigger plots.

Little is known about the role of species richness on ecosystem functioning in tropical ecosystems, and direct evidence of biodiversity effects on leaf area is scarce (Castro-Izaguirre, et al., 2016). At the young stage of the enrichment experiment species richness and LAI relationship is positive but not significant at plot level, meaning that is not conclusive whether species richness increase leaf area or not. Studies implemented in a wide range of ecosystems indicate that effects of biodiversity increase in the course of long-term experiments (Tilman, et al., 2001) (Stachowicz, et al., 2008) (Reich, et al., 2012) (Castro-Izaguirre, et al., 2016). According to Marquard et al. (2013) as field experiments advance, effects are dominated by population-level responses instead by changes at individual level. Thus, it is likely that in the near future the effect of species richness on LAI becomes significant in the enrichment experiment. Architectural complementarity will possible increase in a more mature field experiment because of a better crown spatial arrangement and differences in shade tolerance among species, which may allow mixtures in the experiment to sustain more leaf area (Morin, et al., 2011).

4.4.3 Species identity and species interaction effect on LAI

Two out of the total species pool, *Parkia speciosa* and *Peronema canescens,* showed an above-average contribution to LAI. So, apparently there is a little relationship between diversity and LAI, which was also the outcome of the linear mixed model. *Parkia speciosa* and *Peronema canescens* outperformance might be explained as a consequence of interspecific differences in the display of leaves in the horizontal and vertical space (Castro-Izaguirre, et al., 2016), which enlarged the light capture efficiency among species (Sapijanskas, et al., 2014). Even when species identity apparently largely influences LAI, it is not possible to confirm that the identity effect excludes species interaction. Results showed that interaction coefficient among species slightly exceeded the identity effect on LAI in the enrichment experiment. One possible explanation is the fact that the model does not account for the presence of palms in the mixture, which might be positively interacting with tree species and is reflected in a higher non-linear richness coefficient. The degree of expression of any interaction depends on the relative abundance of the species involved (Kirwan, et al., 2009), but mortality was not included in the model, so is likely that some interactions among certain species became stronger when selective effects removed one or more species from the mixtures, which was reflected on the non-linear richness coefficient.

4.5 Leaf area index in naturally established tree islands

Natural tree islands display high mean LAI values compared to mixtures established in the enrichment experiment. The results show a large mean LAI value and variability of 7.86 ± 2.3 $m^2 m^{-2}$ for the three year old natural island. According to secondary forest dynamic studies in stands younger than 5 years old, during early successional stages vegetation development is very fast, with a rapid increase of leaf area index (Swaine & Hall, 1983) (Uhl, 1987a). Permanent plot studies suggest that this trend continue later in succession, but at lower rate (van Breugel, 2007). The latter was observed on the natural regeneration islands, because LAI increases from the 3 to >10 years old island; however the change is not severe (9.20 ± 2.19 $m^2 m^{-2}$). According to Brown & Lugo (1990) leaf area increases to a maximum in the course of the first 15 years of regeneration, this was depicted on the trend observed in the regenerations islands, where mean LAI on the 30 years old fragment is slightly lower than the > 10 years old fragment. Leaf area measured in the naturally established regeneration is comparable to values observed in some lowland tropical rainforest; for example, LAI of 11 $m^2 m^{-2}$ was reported in Khao Chong, Thailand (Kira, et al., 1964, 1967) (Ogawa, et al., 1965). The fast recovery of leaf area in secondary forest after 10 years of establishment results in corresponding ecosystem funtions of old-growth forest, such as rainfall interception and albedo (Bonell & Bruijnzeel, 2005). Although, little is known in this case about the species present in the studied islands is possible to comprehend why secondary forest research is relevant, motivated mainly by their potential role to support biodiversity and ecosystem services.

A very interesting finding observed between the enrichment experiment and the natural tree islands is the very low mean LAI value of 2.1 m^2 m^{-2} in the plots where no trees were planted, these plots comply the function of abandoned land fragments in an oil palm landscape where no management is applied and natural succession could be monitored. Considering that after 5 years of experiment the mean leaf area is almost four times lower than the three year old natural fragment, it is possible to suposse that oil palm cultivation intensity is severe and may have a strong influence over natural regeneration. Literature support the hypothesis that under moderate land use intensity and the seeds sources nearby, species richness increases very fast during the first years after abandonment (Guariguata & Ostertag, 2001), however if land use intensity in the past was heavy, slower recovery is expected (Uhl, et al., 1988b). If so, and the oil palm cultivation is indeed heavy, is needed to artificially enrich the oil palm landscape for recovering LAI function in Sumatra lowlands.

5 Conclusions

The study here presented contributed to understand how different management practices influence on LAI. Looking at one central variable, LAI, it is possible to conclude that in mature OP plantation is feasible to reduce fertilizer application by 50% without impacting leaf area. However, it is needed to assess LAI response in further researches once the field experiment is more advanced.

