Litter carbon stocks in fragmented dipterocarp forests

Assessing carbon stocks in the litter layer of forest fragments embedded within oil palm plantations in Sabah, Malaysia

Bachelor Thesis by Nils Beaujon
at Van Hall Larenstein, May 2017

LITTER CARBON STOCKS IN FRAGMENTED DIPTEROCARP FORESTS

Assessing carbon stocks in the litter layer of forest fragments embedded within oil palm plantations in Sabah, Malaysia

Bachelor thesis
in
Forest and Nature Management – Tropical Forestry
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Preface

This report was written for my Bachelor thesis at Van Hall Larenstein University of Applied Sciences. The study was carried out in Sabah, Malaysia on behalf of the Socially and Environmentally Sustainable Oil Palm Research programme (SEnSOR) in order to do scientific research that tests and develops better management of oil palm plantations and their environment according to the Roundtable of Sustainable Palm Oil (RSPO).

I am grateful for the chance to join this project and contribute to the research done in Sabah. Many thanks go to my supervisor Peter van der Meer for introducing me to this programme and his support throughout the whole process from writing a proposal, carrying out the fieldwork until finishing the report. Credit also goes to Dr Benny Yeong, our external supervisor who guided us with setting up the research proposals and adjusting our fieldwork. I owe gratitude to dr. Susan Benedick for her help with the research permits and acting as our local collaborator from Sabah.

Thanks go to Wilmar International Limited for arranging accommodation and food and allowing us access to their plantation sites. Thanks to SEnSOR for financial support and the Danum Valley Management Committee for allowing our stay in Danum Valley where we could make use of the lab and expertise of the personnel, thanks Mike.

My study on litter carbon stocks was part of a research project together with two of my colleagues who did similar studies on tree and liana carbon stocks. Thanks Alwin and Sake for the nice time we had together in the field and the support during the project. Many thanks to Tamby, the first person we met in Sabah, who acted as our research assistant and accompanied us during our entire stay in Sabah.

Nils Beaujon
Velp, May 2017

Abstract

Forested areas in Sabah, Malaysia have become more fragmented and have decreased in size, many of the forest fragments being isolated within palm oil plantations. An increasing number of palm oil producers is interested in producing in a more sustainable way, including the management of forest fragments within the plantation landscape that contain high conservation values (HCV) or high carbon stocks (HCS). The fragments vary widely in size and it is important to gain insight into the effects of fragment size on each of the components of the forest ecosystem.

This report is part of a collaborated study initiated by the SEnSOR programme to assess each of the compartments of aboveground carbon (AGC) stocks in fragmented lowland dipterocarp forests in Sabah. The biomass and carbon contents of living trees and coarse woody debris, lianas, fine woody debris (FWD) and litter, were studied and reported in three parts. The litter and FWD carbon stocks elaborated in this report are important components of AGC because they are an indicator of the health of the forest and form the link between key ecosystem processes, such as litterfall and decomposition. Litter is defined as all dead biomass on the forest floor with a diameter smaller than 1 cm, fine woody debris includes all dead biomass with a diameter between 1 and 10 cm. We collected samples and data of each forest component in twelve forest fragments ranging in size from 12 to 3529 hectares and two continuous forest sites, during June and July 2016.

The average litter biomass among all sampled sites was 6.94 ± 1.15 Mg/ha, and the average litter carbon stock was 3.25 ± 0.54 Mg/ha. The variation found in litter carbon stock among different fragment sizes was relatively small and showed no pattern with area size. No significant relation was found between the litter carbon stock and the area size. The biomass and carbon stock of FWD were respectively 1.64 ± 0.64 Mg/ha and 0.77 ± 0.30 Mg/ha. The amount of FWD was higher in smaller fragments than in larger fragments. The relative proportion of the litter and FWD as part of the aboveground carbon stock related negatively to the fragment size. The litter and FWD proportion were significantly higher in small fragments than in large fragments, due to a decline of living tree carbon (largest proportion of AGC) with decreasing fragment size.

The observed changes in biomass dynamics and carbon proportions between large and small forest fragments lead to the conclusion that small forest fragments are generally of lower quality (in the context of carbon stocks: reduced total carbon stock, an increased proportion of dead biomass compared with living biomass) than large patches of forest. Therefore, it should be prevented to form small isolated fragments and instead allow for the preservation of large forested areas or to connect forest fragments with each other. Further research including larger sample sizes could aid in determining lower limits for the fragment size of areas that contain high conservation values or high carbon stocks. Important subjects to study would be long term monitoring on the effects of forest fragmentation and separate research on the effects of logging and time since fragmentation or logging.

List of Abbreviations and Acronyms

All abbreviations and acronyms in the report are written in full and described below in this list.

Abbreviation	Full name / description		
HCVF	High Conservation Value Forest		
HCS	High Carbon Stock		
VJR	Virgin Jungle Reserve (Category VI Forest Reserve, see Appendix 5)		
CF	Continuous Forest		
SEnSOR	Socially and Environmentally Sustainable Oil Palm Research programme		
RSPO	Roundtable on Sustainable Palm Oil		
C	Carbon		
AGC	Aboveground Carbon (= carbon in all living or dead biomass above the soil)		
FWD	Fine/small Woody Debris		
CWD	Coarse Woody Debris		
g	gram		
kg	kilogram	=	1,000 gram
Mg	megagram	=	10^6 gram or 1 ton
Tg	teragram	=	10^{12} gram or 10^6 ton
Pg	petagram	=	10^{15} gram or 10^9 ton
cm	centimeter	=	0.01 meter
m^2	square meter		
ha	Hectare	=	10,000 square meter
ppm	parts per million		
CO_2eq	carbon-dioxide equivalent		
°C	degrees Celsius		
y	year		

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1. Introduction

Tropical forests play an important role in providing ecosystem functions. These ecosystem functions include biodiversity, carbon storage, erosion control and watershed management among many more. Litter is an essential part of the forest ecosystem that represents the carbon and nutrient flux from dead biomass to soil organic matter and living organisms (Parsons et al., 2009). In addition, the litter layer is home to a wide variety of invertebrates, fungi and microorganisms, supporting high biodiversity levels (EFSA, 2010). Unfortunately, these tropical forest ecosystems are under threat of multiple ongoing processes, such as logging and land conversion for agriculture. Fragmentation and degradation of natural ecosystems are the primary causes of decline in biodiversity; isolating populations and dividing vast forested areas into small fragments that support a lower amount of species (Edwards et al., 2010; Ferraz et al., 2014; Tawatao et al., 2014; Wilson et al., 2016). Currently, half of the remaining forest on earth is within only 500m of the forest edge (Haddad et al., 2015). The amount of carbon stored in tropical forests is also decreasing. Tropical forests contain about 25% of the total amount of carbon in the terrestrial biosphere (Bonan, 2008). Converting or degrading forests lowers the carbon stock and emits substantial amounts of greenhouse gasses into the atmosphere.

During the 20th century, the carbon dioxide concentration in the atmosphere has increased dramatically. From 2002 to 2011 the carbon dioxide concentration in the atmosphere was rising at the fastest observed decadal rate of change yet (2.0 ± 0.1 ppm/y) (IPCC, 2014). One of the main factors leading to this rapid increase has been land use conversion; forested areas that have been converted into agricultural, urban or industrial areas. Global forestry and land use change combined, contributed annually about 4-6 $PgCO_2eq/y$ to the atmosphere in the years 1970 – 2009 (Smith et al., 2014). This is about 12% of the total amount of greenhouse gasses emitted annually.

Vast areas of forested land in Sabah (Borneo, Malaysia) have been subject to changes in land use (Bryan et al., 2013; Gaveau et al., 2014). Over the past decades a lot of forested areas have been fragmented and decreased in size; the total amount of forested land in Sabah decreased from over 60% in 1980 to about 51% in 2010 (Reynolds et al., 2011). The primary driver for land use change in Sabah has been the demand for palm oil (retrieved from cultivated oil palms: *Elaeis guineensis*) (Reynolds et al., 2011). The percentage of land surface used for palm oil plantations in Sabah increased from 3.5% in 1980-1990 to about 20% of the total land area in 2012 (MOPB, 2013). This increase in palm oil plantations was boosted by the National Agriculture Policy, implemented in 1984 to increase the amount of agricultural land to support socio-economic development (Murad et al., 2008). Currently, Sabah exports 12% of the world's crude palm oil and is the third largest producer after Indonesia and Peninsular Malaysia (Sabah Forestry Department, 2015b). Approximately 30% of that is certified as sustainable palm oil.

The rapid increase in oil palm plantations is not without valid reason: it produces high amounts of nutrition that can be used for a variety of products that are valuable in a world that consumes increasingly more each year. In addition, it provides labour in areas that are yearning for economic growth. However, the losses in biodiversity and carbon stock are immense, and even sustainable palm oil does still have its flaws and risks associated. Therefore, it is vital to improve the requirements and monitoring of sustainable palm oil and to convince consumers of the importance of certified products.

Recently, the State Government of Sabah decided to implement a jurisdictional approach to have all crude palm oil certified as sustainable by the Roundtable for Sustainable Palm Oil (RSPO) by the end of 2025 (Sabah Forestry Department, 2015b). This goal was initiated by the Sabah Jurisdictional Certification Steering Committee and is supported by government agencies, the RSPO, NGO's and scientific organisations. The demand for sustainable palm oil is also increasing. The European Union, for example, aims at only importing certified sustainable palm oil by 2020 by recommending each state to implement restrictions against importing unsustainable palm oil (van der Velde, 2017). One of the certification requirements for sustainable palm oil by the RSPO is to set aside and manage the areas wherever high conservation values (HCV) have been identified (RSPO, 2013). These areas are forest fragments surrounded by oil palm plantations, which are managed to ensure that the HCV's are maintained and enhanced (Brown & Senior, 2014). In addition to HCV's, a lot of attention is going to areas that contain high carbon stocks (HCS). Currently, the HCV and HCS approach are being integrated into one approach to improve the efficiency of implementation (G. Rosoman et al., 2017).

This study is conducted on behalf of the SEnSOR programme, part of the South East Asia Rainforest Research Partnership (SEARRP). The SEnSOR programme was initiated to generate independent scientific research that increases the knowledge needed for sustainable palm oil cultivation in three main areas: Biodiversity, Environment and Society (SEnSOR, 2017). The key issue that we are investigating in this study is the aboveground carbon (AGC) storage of forest fragments such as HCV areas within palm oil landscapes. Other components of the AGC, the tree, course woody debris (CWD) and liana carbon stock, were studied by Alkema (2016) and de Winter (2016). Better understanding of the carbon stocks and dynamics in forest fragments can improve management decision making and aid in refining guidelines for the HCV/HCS areas embedded within palm oil plantations (SEARRP, 2017).

Here, we look at the litter and fine woody debris (FWD) standing stock biomass (quantity of dead biomass on the forest floor) and carbon (roughly half of the biomass weight is carbon) in relation with forest fragmentation and logging effects. The litter standing stock is a fundamental part of the forest ecosystem and information on the litter carbon content can help to get a better understanding of climate change models and the effect of fragmentation on the carbon cycle (Parsons et al., 2014). Litter biomass is the main supply of energy to soil fauna and micro-organisms and functions as a link between plant and soil communities. Processes that affect the species composition and richness of the forest have an indirect influence on the decomposability of the litter. Forest fragmentation and logging practices are examples of such processes that are known to affect the species composition and the biodiversity of tropical forests (Nascimento & Laurance, 2004). Canopy species differ in structure and architecture, affecting the amounts of light, rainfall and evapotranspiration and other microclimatic conditions. These microclimatic conditions alter the forest floor and air temperature. In the majority of the cases, a higher tree species diversity results in higher decomposition rates, attributed to effects such as a higher nutrition and habitat diversity (beneficial for soil fauna diversity) and variation in canopy species traits (Paudel et al., 2015).

Previous inventories of litter biomass standing stock in unlogged primary lowland dipterocarp forest in Sarawak averaged 5-10 Mg/ha (megagrams per hectare) (Proctor et al., 1983). The carbon stock would be 2-5 Mg/ha (~ 50% of biomass). With an average of 3.5 Mg/ha carbon in the litter layer, the total amount of all forests in Sabah combined is about 13.2 teragram (Tg = million tonnes) of litter carbon. For comparison, this is almost as much as the total amount of carbon stored in living trees in the Netherlands: 15.87 Tg (Nabuurs & Mohren, 1994). The components of the forest that contain the highest percentage of the total carbon stock are the large live stems (tree stems with a diameter higher than 10 cm) and the soils, together accounting for approximately 75% of the total carbon stock (Berenguer et al., 2014).

We define the aboveground carbon (AGC) stock as all carbon in biomass above the soil, including dead biomass such as litter and woody debris (soil and belowground tree carbon are excluded from AGC). Litter usually accounts for around 5% of the AGC stock in tropical forests, but this percentage can be higher in degraded forest (Berenguer et al., 2014).

The quantity of litter on the forest floor is mainly determined by these two processes: litterfall and decomposition. Both processes have been studied previously in relation with forest fragmentation in Sabah. Yeong (2016a) found that dipterocarp seedlings, and in particular light demanding species, showed increasing growing speed at decreasing forest fragment size (and growing about 60% faster in forest fragments than in continuous forest). It is likely that this increase in growing speed is caused by edge effects leading to higher amounts of light available to the seedlings. A higher growing rate of light-demanding species could increase the annual litterfall, increasing the total litter standing stock (Seidelmann et al., 2016). The incoming radiation increases temporarily, resulting in higher litterfall and lower decomposition rates. Similar processes take place when forested areas are selectively logged. It is to be expected that forests that have been logged over contain lower total aboveground carbon stocks.

Research on the effects of fragmentation of forested areas has mostly been situated in the neotropics (Laurance et al., 2011; Nascimento & Laurance, 2002). In previous years a few studies showed that fragmentation of forest patches scattered across palm oil plantations in Sabah affect the biodiversity of animals and plants (Benedick et al., 2006; Tawatao et al., 2014). Less is known about the current carbon stock in these fragments and if there is a correlation between the size of the fragments and the litter carbon stock. This study was conducted to fill these knowledge gaps that exist in understanding of litter in fragmented tropical forests. More knowledge in these fields will assist in creating improved guidelines and legislation for sustainable cultivation of oil palms, and promote better conservation of HCV and HCS areas.

1.1 Objective

The aim of this study is to understand whether and how litter carbon stocks of dipterocarp forests in Sabah are impacted by fragmentation size and logging. To do so, we have to quantify the carbon stock in the litter layer of fragmented forests and compare them to site characteristics such as the size. To define how we want to realise these research objectives, we formulated the following research questions:

1.1.1 Research Question

What is the role of litter within the aboveground carbon stock of dipterocarp forest in Sabah, and how is it affected by fragmentation or logging history?

- *What is the current amount of biomass present in the litter layer of forest fragments embedded within oil palm plantations in Sabah?*
- *Is there a relation between the size of the fragments and the litter carbon stock present, and if so, how are they related?*
- *Is there a relation between the size of the fragments and the fine woody debris carbon stock present, and if so, how are they related?*
- *Is there a difference in carbon stock of the litter layer of logged and unlogged forests?*

1.1.2 Hypotheses

According to the literature study prior to collecting field data we formulated the following hypotheses we were going to test:

- *The biomass present in the litter layer are approximately 5-10 Mg/ha as seen in similar studies on litter standing crop* (Hughes et al., 1999; Proctor et al., 1983)
- *Fragmented forests are impacted by biomass distribution from large trees to smaller trees, woody debris and litter* (Nascimento & Laurance, 2004). *As a result, smaller forest fragments contain higher carbon stocks in the litter layer of the fragment.*
- *There is relation between the size of forest fragments and the fine woody debris carbon stock, with higher FWD carbon stocks in smaller forest fragments.*
- *There is a difference in the carbon stock of the litter layer between logged and unlogged forests; the litter layer in previously logged forests contains a higher carbon content than unlogged forests.*

In this report we start by describing the methodology that was designed to answer the research questions. The results then display a dry representation of the outcome of the field data manipulated with calculations and statistical analysis. These results are then explained further and discussed in relation with other studies in the discussion. Additionally, the discussion describes the limitations that we encountered and how similar studies could be improved. The conclusion and recommendations sum the most important findings and how these could impact management practices. References and appendices can be found in the final part of the report.

2. Method

2.1 Area description

All forest fragments that were studied are located within the Malaysian state of Sabah, on the north-eastern part of Borneo and range in size between 12 and 3529 ha. Sabah has a climate that is typical of the a-seasonal tropics with mean annual temperatures of 27 °C and annual rainfall of 2800 mm (Walsh et al., 2011). The field work was carried out during June and July. It can be assumed that sampling in different seasons would not have a significant impact on the results of the research, as other studies in the same region showed no major impact on the amounts of litter present (Ogawa, 1978). The study areas consisted mostly of either old growth or disturbed mixed lowland dipterocarp forests.

The locations of the study-sites can be seen in Figure 1, with the names and coordinates displayed in Table 1. Within all fourteen of these sites, research plots have been established previously and several studies have been carried out at those exact plot locations, including research on leaf litter decomposition rates (Yeong et al., 2016b).

Six of these sites are HCVFs embedded within oil palm plantations (# 4, 5, 6, 7, 11 and 12), located at either Sabahmas - or Rekahalus plantation, owned by Wilmar International Limited (Wilmar is member of RSPO since 2005). These HCVFs have been gazetted in the 1990s during the conversion of land into oil palm plantation. These sites have been logged over the past decades. Initially these areas were not converted to plantation due to unsuitable characteristics for agricultural exploitation such as infertile soil or steep slopes. The HCVFs have usually been logged in the past decades and are generally located at sites less suitable for oil palm production. Other fragments, called Virgin Jungle Reserves (VJRs), have been protected by the Forestry Department (Tawatao et al., 2014) and are assumed to be unlogged since the VJR label was applied. These sites are generally in a better state than the HCVFs but small scale illegal logging may still have taken place in these areas. The fragmented areas (HCVFs and VJRs) are also compared with continuous forest (CF) that has been logged.

The six VJR sites that were included in the study (# 1, 2, 3, 8, 9 and 10), have been protected by the Forestry Department in their current status of Class VI Forest Reserves since 1984. The VJRs are primarily intended for research and biodiversity conservation (Sabah Forestry Department, 2005a). A table with description of the different forest reserve classes can be found in Appendix VIII; and Appendix IX shows a map of Sabah with the locations of these forest reserves in 2015 (Sabah Forestry Department, 2015a). The Forestry Department has changed the classification of some of these sites over time. Keruak for example, a site located near Kota Kinabatangan, was first gazetted in 1930, then classified as a class IV forest for the protection of bird nests in 1935, placed under class III Domestic Forest in 1948, classified as class I for the protection of aesthetic, archaeological or historical values and finally re-gazetted as class VI (Virgin Jungle Reserve). Currently, Keruak is also used by locals for wood and edible nest collection and eco-tourism in addition to research and biodiversity conservation (Sabah Forestry Department, 2005b). The situations are similar for the other VJRs.

The two remaining sites were located at Malua Forest Reserve (# 13 and 14), a selectively logged continuous forest. Malua forest reserve was logged in the 1980s and in 2003-2006, with diameter limits between 120 and 150 cm depending on the species (Reynolds et al., 2011). This location serves as comparison material with the smaller logged forest fragments.

2.2 Study site

Table 1: Site locations with their corresponding size, logging status and coordinates.

#	Site	Location	Area (ha)	Logged	Coordinates
1	Ulu Sapa Payau Virgin Jungle Reserve	Telupid	720	N	N5° 39.631' E117° 15.972'
2	Sapi A Virgin Jungle Reserve	Beluran	45	N	N5° 41.812' E117° 24.155'
3	Sapi C Virgin Jungle Reserve	Beluran	500	N	N5° 43.478' E117° 24.724'
4	Jatu	Rekahalus Plantation	12	Y	N5° 43.870' E117° 29.169'
5	Water Catchment	Rekahalus Plantation	120	Y	N5° 46.496' E117° 28.837'
6	Meranti	Rekahalus Plantation	30	Y	N5° 47.056' E117° 30.012'
7	Rekasar	Rekahalus Plantation	85	Y	N5° 47.864' E117° 30.085'
8	Lungmanis Virgin Jungle Reserve	Sandakan	3529	N	N5° 43.510' E117° 41.139'
9	Materis Virgin Jungle Reserve	Sukau, Kinabatangan	250	N	N5° 30.731' E118° 01.284'
10	Keruak Virgin Jungle Reserve	Sukau, Kinabatangan	220	N	N5° 30.665' E118° 17.106'
11	Yong Peng	Sabahmas Plantation	57	Y	N5° 08.071' E118° 25.641'
12	Sabasar	Sabahmas Plantation	88	Y	N5° 08.338' E118° 26.523'
13	Malua B - Gate	Malue Forest Reserve	Continuous	Y	N5° 07.141' E117° 40.497'
14	Malua A - Near SBE	Malue Forest Reserve	Continuous	Y	N5° 05.718' E117° 39.994'