It was expected to find a linear relationship between species richness and LAI, however the trend shows that other variables have a stronger influence at the current stage of the enrichment experiment. Plot dynamics at different species richness levels may have being biased by light competition, remaining oil palms and phenotypic plasticity. Mean LAI was not different across plots grouped by size where palms were removed, suggesting that the leaf area is independent of the species pool, then is likely that other native tree species mixtures perform better in terms of LAI.

The sampling design adopted could have resulted in a selection type effect of tall individuals and palms repeatedly encountered in bigger plots. It is expected that once the enrichment experiment matures the effects of biodiversity on LAI increase and population-level responses dominate. Leaves display of *Parkia speciosa* and *Peronema canescens* may have contributed to the outstanding performance of these species; however, species interaction showed to be slightly stronger when explaining LAI variability at individual plot level. The coefficient interaction of species could increase during the next years, so is advisable to run the model again when new LAI data is available.

Natural regeneration shows large mean LAI values compared to enriched plots, demonstrating that secondary forest succession is more effective on recovering leaf area compared to manipulated enrichment experiments. However low LAI values of plots where no trees were planted suggests that OP cultivation is a severe land use type, therefore tree enrichment is necessary in order to restore leaf area index in the oil palm landscape.

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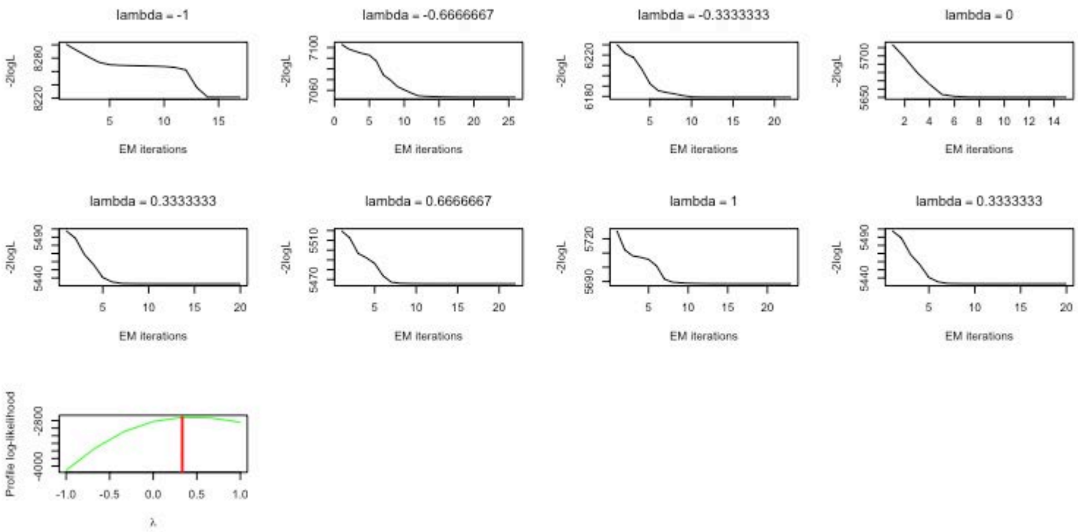
7 Appendixes

Plot ID	Side (meters)	South	East
1	40	01.69346 °	103.39108 °
2	40	01.69215 °	103.39104°
3	40	01.69211°	103.39200°
4	40	01.69345°	103.39204°
5	5	01.69352°	103.39160°
6	5	01.69330°	103.39172°
7	5	01.69292°	103.39162°
8	5	01.69250°	103.39162°
9	5	01.69212°	103.39178°
10	5	01.69165°	103.39190°
11	5	01.69246°	103.39133°
12	5	01.69272°	103.39130°
13	5	01.69285°	103.39106°
14	5	01.69314°	103.39091°
15	5	01.69385°	103.39086°
16	5	01.69401°	103.39134°

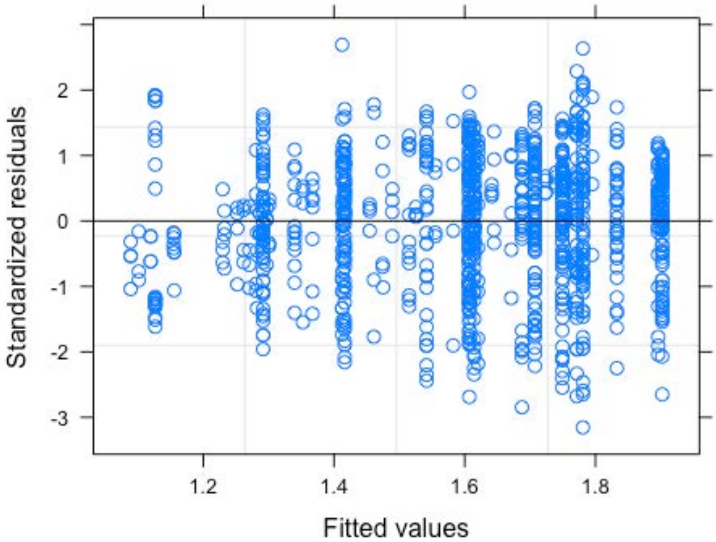
Appendix 1*. Experimental plots locations on the surroundings of the meteorological tower in the state owned plantation PTPN VI.*