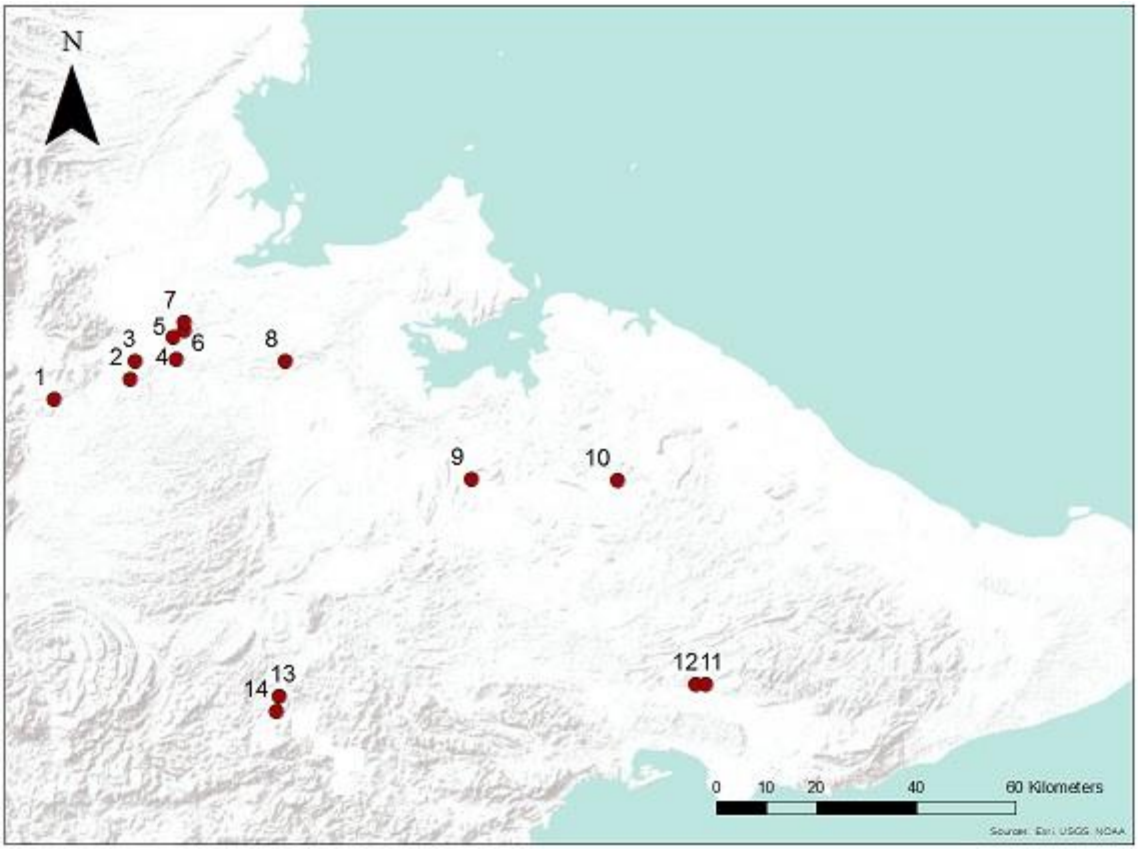

Figure 1: Plot locations depicted in a map of South-eastern Sabah (Esri, 2016)***. Most of the fragments are located within a landscape of oil palm plantations, sites 13 and 14 are located in continuous logged forest.***

2.3 Data collection

The litter standing stock was measured by collecting litter samples, converting the biomass weight to carbon content and extrapolating the outcome to values per hectare. The litter layer was defined according to the greenhouse gas inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC). The IPCC guidelines define litter as an organic horizon (all leaves, twigs, small branches, fruits, flowers, roots, and bark) on the mineral soil surface (IPCC, 2006). Basically this includes all dead organic matter on top of the mineral soil layer except large biomass fractions. Definitions of the sizes of litter fractions vary, the most commonly used classification was applied in this study: course woody debris includes all downed woody debris with a minimum diameter of 10 centimeter (cm) at the widest point, the downed woody debris with a diameter of 1-10 cm is defined as fine or small woody debris (FWD), and everything below 1 cm diameter is considered litter (Ugawa et al., 2012; Yan et al., 2006).

Three litter samples were collected and weighed at each of the plots (20 x 50 meter (m) for tree and liana sampling), 7 m from the center in three directions (north-east, north-west and south). See Figure 2 for a schematic view of the plots. All plots are located at least 100 m within the outside borders of the fragment to minimize the influence of edge effects.

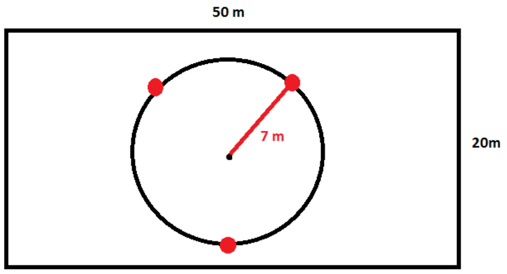

Figure 2: The plot design with three sampling points located at a distance of 7 meters from the centre.

The samples were collected from 30 x 30 cm square quadrants (900 cm^2). The samples included all litter on top of the soil as defined by IPCC. Litter pieces such as leaves or branches that crossed the border of the quadrant were cut in two pieces to include only the parts that were located within the 30 x 30 cm quadrant. Any soil particles and living biomass present within the litter layer were excluded from the samples wherever possible. The slope was measured using a clinometer at three points per plot.

The samples were collected and weighed with a scale in the field, using a level to ensure proper weighing on uneven terrain. Afterwards, a composite sample of approximately 100 grams (g) was created by mixing the three weighed samples. The surplus of collected litter was returned to the forest floor. The mixed sample was stored in plastic bags and taken back to the field station to determine the moisture content for the calculation of biomass content. This is a standard procedure for sampling the litter standing stock carried out in many biomass inventories where accurate values of the standing stock are required (CMD UNFCCC, 2015; Pearson et al., 2005).

The mixed samples were then dried to remove the moisture and weighed afterwards to measure the dry mass. In order to assess the effectiveness of sun-drying, the samples were first sun-dried for 10 days and weighed. Afterwards, the samples were oven dried at a temperature of 70° C for at least two days to a constant weight with no excess moisture left and their weight compared with the weight after sun-drying. See appendix VI for the results of a comparison between sun- and oven drying.

One of the easiest and fastest ways to measure the litter standing stock would be to measure the litter depth and multiply this with a constant factor to get an estimate of the biomass weight. However, such a constant factor would only be valid for forests with comparable species composition and climatic conditions. This method was tested by measuring the litter depth and analysing how well the litter depth correlates with the litter biomass that was calculated. The resulting factor that describes the relation between litter depth and biomass in this particular forest type and climate, could prove useful in future research on standing litter stock in the same region.

2.4 Determining Biomass and Carbon content

The fresh and dry litter weight values retrieved from the field and the lab, were stored in databases for the calculation of biomass and carbon content of the litter and FWD fractions. All biomass and carbon data was converted to units of megagrams (1 Mg = 1000 kg = 1 ton) per hectare (1 ha = 10000 m^2), allowing for easy comparison with the results of other studies. The following formula was used to calculate the litter biomass per area unit (Mg/ha):

B = ((Sf / Sd) * Sm * 100) / A

Where:

B	=	Biomass in Mg/ha
Sm	=	Weight main sample (g)
Sf	=	Weight fresh mixed-sample (g)
Sd	=	Weight dry mixed-sample (g)
A	=	Area quadrant (cm^2) = 30 * 30 = 900

The conversion from biomass to carbon content was calculated with average carbon percentages found in other studies carried out in the same region. Burghouts (1992) found an average carbon content of 46.90 **%** in primary forest litter biomass in Danum Valley, Sabah. This value was used to determine the carbon content of litter and FWD of the sampled plots:

C = B * 0.469 where, **C** = Carbon content (Mg/ha), and **B** = Biomass (Mg/ha)

The biomass and carbon averages were calculated per sample, plot and site and were subsequently used for statistical analyses.

2.5 Statistical analysis

The data was analysed with Microsoft Excel and IBM SPSS Statistics. In Excel, T-tests and ANOVA tests were executed to check for significance of difference in litter carbon totals between sites with different logging history and category (VJR, HCVF or CF).

Regression analysis tables and graphs were created with SPSS to test how strongly the data is affected by different variables such as the fragmentation size and the logging status. Significance in the regression analyses is tested with the ANOVA model. SPSS was also used to check for the correlation between other parameters, for example to look at the correlation between litter depth and the litter carbon stock. When looking at the effect of the fragmentation size, the area size was converted to the logarithm of the size to allow for better comparison among small fragments, large fragments and continuous forest alike.

3. Results

This study looked at the carbon content of litter standing stock and fine woody debris in forest fragments of varying area size. The field data was collected during June and July 2016. In total, 46 plots were sampled at 14 different sites located in Sabah (12 forest fragments, of which 6 were HCVF's and another 6 were VJR's, 2 sites were located in logged continuous forest for comparison with the fragments). One of the forest fragments, the Water Catchment, was excluded from the results. The area was highly degraded due to liana cuttings carried out in the year prior to our visit to the plots, making the data retrieved there unsuitable to compare with data from the other forest fragments.

3.1 Biomass and carbon standing stock

The results for average biomass and carbon content of the litter layer and fine woody debris are displayed in Table 2. The average biomass content in the litter layer ranges between 6 and 8 Mg per hectare with standard deviations of around at the majority of the sites. The litter layer at Materis VJR (250 ha) contained the lowest biomass average of 4.25 Mg/ha and the smallest fragment Jatu HCVF (12 ha) showed a relatively high biomass average of 8.16 Mg/ha. At these two sites we also recorded the lowest (Materis, 6%) and highest (Jatu, 45%) average slope percentage. There is a clear difference in the average slope of the sites. The HCVF's for example, are located on slopes averaging almost 40 %, while many of the VJRs were located at slopes with averages below 20% in the sampled plots.

The average carbon stock in the litter layer was 3.1 ± 0.66 Mg/ha in the unlogged fragments (VJR), and 3.3 ± 0.43 Mg/ha in the logged fragments (HCVF). The amount of FWD biomass found in the plots are relatively low when compared with the litter layer, averaging 1.6 ± 0.63 Mg/ha.

Table 2: Average biomass and carbon values of Litter and Fine Woody Debris measured per site sorted by ascending area size of the forest and expressed in Megagram per hectare. Other parameters are the Category (either High Conservation Value Forest, Virgin Jungle Reserve or Continuous forest), Logging status, Litter Depth and the Slope percentage.

Site	Cat	Area (ha)	Logged	Litter Depth (cm)	Slope (%)	Litter Biomass (Mg/ha)	Litter Carbon (Mg/ha)	FWD Biomass (Mg/ha)	FWD Carbon (Mg/ha)
Jatu	HCVF	**12**	Yes	1.65	45	**8.16**	**3.83**	**0.99**	**0.46**
Meranti	HCVF	**30**	Yes	1.32	44	7.60	3.57	1.81	0.85
Sapi A	VJR	**45**	No	1.60	34	7.91	3.71	2.64	1.24
Yeong Peng	HCVF	**57**	Yes	1.36	40	6.07	2.85	2.06	0.97
Rekasar	HCVF	**85**	Yes	1.74	20	7.95	3.73	2.57	1.21
Sabasar	HCVF	**88**	Yes	1.23	44	6.05	2.84	1.46	0.68
Keruak	VJR	**220**	No	1.66	18	7.69	3.61	2.42	1.14
Materis	VJR	**250**	No	1.34	6	**4.25**	**1.99**	**0.95**	**0.45**
Sapi C	VJR	**500**	No	1.78	11	6.04	2.83	1.41	0.66
Ulu Sapa Payau	VJR	**720**	No	1.70	11	6.25	2.93	1.52	0.71
Lungmanis	VJR	**3529**	No	1.68	24	7.63	3.58	1.67	0.78
Malua A	CF	**∞**	Yes	1.87	32	7.85	3.68	0.63	0.29
Malua B	CF	**∞**	Yes	1.87	24	6.76	3.17	1.19	0.56

3.2 Relation between forest fragment size and litter carbon stock

The average litter carbon stocks (per hectare) show little variation between different sizes of forest fragments (see Figure 3). There is a slight increase of litter carbon stock with increasing area size, mainly due to relatively high values recorded in continuous forest (Malua Forest Reserve). Linear regression analysis between the area size and C stock confirms that there is no significant difference in the data that we collected ($R^2 = 0.016$ / $p = 0.693$). The full report of the statistical analysis in SPSS can be found in Appendix I.