Plot ID	Area (Km^2)	South	East
NP1	10	01.954253°	103.257503°
NP2	160	01.939170°	103.264050°
NP3	40	01.934390°	103.250850°

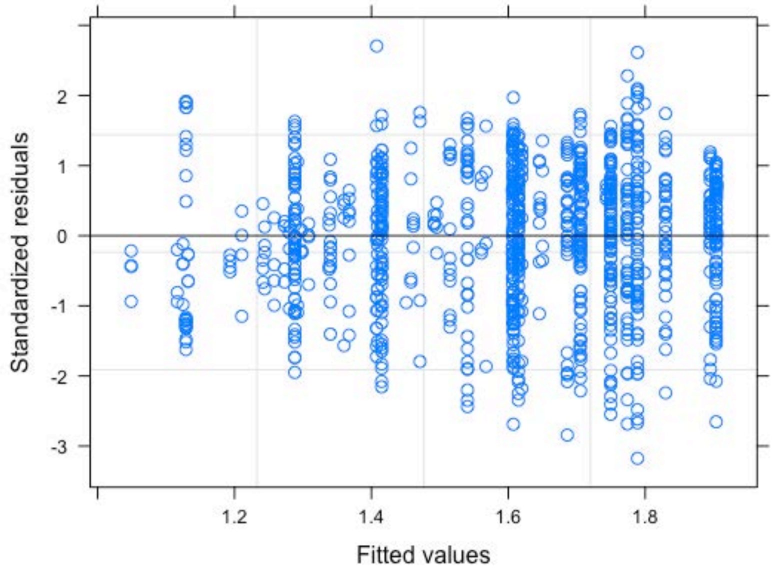
Appendix 2. *Naturally established plots locations on the surroundings of PT. Humusindo.*



Appendix 3. *LAI transformation according to the optimum boxcox function in R, the response variable by the power of 0.33 was the best transformation.*



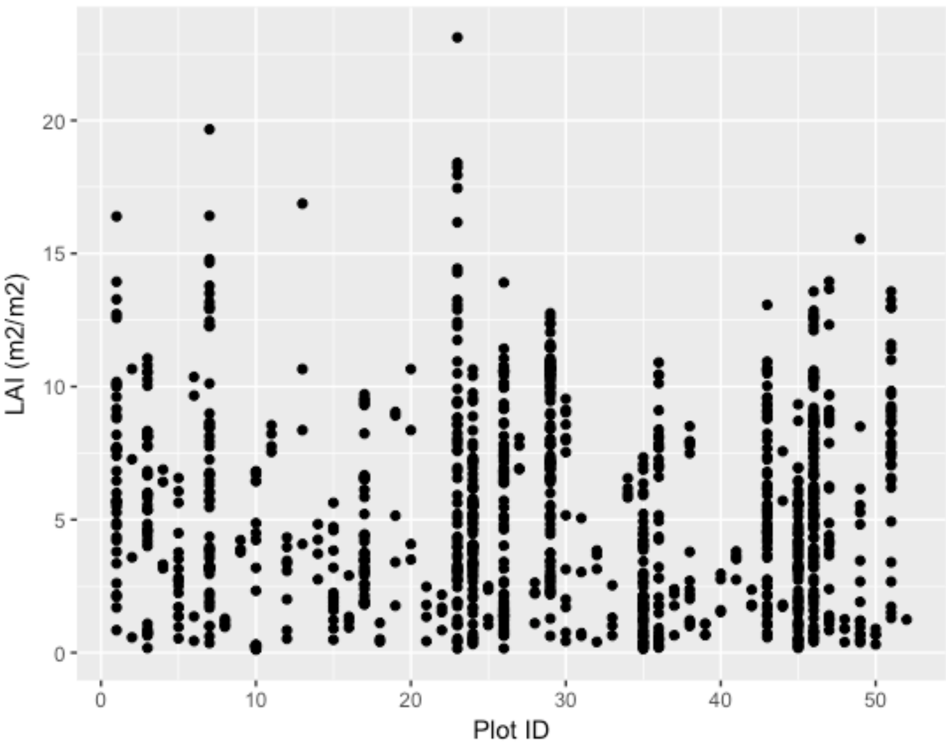
Appendix 4. *Plot of residuals for the linear mixed model applied to the BEE. LAI data was transformed by the power of 0.33 due to homoscedasticity violation. Fixed effects are species richness (R) and plot size side, random effect is Plot.ID.*



Appendix 5. *Plot of residuals for the linear mixed model applied to the BEE to test the interaction between plot size and species richness.*

	numDF	denDF	F-value	p-value
(Intercept)	1	1024	1552.5860	<.0001
SIDE	1	48	8.5413	0.0053
R.LEVELS	1	48	1.2692	0.2655
SIDE:R.LEVELS	1	48	1.9878	0.1650

Appendix 6. *Result of the anova () function for the linear mixed model applied to test the interaction between plot size and species richness in the BEE. The interaction is not significant p=0.165.*



Appendix 7. *Plots where more measurements were taken show a higher variability and extreme LAI values. Some tree species that perform well in terms on LAI were repeatedly encountered in bigger plots.*