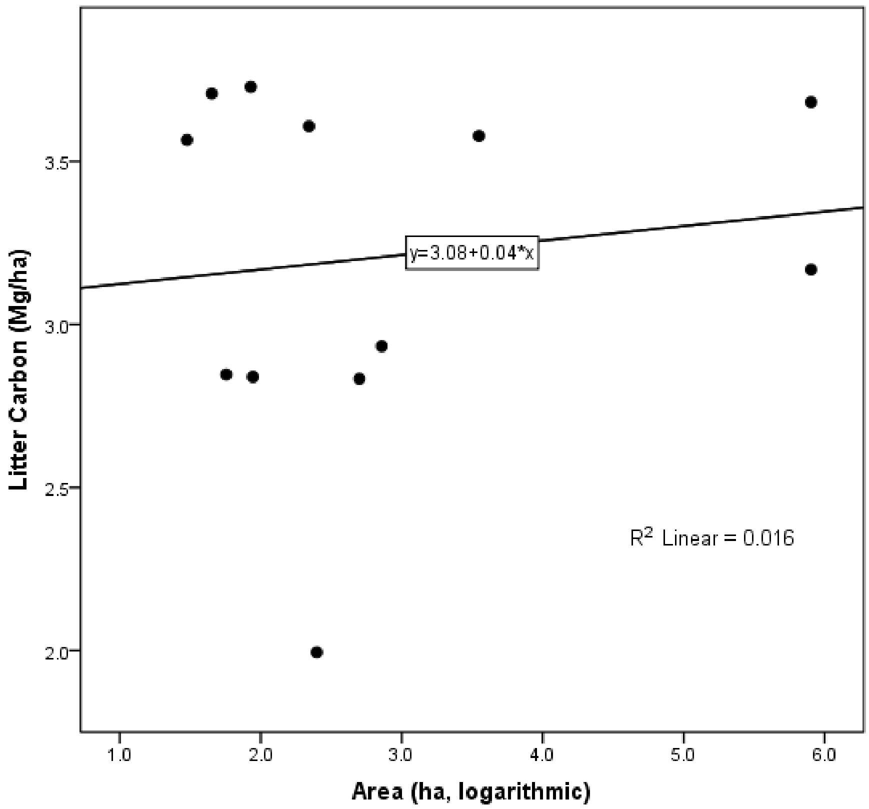

Figure 3: Linear regression of the forest fragment size compared with the average litter carbon content calculated for the site (the area size on the x-axis is displayed logarithmically to allow better comparison of the forest patches varying in size).

3.3 Logging impact on litter carbon stocks

All sampling sites have been labelled as logged or unlogged sites. The HCVF's and CF have been logged and the VJR's are considered unlogged for the past couple of decades. Single factor ANOVA tests (Microsoft Excel) were executed in Excel to look for differences in carbon content between these three different categories and yielded non-significant results. The p-values between the groups are stated below in Table 3, and the complete ANOVA report can be found in Appendix II.

Table 3: Single factor ANOVA results on litter carbon stocks between High Conservation Value Forest, Virgin Jungle Reserves and Continuous Forest.

Single factor ANOVA	**HCVF - VJR**	**VJR - CF**	**HCVF - CF**
P-value	0,5663	0,5070	0,8048

A T-test to compare the unlogged (VJR) and logged (HCVF and CF combined) sites, could also not prove a significant difference The p-value for this T-test was 0,4471 (see Appendix III).

3.4 Stepwise linear regression on litter carbon stock

Stepwise linear regression was used to compare how strongly the other variables affect the variability of the carbon content in the litter layer. Changes in R-square can be seen in Table 4. The following variables were used:

Dependent variable: C Litter (Mg/ha)
Independent variables: Area size, Slope (%), Litter Depth (cm), Tree Carbon (Mg/ha), Liana Carbon (Mg/ha), CWD Carbon (Mg/ha)

Table 4: Model summary of stepwise linear regression comparing the influence of litter depth, slope and tree carbon on the variability of the litter carbon stock.

Model Summary

					Change Statistics				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	,647[a]	,419	,405	,8487112	**,419**	30,302	1	42	,000
2	,697[b]	,485	,460	,8085938	**,066**	5,271	1	41	,027
3	,733[c]	,537	,503	,7762423	**,052**	4,489	1	40	,040
4	,768[d]	,590	,548	,7399526	**,053**	5,020	1	39	,031

a. Predictors: (Constant), Litter Depth (cm)

b. Predictors: (Constant), Litter Depth (cm), Slope (%)

c. Predictors: (Constant), Litter Depth (cm), Slope (%), Tree Carbon (Mg/ha)

d. Predictors: (Constant), Litter Depth (cm), Slope (%), Tree Carbon (Mg/ha), Area

Results of the regression indicate the strong relation with litter depth (explains 40 % of the variability in the litter carbon data), but also the slope (R^2 change of 0.066) and the amount of tree carbon (R^2 change of 0.052) are of influence. The liana and dead tree carbon amounts were excluded due to low correlation.

3.5 Litter depth

The litter depth is strongly related to the amount of litter biomass. At the sites that were sampled in this study, the conversion rate would be roughly like this: (litter biomass) = 0.56 + 3.86 * (litter depth). Statistical tests also proved this relation to be very strong (R^2 = 0.358, p = 0.000). There were no noticeable differences between logged and unlogged data, or between fragmentation categories. See Figure 4.

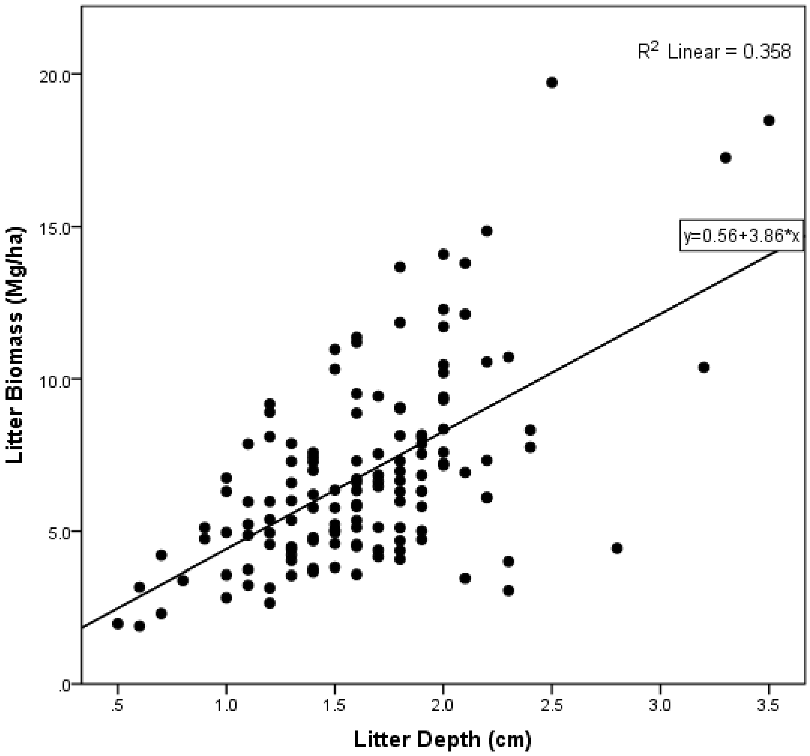

Figure 4: The litter depth and the litter biomass are strongly related. The variability increases with larger amounts of biomass and higher litter depths.

3.6 Slope percentage

The slope is of considerable influence on the litter layer. On flat land and really steep slopes the litter carbon is lowest while the highest values of litter carbon were found at slopes between 20 and 40 %. See Figure 5 and Table 5 for the statistics (R^2 = 0.686, p = 0.005).

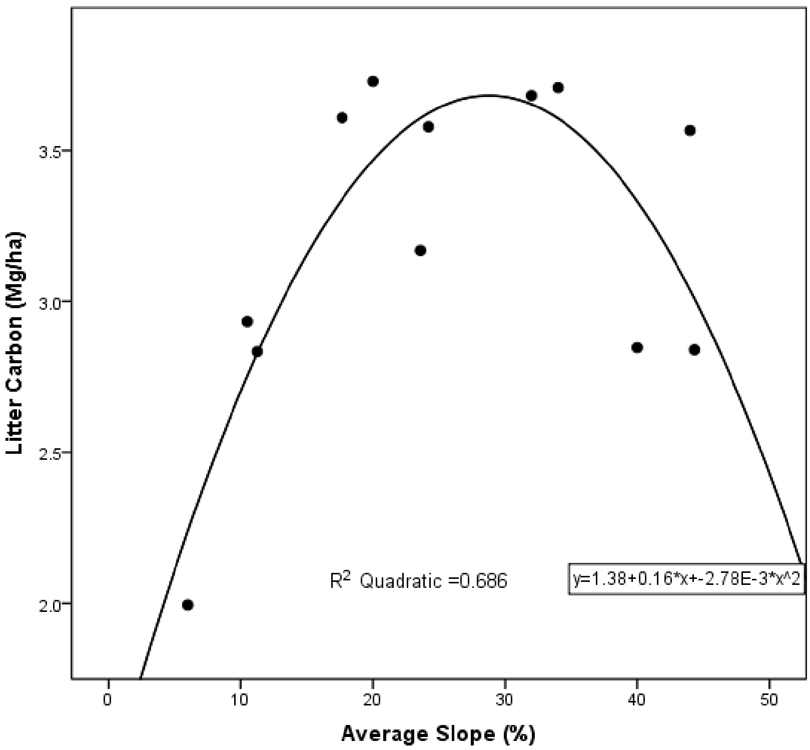

Figure 5: Quadratic trendline of Litter carbon compared with the slope. Litter carbon was highest at a medium slope between 20 and 40 %, both lower and higher slope percentages resulted in lower litter carbon stocks.

Table 5: Summary of SPSS regression statistics of litter carbon compared with the slope. Note that the R-Square is relatively high and that the model describes a significant relation between the litter carbon and the slope percentage.

Model Summary and Parameter Estimates

Dependent Variable: Litter Carbon (Mg/ha)

Equation	Model Summary					Parameter Estimates		
	R Square	F	df1	df2	**Sig.**	Constant	b1	b2
Quadratic	**.686**	9.823	2	9	**.005**	1.380	.160	-.003

The independent variable is Slope (%).

3.7 Relation between forest fragment size and Fine Woody Debris

The fine woody debris carbon stock is negatively related with the area size ($R^2 = 0.509$, $p = 0.008$), see Appendix IV for the SPSS. This means that the FWD carbon stock is decreasing with increasing fragment size. The continuous forest and largest fragments contained far lower amounts of FWD on the forest floor than the smaller fragments.

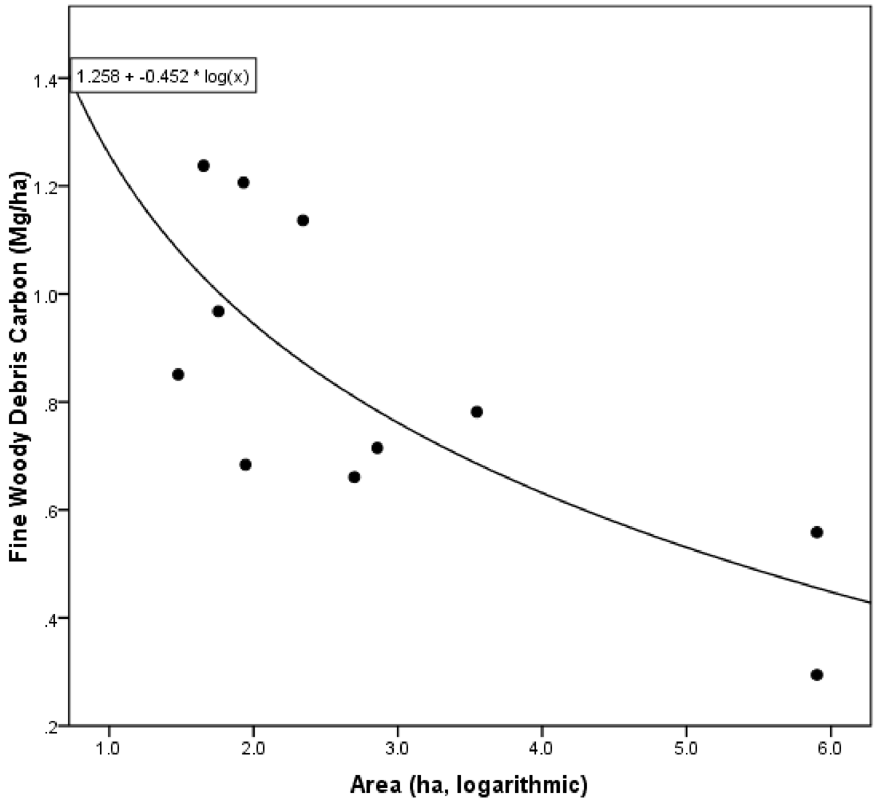

Figure 6: Logarithmic regression of the FWD carbon content compared with the forest fragment size on a logarithmic scale. The FWD carbon stock is negatively affected by the area size of the fragments.

3.8 Total Aboveground Carbon

The total aboveground carbon stock includes carbon stocks of other aboveground forest compartment such as the live trees, lianas and course woody debris. Figure 7 shows the total amounts of the AGC stock of all forest components that we measured. While it is clear that the live tree carbon is the largest component, it is also obvious that the percentage of carbon in dead biomass is a lot higher in the smallest fragments than in the larger fragments and the continuous forest. This can be seen in more detail in the following SPSS graphs (Figure 8 and Figure 9); those graphs display the litter proportion and FWD proportion of the AGC against the area size.

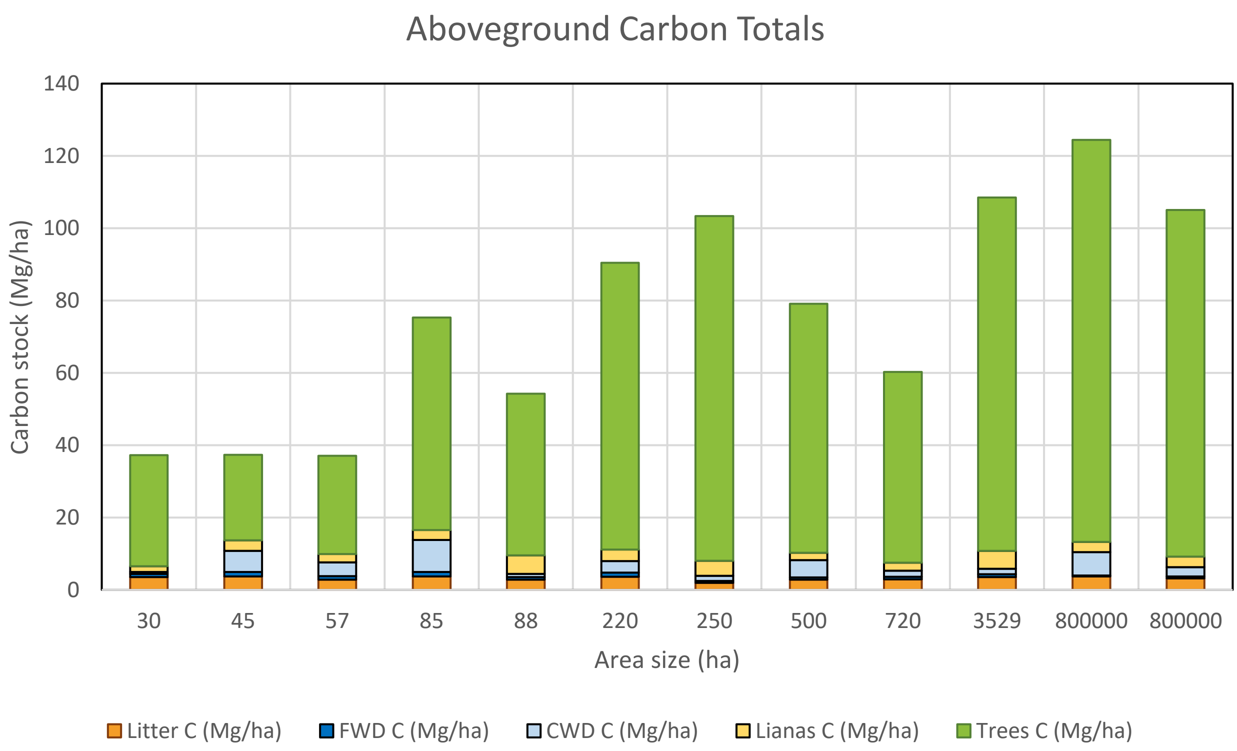

Figure 7: The totals of Aboveground Carbon per forest compartment measured at each of the sites. The forest components displayed are (from bottom to top): Litter (orange), Fine Woody Debris (dark blue), Course Woody Debris (light blue), Lianas (yellow) and Live Trees (green).

3.8.1 Litter percentage of AGC

The percentage of the aboveground carbon stock that is represented by the litter standing stock is related to the fragment size. Figure 8 displays the logarithmic trendline that describes this relation. The highest proportions of litter carbon were found in the smallest fragments, and the proportion decreases gradually with increasing area size. This relation was tested in SPSS with a logarithmic curve estimation of the regression and proved to be significant ($R^2 = 0.459$, $p = 0.009$ see Appendix V).

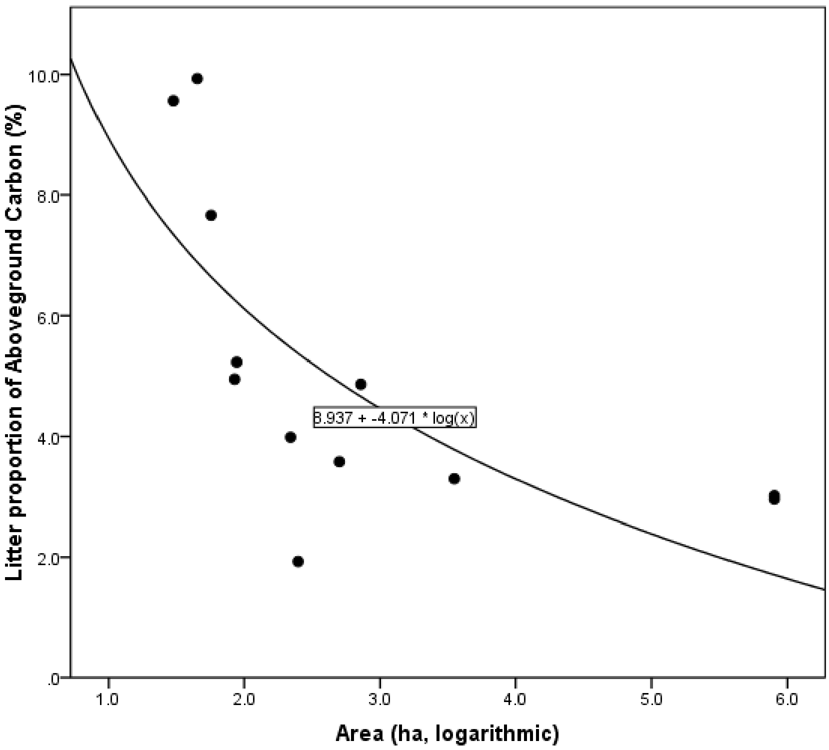

Figure 8: Logarithmic trendline of the litter proportion of the aboveground carbon expressed in percentages against the logarithmic size of the studied sites. The litter proportion of AGC decreases with increasing area size.

3.8.2 Fine Woody Debris percentage of AGC

The percentage of the aboveground carbon stock that is represented by the fine woody debris standing stock is related to the fragment size. Figure 9 displays the logarithmic trendline that describes this relation. Similar to the litter proportion, the highest proportions of FWD carbon were found in the smallest fragments, and the proportion decreases gradually with increasing area size. The relation was tested in SPSS with a logarithmic curve estimation of the regression and proved to be significant ($R^2 = 0.556$, $p = 0.003$, see Appendix VI).

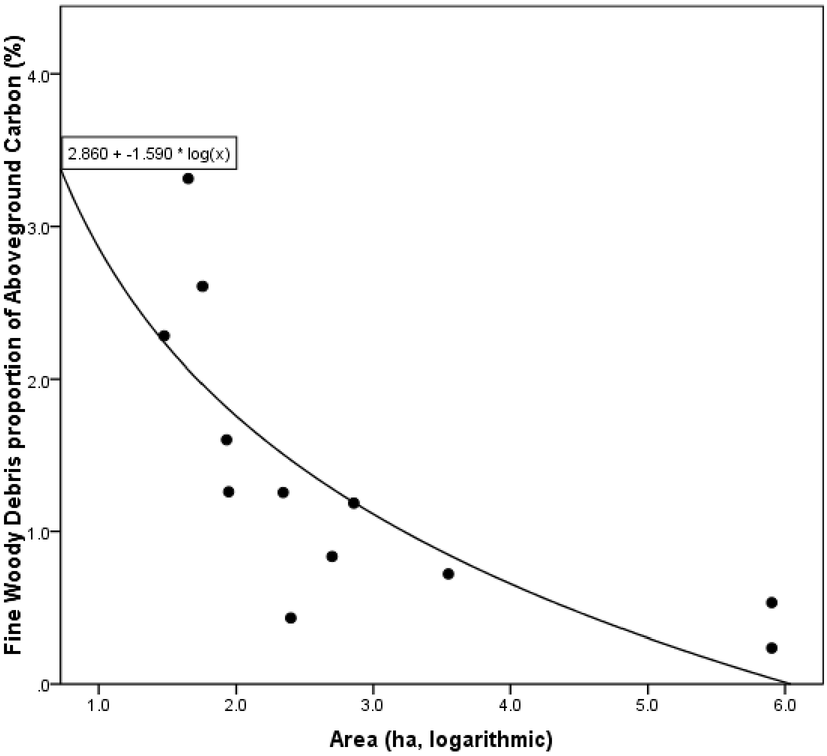

Figure 9: Logarithmic trendline of the proportion of fine woody debris as part of the aboveground carbon stock displayed in percentages against the logarithm of the area size. The FWD proportion of AGC decreases with increasing area size.

4. Discussion

In this chapter, the results of the study are discussed and compared with existing literature. Additionally, suggestions will be provided on how to improve the methodology and approach for similar studies in this field. In short, the results of the average biomass and carbon values were comparable with other lowland rainforests that have been assessed in the past. The average litter biomass content in our study area varies between 6-8 Mg/ha. Spain (1984) found a range of 5-10 Mg/ha litter biomass in both undisturbed and previously logged Australian tropical rainforest, and Nascimento & Laurance (2002) recorded 6-10 Mg/ha in undisturbed central Amazonian rainforest.

4.1 Effect of forest fragmentation on litter and fine woody debris carbon stock

Our hypothesis, stating that the litter carbon stock decreases with increasing forest fragment size, could not be supported with the results of this study. Our results suggest that there is no pattern in the litter carbon stock among forest fragments of different sizes. However, in contrast with the litter carbon stock results, the fine woody debris carbon stock did show a negative relation with forest fragment size. Fine woody debris decreased with increasing fragment size, resulting in the highest values of FWD found in small fragments. In the Amazon, similar results were found, where FWD was positively affected by disturbance of the forest, while differences in litter biomass were minimal among disturbance gradients (Berenguer et al., 2014). One of the explanations for the lack of relation between litter carbon stock and fragment size are that other factors that could not be excluded from the experimental design, such as the slope, had a similarly high effect on the litter. Causes of this disparity between litter and FWD may be explained by the fact that the litter layer can restore to its former state before disturbance faster than the FWD does, and is less impacted by the size of the forest fragment.

The forest fragments do not only vary in size but they are also surrounded by different types of landscapes (they are often surrounded by oil palm plantation area, but sometimes the fragments border to other types of areas such as tar roads, villages or rivers). The distance from one fragment to other fragments or to continuous forest is also highly variable (degree of isolation). The distance from the studied fragments to CF ranges from 6 to 69 km (Hill et al., 2011). The degree of isolation of the fragments affects the ability of animals to move and seeds to be dispersed between fragments. Isolated patches will not be able to sustain the same amount of species as fragments that are closely connected, and this will also have its effect on the carbon stock in the forest (Haddad et al., 2015).

4.2 Total aboveground carbon (trees, lianas and dead organic matter)

To compare the litter and FWD carbon stock with the total aboveground carbon stock, we make use of the data on living tree-, CWD- and liana carbon stocks that was retrieved from the same plots and during the same timeframe (Alkema, 2016; de Winter, 2016). In the smallest fragment, Jatu, we recorded exceptional high biomass values for each of the studied aboveground forest components. Because this site also contained the highest slope value observed (an average of 45%), we are inclined to assume that this site was logged less intensively and received less human-induced disturbance due to the steep terrain. Steep slopes limit the access to the area for large logging operations; and it is prohibited at to carry out logging operations at high slope percentages (Pinard & Putz, 1996). This site was not converted to palm oil plantation but instead labelled as a high conservation area, most likely because the steep slopes rendered the area unsuitable for profitable palm oil cultivation.

The aboveground carbon stock includes all dead biomass components that were measured (litter, FWD and CWD). The total aboveground carbon stock (the combined carbon stock present in living trees, dead trees, lianas and litter standing stock) ranged from about 40 Mg/ha in the smallest fragments to 120 Mg/ha in continuous forest. Living trees accounted for an average of 84% of the total, while litter represented 5.1 % on average, CWD also represented 5.3 %, FWD 1.4%, and lianas 4.5%. The tree carbon stock increased with increasing fragment size, while lianas and litter showed no clear relation with the fragment size. Therefore, the percentage of litter carbon stock of the total AGC stock did show a clear negative relationship with the size of the forest fragments. The proportion represented by litter carbon was higher in the smallest fragments and lower in the largest fragments and continuous forest. Likewise, the FWD percentages of the AGC stock were also decreasing with fragment size.

The proportion of the AGC that is comprised of dead biomass is significantly higher in the smaller fragments and disturbed (logged) forests. The percentage of aboveground carbon is displayed in Figure 10. The smallest fragments do clearly contain a larger amount of carbon in aboveground dead biomass (Litter + FWD + CWD) than the largest fragments and the continuous forest that we measured. While the carbon present in dead biomass is a relatively small pool (generally lower than 10%) in the largest fragments it can contain more than 25% of the total AGC in fragments smaller than 100ha. The litter proportion was 9.6% in the smallest fragment and 3.0% in continuous forest. With these relatively high percentages of dead biomass compared with the total AGC in the smallest fragments, it can be concluded that the forest in these fragments are in worse shape than the forest in the larger fragments.

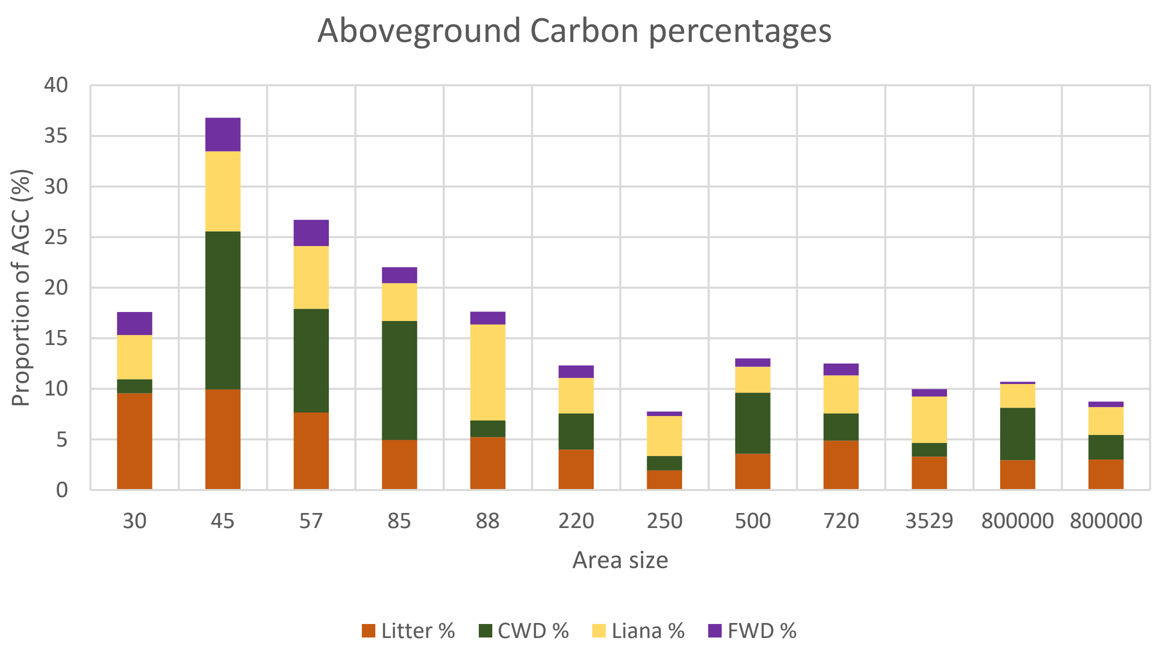

Figure 10: Graph showing the proportion of Litter, Lianas, Coarse Woody Debris and Fine Woody Debris as percentage of the total Aboveground Carbon. The remainder of the AGC consists solely of Live Trees, the largest contributor to the carbon stock.

4.3 Logging history of the forest fragments

The average litter carbon stocks were similar at logged and unlogged forest sites. No significant differences were found between the sampled sites. This was also the case for FWD carbon stocks. The HCVF sites were defined as being logged, and the VJRs and CFs as being unlogged. However, the logging history was not exactly the same for each "logged" site or for each "unlogged" site that was studied (Sabah Forestry Department, 2005a, 2005b). Logging intensity and the time since last known logging operation of the logged forests differs significantly (Yeong, 2015). In addition, some of the HCVFs (where logging was prohibited for the past decades), have had either small scale local community logging or illegal logging operations taken place (Tawatao et al., 2014). Most of the logged forest fragments have been logged intensively before fragmentation took place and this was likely done without diameter limits or slope restrictions, resulting in highly degraded forest. The unlogged sites have been labelled with various protection labels (both higher and lower protection levels) over the years before being labelled as VJR, and have experienced repeated disturbance due to fragmentation or from nearby villages (Yeong et al., 2016b). This indicates that it is difficult to compare between the sites purely based on being logged or unlogged, because different logging intensities, varying logging practices and the time since last logging operation, all affect the amount of biomass that is stored in the forest.

In this study almost all of the logged fragments were small in size (<100 ha) while the unlogged fragments were almost exclusively larger sized. It is recommended that future research primarily focussing on the influence of logging, would be carried out in a set of sites that have a more similar logging history and don't vary as much in size. That would allow for more accurate comparison between groups of logged and unlogged sites.

4.4 Slope

Our results indicate a relation where the amount of litter biomass increases with increasing slope percentage until a certain point between 20-40% slope where the amount of litter biomass starts decreasing. An explanation for this behaviour could be that the litter accumulates more on medium slopes and has a smaller contact surface with the soil than on low percentage slopes. However, if the slope percentage is very high (40% +), smaller amounts of litter can accumulate before it is transported further downward leading to less thick litter layers on steep slopes.

Other factors that are of influence are the way the area is managed based on how steep the area is. Some of the forest fragments, especially the HCVF's embedded within plantations are located mainly on steep slopes and/or mountain ridges. These and other steep slopes were probably logged less intensively in the past as low impact logging rules permitted it to prevent soil erosion and protect water quality (Pinard & Putz, 1996). In contrast, the plots sampled in continuous forest (Malua Forest Reserve) are generally less steep. Thus, more logging might have taken place in Malua than in the steeper fragments. The slope also affects the growth of plants and the species composition as well as the distribution of litterfall along the forest floor resulting in different amounts of litter standing stock present at the plots. This possibly contributes to a higher variance in the amount of litter standing stock present as there are more spots where litter accumulates and open spots, at the steepest parts of the forest where the litter is easily transported down the slope. The variance in litter biomass was a lot higher on slopes of 25% and higher (standard deviation: 1.7) than on slopes below 25% (standard deviation: 1.2), while the average biomass was almost identical.

4.5 Effect of species composition on litter and FWD

It is suggested in multiple studies that litter characteristics and processes such as litterfall and decomposition are variable among different tree species (Facelli & Pickett, 1991; Scherer-Lorenzen et al., 2007). Different tree and liana species produce varying amounts of annual litterfall and the decomposition rates are influenced by the species, due to the unique chemical composition of each species. Changes in these processes affect the quantity of litter standing stock found at the forest floor. Changes in liana abundance could also affect this, because lianas can contribute to a significant amount of the leaves produced in the forest, even if the liana carbon stock is relatively low (van der Heijden et al., 2015). However, tree species identification was incomplete and could therefore not be used for comparison with our litter data. It might prove an interesting subject for future research to look in detail at the effect of tree species on the litter standing stock, especially in relation with dominant tree species in the forest. Even though the forest fragments visited in this study all contained the same forest type, there was still a lot of diversity in the species composition and abundance per species.

The carbon content percentage of litter also tends to differ per tree species. It could explain differences in carbon content percentages of litter biomass in logged or undisturbed forests described by Burghouts (1992). To calculate the carbon content in the litter layer more accurately, the carbon percentage in biomass should be analysed at the different forests types and disturbance grades where samples were taken. The few dominant species that contribute to the majority of the litter mass may vary in the carbon percentages that they contain. Soil moisture and temperature amplitudes were not significantly affected by the species richness of canopy trees (Seidelmann et al., 2016). Litter decomposition rates were more affected by tree species richness than by topographic effects.

4.6 Topography and microclimate in relation with fragmentation

The topography of the forest is a factor that indirectly influences the decomposition rates of litter. Topography affects the duration and intensity of solar radiation, which impacts the microclimate by changing air temperature and moisture content. For example, higher decomposition rates occur on slopes facing north, than on slopes facing south or upper slope locations where the influence from solar radiation is higher (higher temperatures and lower moisture content). These factors are less pronounced in undisturbed forests or forests with dense canopies (Seidelmann et al., 2016). Thus, it future inventories should include the direction of the slopes in the general description of the plots.

Litter decomposition is mainly affected by the moisture and temperature of the forest floor. The canopy is generally less dense in fragmented and logged forests resulting in higher levels of sunlight penetrating the lower layers of the forest, increasing the temperature and evapotranspiration. The lower moisture content in the litter layer has a negative effect on the decomposition processes and makes it a less preferred habitat for many organisms that live in the litter layer. As a result the decomposition rate of litter in forest fragments is lower than in continuous forest (Yeong et al., 2016b), resulting in a longer retention time of litter on the forest floor.

The differences in microclimate on the forest floor might be the main reason of variation in amounts of litter in degraded or fragmented areas. Logged or fragmented forests receive higher amounts of solar irradiation penetrating the forest and reaching the lower parts, leading to higher air temperatures and lower moisture content in the litter and upper soil layers. In a study that was carried out at the same forest fragment sites where we sampled our data, Yeong (2015) found that the mean temperature in continuous forest was about 2 °C lower than in forest fragments, and that the soil moisture in CF was 10% higher than in fragments. The fragment size was directly related with higher air temperatures and lower moisture content in smaller fragments (Yeong et al., 2016b).

These changes had a higher impact on the litter layer than the differences in leaf traits or differences in tree species. Higher temperature alone could cause the decomposition rates to rise if there is enough moisture present, but whenever the moisture content decreases it will almost certainly result in reduced decomposition rates. This is due the fact that a lower moisture content in the air and the forest floor is less favourable for functioning of the soil fauna and other decomposers. Litterfall is also affected by microclimatic conditions, but the main drivers of changes in litterfall are rainfall and storm intensity and frequency (Paudel et al., 2015).

4.7 Biomass redistribution

In forest that have been affected by fragmentation, the quantity of biomass is partially redistributed from old/large trees to smaller trees and dead organic matter (woody debris and litter) (Nascimento & Laurance, 2004). In addition, the rate of carbon cycling is probably likely in fragmented forests, due to higher tree mortality rates and increased percentages of pioneer trees and lianas. However, this effect would be more prominent at the edges of the fragment than in the core where the influence of edge effects is a lot lower. Thus, It is expected that smaller fragments (with more edge area %) would see a higher effect of this process than the larger fragments. It results in higher amounts of litter standing stock biomass in the smallest fragments. This effect could be observed at the percentage of the litter, FWD and CWD fractions of the total aboveground carbon at the sites that we studied in Sabah. This could mostly be attributed to the lower amounts of living tree biomass with decreasing fragment size and to a lesser degree to the portion of dead biomass that was higher in large and less disturbed fragments.

Nascimento & Laurance (2004) actually also recorded increased decomposition rates near edges and more fragmented forests. They contributed these increased rates to a higher amount of pioneer species that are generally smaller and have lower wood density and lower concentrations of secondary compounds that can reduce the functionality of decomposers. The increased temperatures near edges could also enhance decomposition by increasing metabolic rates of decomposers. However, because edge effects are also known to reduce the moisture content, which has detrimental effects on the decomposition, mainly due to lower fungal activity. Decomposition rates are usually more sensitive to those changes in moisture content than to increased temperatures (Seidelmann et al., 2016).

4.8 High carbon stock and conservation value integration

The High Carbon Stock (HCS) Approach identifies and protects forest areas that contain store high amounts of carbon per hectare in a similar way as HCV areas are dealt with. Currently, the initiators of HCS and organisations involved in the palm oil industry are working on a collaborated effort to combine the methodologies into a converged approach including HCS and HCV identification (HCV Resource Network, 2017). A new HCS toolkit has been released in May 2017 and a new integrated HCV/HCS assessment manual is to be launched in June 2017, and from then on it will be compulsory for new assessments to follow the new manual. The new method could improve the effectiveness of both individual guidelines and make it more efficient for the stakeholders to make decisions and implement management practices, resulting in faster assessments and lower costs. Because larger areas can be assessed as a whole, it is easier to create corridors and networks of high value forest (for both biodiversity and carbon storage).

The HCS areas are subdivided in categories depending on the size of the core area of the forest fragment. Fragments with a core area smaller than 10ha (for 10 ha core, the total area needs to be at least 25 ha if it is shaped perfectly circular, else more) are of low priority, 10 - 100ha core are of medium priority, and >100ha core are defined as high priority patches (B. G. Rosoman, 2016).

Research on biodiversity and dipterocarp seedlings also led to recommendations by SEnSOR for a minimum size of forest fragments. To support the regeneration of dipterocarp trees, it is recommended for forest fragments to contain at least 200ha core area (100m from the border) (Lucey et al., 2016). Also, it is recommended to have a core area above 20ha to have higher biodiversity numbers than those present in palm oil plantations.

The forests patches are also identified on basis of thresholds on the estimated aboveground carbon stock. First, the ecological forest type is identified and any patch with a AGC value higher than the mean for that forest type is classified as High Density Forest (HDF), any patch with an AGC stock between 75 Mg/ha and the mean for the forest type is classified as Low Density Forest (LDF) and the patches with an AGC stock between 35 and 75 Mg/ha are considered Young Regenerating Forest (YRF) (B. G. Rosoman, 2016). Any patch with an AGC lower than 35 Mg/ha is not identified as HCS forest (but instead is called scrub - or open land).

Although promising, there are some risks involved with this integrated approach. The conversion from agricultural or degraded forest land (= low carbon stock) to palm oil plantation (= usually low-medium carbon stock) could theoretically increase the current amount of carbon stored. This integrated approach applauds such a land use conversion and allows landowners to allocate these gains in carbon stored to be removed elsewhere by conversion of forested land into plantations. The flaw here is that the current state of low carbon stock areas are decisive instead of the potential or previously held carbon stock. Degraded land might store more carbon when they are converted to palm oil plantation, but this is still a lot lower than what it could potentially store if it would be restored to its former or potential state previous to degradation.

Many of the smaller HCV fragments that we studied do not contain large forest cores and would be identified as low or medium priority patches. In addition, about half of all the fragments we visited contained lower than 75 Mg/ha AGC placing them in the category of Young regenerating forest. More importantly, some of the fragments contained carbon stocks almost equal to the lower bound of 35 Mg/ha, similar to the amount of carbon that palm oil plantations can contain at maturity (Kho & Jepsen, 2015).

4.9 Litter depth as predictor for standing biomass stock

The litter depth correlated strongly with the litter standing stock suggesting that it would be possible to use litter depth measurements for standing stock estimates of litter when time constraints do not allow for litter sample collection. Observations made by measuring the litter depth with a metal ruler are influenced by the amount of pressure applied to the litter while reading the ruler. Varying amounts of pressure applied to the litter will result in different observed values of litter depth. It is important that a constant weight is used to apply the pressure, whenever this method is used. Estimating the litter standing stock with litter depth values is a relatively inaccurate way of measuring litter, but it can be a valid option when sampling time is an issue and it is not required to obtain a high level of accuracy (as could be the case with total carbon estimates for climate models). An added benefit is that measuring the litter depth does not require any destructive sampling.

The relation between litter depth and litter biomass weight is affected by the forest type, so it is needed to have a conversion factor for the relevant forest type(s) that are studied. This conversion factor can be calculated from other studies or by carrying out a small pre-study on the litter biomass. An alternative to measuring the litter depth to predict the standing biomass stock, would be to measure the litter volume in the field and compare this with a conversion factor for the forest type to calculate the biomass (Parsons et al., 2009). This is an in-between approach that is slightly more accurate than measuring the litter depth but does require more effort and materials. The most problematic issue with both these methods is that they do not allow for a reasonable correction of the moisture content in the litter when sampling. This can lead to large overestimations of the litter biomass if the fieldwork is done while or shortly after rainfall. Our results showed that moisture in the litter layer can account for up to 70 % of the total weight of the litter sample.

4.10 Critical analysis

Multiple factors could not be excluded from having an effect on the results of the study and some improvements can be made to our methodological approach. In this chapter we discuss the methodology we used and additional influences that we could not exclude from our results. It serves as a critical analysis of our study and allows future researchers in this field to come up with improved methodologies.

4.10.1 Climate/weather:

The seasonal differences in the study area are minimal, but annual difference can still be considerable due to climatic events that don't repeatedly occur every year vary in level of intensity. Examples of such climatic events that have an effect on the litter layer, are extended dry periods (resulting in lower rates of decomposition) or local heavy weather (resulting in a higher rate of litterfall) (Spain, 1984). To gain insight in these extreme weather dynamics the fieldwork would need to be repeated over multiple years and the data to be compared with climatic and local weather information. Rainfall variability does also affect the litter layer by increasing litterfall during high intensity rainfall and decomposition by increasing the moisture content at the forest floor (Paudel et al., 2015).

4.10.2 Methodology:

The data consists of litter biomass weight measured of three 30 x 30 quadrants per plot with 3-6 plots per site. The same amount of samples was collected for FWD. The quadrant size and the number of samples per plot sufficed for estimating the litter standing stock, but the number of plots per site was too low in a few cases to account for the spatial variability of the sites. The smaller fragments (the smallest fragment was 12 ha) contained a small core area (at least 100m from the edges), making it impossible to sample a higher amount of plots while still keeping a pre-determined distance between the plots and from the edge. In some cases, access to the plots was obstructed by overgrowth of the paths or newly formed canopy gaps, essentially rendering some plots unable to be sampled or otherwise increasing the time spent to get to a specific plot. These events led to a smaller number of plots being sampled in total than we had planned beforehand. In the larger fragments it would be possible to sample more plots per site if more time would be available for field work. This should give more reliable results and give a better representation of the fragments as a whole. A higher amount of sites sampled would also allow better use of regression statistics to test the relation between different variables.

The quadrant size used for FWD sampling was the same as used for litter sampling (30 x 30), because we did not have enough time in the field at our disposal to set up larger separate FWD quadrants or transects. Recommendations for future studies would be to raise the quadrant size for FWD and the number of plots sampled in the larger forest fragments. Alternative sampling methods such as transect sampling of FWD could also prove valuable instead of quadrant sampling to estimate the average biomass.

Two different methods were used to dry the litter samples. We wanted to compare the oven drying with sun-drying because sun-drying could prove a useful substitute for oven drying whenever there is no access to an oven. It turned out that ten days of sun-drying yielded results with an average error of 13% moisture still present in the samples. Therefore, we don't recommend the use of sun-drying over conventional oven drying. A more detailed description and the results of the comparison can be found in Appendix VII.

4.10.3 Plot locations

The sampling plots that we used in this study have been sampled before for a number of other inventories. Unfortunately, some of these plots were not suitable anymore due to canopy gaps or other disturbances. Therefore, a couple of plots were excluded from this study and replaced by newly set up plots nearby. In result, the distance between the plots was sometimes lower than the pre-determined minimum of 200m. Also, because there were major differences in slope percentages between the plots, some of the variation in the samples could be attributed to the slope. To limit the influence of this factor it would be advised to avoid plots on extremely steep slopes whenever possible (decreasing the range of slope percentages of the different plots).

One of the HCV areas, the Water Catchment (site #4 in figure 1) part of the Rekahalus plantation, was not suitable for sampling due to a significantly changed forest structure. This change was caused by climber cuttings carried out in 2015. The litter layer consisted mainly of climber bamboo twigs and leaves instead of the usual mix of tree/liana twigs and leaves, and could therefore not be compared with the samples collected from other forest fragments.

4.11 Relevance to major issues
(such as climate control, deforestation, carbon storage, sustainable palm oil)

This study was conducted to gain more insight into factors that affect the carbon stocks in the litter layer and to assist in obtaining scientific knowledge that is vital for sustainable palm oil guidelines. It is clear that aboveground carbon decreases with decreasing fragment size and that the proportion of dead biomass (among which litter) becomes larger in the smallest fragments. This means that the smallest fragments are of lower quality and contain less carbon. Fragments set aside for conservation purposes should therefore be of a large enough size to support higher carbon stocks. In the greater scheme of things, it will have implications for management practices when climate or carbon storage goals have to be met. The sustainable palm oil requirements should be altered accordingly to make sure that high conservation value or high carbon stock areas are not harmed or isolated into small fragments that do not support the former carbon stock or conservation values. Together with the studies on liana, live tree and CWD studies and the ongoing studies of the SEnSOR programme this will aid in supporting changes in the policies and management guidelines for sustainable palm oil in South-East Asia.

5. Conclusion and Recommendations

5.1 Conclusion

The current amount of biomass present in the litter layer in fragmented dipterocarp forests in Sabah averages between 6 - 8 Mg/ha, with average carbon stock amounts of 3.25 ± 0.54 Mg/ha. This corresponds with most other Asian tropical forests where the litter layer was studied. The amount of FWD on the forest floor, a smaller fraction of the aboveground total, averaged at 0.5 – 2.5 Mg/ha biomass and 0.77 ± 0.30 Mg/ha carbon.

No direct relation was found between the forest fragment size and the amount of carbon stored in the litter layer. This indicates that there is either no strong effect of fragment size on litter carbon, or other factors even the effects out of such a relation.

However, totals of aboveground carbon stock per hectare (including tree, liana and litter data together), do show an increase in carbon stock with increasing fragment size. This is mostly due to the tree carbon data accounting for the vast majority of the carbon stock (living trees accounted for an average of 87,2% of the total AGC stock, while litter represented 4,2 % of the total). As a result, the proportion of litter and FWD of the total AGC stock did also clearly relate to the forest fragment size. The percentages representing litter and FWD were significantly higher in the smallest fragments (above 10%) compared with the larger fragments and the continuous forest sites (lower than 4%).

The lower amounts of total AGC and a higher proportion of dead biomass carbon in smaller fragments lead to the conclusion that small forest fragments (especially when smaller than 100 ha) are not preferred when high carbon stocks are the goal. The smallest forest fragments contained similar AGC levels as some palm oil plantations were reported to contain (~35 Mg/ha). It also means that the health of the litter layer in the smallest fragments might be harmed leading to lower turnover rates. It is hard to identify an exact number at which forest fragment size the effects become problematic, but these results can aid in making such decisions when combined with other studies.

Logging practices did not have a significant impact on the litter carbon stock in the forest fragments that we sampled. No significant difference was found between the logged sites and the unlogged sites. Because each forest fragments was of a unique size, and the logging history of each site differed; it was impossible to exclusively look at the logging impact between fragments of the same size. Future research looking at logging impact would benefit from additional sites added to the pool, for example creating paired forest fragments of a similar size that were logged and unlogged.

5.2 Recommendations

Multiple improvements can be implemented on the methodology that we used for future studies. The litter depth can be used as a tool to estimate litter standing stock values when the AGC stock needs to be estimated quickly, because the correlation is strong enough to calculate usable values. The slope orientation can have a significant effect on the litterfall and decomposition dynamics via microclimatic differences, and it would be insightful to add the slope direction as a parameter in the forest inventories to assess the differences. It is also recommended to measure the fine woody debris with larger sized quadrants or along transect lines to reduce variability. Finally, it would be interesting to gain more insight in temporal variation by repeating these studies every couple of years to see if the carbon stocks change over time and if so, how they change. If changes are found they could for example be compared with climatic data. Our study looked at the total size of forest fragments while all samples were taken in the forest core. Future studies should put more emphasize on the same effects in relation with the core area size. The outcome of such studies will increase scientific confidence to identify fragment size thresholds and management improvements help minimize the impact of oil palm plantations on forest carbon stocks and biodiversity.

It is clear that in general, small fragments support lower carbon stocks and that this also relates to ecological processes and species diversity in the forest. Small fragments are expected to have a reduced total carbon stock and a higher percentage of dead biomass than large fragments. The following recommendations can be made for management and policy making related to palm oil plantations and high conservation value forest:

- Patches that are smaller than 100 ha have relatively low potential concerning carbon stocks (similar to levels found in oil palm plantations) and have a large proportion of the carbon stored in dead biomass instead of living vegetation. Such findings are complimentary with recent research on biodiversity, which concluded that forest fragments need at least 20 ha core area to support species numbers above those found in oil palm plantations (Lucey et al., 2016).

- If possible, it should be avoided to form small isolated forest fragments, because they are likely to decrease in value immediately, and more over time.

- If forest patches are to be protected for high conservation values or high carbon stocks, priority should go at conserving larger fragments and connecting existing fragments with each other or with continuous forest.

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7. Appendices

Appendix I: Linear regression analysis between litter carbon and area size

These tables show the results of SPSS linear regression analysis between the litter carbon stock and the fragment area size. The R-Square (R^2) value indicates the amount of variance in the dependent variable (in this case Litter Carbon) that can be explained by the independent variable (in this case the Area size). R-Square ranges from 0 (no correlation) to 1 (perfect correlation). SPSS uses an ANOVA model to test for the significance of the relation between the variables, this is expressed in the p-value (the p-value is displayed under the label "Sig."). The p-value indicates the strength of the null-hypothesis, a p-value below 0.05 is required to be able to say that there is a significant relation. The results indicate that there is no significant relation between litter carbon and the area size: the p-value is 0.693, a lot higher than the required 0.05.

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Area (ha logarithmic)[b]	.	Enter

a. Dependent Variable: Litter C (Mg/ha)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.127[a]	.016	-.082	.554594109525934

a. Predictors: (Constant), Area (ha logarithmic)

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.051	1	.051	.165	**.693[b]**
	Residual	3.076	10	.308		
	Total	3.127	11			

a. Dependent Variable: Litter C (Mg/ha)

b. Predictors: (Constant), Area (ha logarithmic)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	3.080	.352		8.758	.000
	Area (ha logarithmic)	.044	.109	.127	.406	.693

a. Dependent Variable: Litter C (Mg/ha)

Appendix II: Single value ANOVA tests on **litter** carbon between HCVF, VJR and CF

ANOVA report of grouped analysis in excel displaying the differences between the litter carbon stock values found within three forest site categories HCVF, VJR and CF. The P-value is used to assess the significance of difference between the groups. A P-value below 0,05 indicates a significant difference. The amount of variance is clearly lower among the HCVF fragments than in the plots within VJR or CF.

HCVF - VJR

SUMMARY

Groups	*Count*	*Sum*	***Average***	***Variance***
HCVF	13	43.02953	**3.309964**	**0.529805**
VJR	21	65.18193	**3.103902**	**1.306381**

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	***P-value***	*F crit*
Between Groups	0.340943	1	0.340943	0.33585	**0.566293**	4.149097
Within Groups	32.48527	32	1.015165			
Total	32.82622	33				

VJR - CF

SUMMARY

Groups	*Count*	*Sum*	***Average***	***Variance***
VJR	21	65.18193	**3.103902**	**1.306381**
CF	10	34.252	**3.4252**	**2.088816**

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	***P-value***	*F crit*
Between Groups	0.699318	1	0.699318	0.451404	**0.506986**	4.182964
Within Groups	44.92696	29	1.549205			
Total	45.62628	30				

HCVF - CF

SUMMARY

Groups	*Count*	*Sum*	***Average***	***Variance***
HCVF	13	43.02953	**3.309964**	**0.529805**
CF	10	34.252	**3.4252**	**2.088816**

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	***P-value***	*F crit*
Between Groups	0.075057	1	0.075057	0.062654	**0.804781**	4.324794
Within Groups	25.157	21	1.197952			
Total	25.23206	22				

Appendix III: T-test comparing **litter** carbon stocks in unlogged and logged forest

This table contains the outcome of the t-test that compares the litter carbon values found in unlogged forest (comprising of all VJR and CF plots) with the values found in logged forest (comprised of all HCV plots). Note that the averages are very similar and that the P two-tail value is a lot higher than 0.05, so no significant difference between litter carbon in unlogged and logged forest.

t-Test: Two-Sample Assuming Equal Variances

	Unlogged	*Logged*
Mean	**3.103902**	**3.360067**
Variance	**1.306381**	**1.146912**
Observations	21	23
Pooled Variance	1.222849	
Hypothesized Mean Difference	0	
df	42	
t Stat	-0.7675	
P(T<=t) one-tail	0.223538	
t Critical one-tail	1.681952	
P(T<=t) two-tail	**0.447075**	
t Critical two-tail	2.018082	

Appendix IV: Regression analysis between **FWD** carbon stock and area size

Here are the results of SPSS analysis between FWD carbon stock and the fragment area size. The adjusted R square indicates that 40% of the FWD carbon stock data can be explained by the area size. The relation between FWD carbon stock and area size of the fragments is significant as the Sig.(= p) value is lower than 0.05 (p = 0.008).

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.747	.558	.509	.204

The independent variable is Area (ha logarithmic).

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.473	1	.473	11.375	.008
Residual	.374	9	.042		
Total	.847	10			

The independent variable is Area (ha logarithmic).

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Area (ha logarithmic))	-.452	.134	-.747	-3.373	.008
(Constant)	1.258	.142		8.868	.000

Appendix V: Regression analysis between **litter** proportion of AGC and area size

These tables display the statistics of a logarithmic trendline for the regression between litter proportion of AGC and the area size. The logarithmic trendline gives a good prediction of the data and the relation between the variables is significant.

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.713	.508	**.459**	1.931

The independent variable is Area (ha logarithmic).

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	38.456	1	38.456	10.316	**.009**
Residual	37.279	10	3.728		
Total	75.735	11			

The independent variable is Area (ha logarithmic).

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
ln(Area (ha logarithmic))	-4.071	1.268	-.713	-3.212	**.009**
(Constant)	8.937	1.323		6.753	.000

Appendix VI: Regression analysis of **FWD** proportion of AGC and area size

These tables display the statistics of a logarithmic trendline for the regression between FWD proportion of AGC and the area size. The logarithmic trendline gives a good prediction of the data and the relation between the variables is highly significant.

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.772	.596	**.556**	.630

The independent variable is Area (ha logarithmic).

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	5.864	1	5.864	14.774	**.003**
Residual	3.969	10	.397		
Total	9.833	11			

The independent variable is Area (ha logarithmic).

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Area (ha logarithmic))	-1.590	.414	-.772	-3.844	**.003**
(Constant)	2.860	.432		6.624	.000

Appendix VII: Drying method comparison

All litter samples were dried using a drying oven. To allow comparison of drying methods, most of the samples were first sun-dried and weighed before oven drying. Sun-drying can be appealing when there is limited access to a drying oven or to cut logistic costs for transporting the samples to a lab.

Drying the samples without the use of an oven and using the sun instead resulted in less moisture being removed from the samples even after 10+ days of sun-drying. The average amount of extra moisture removed by drying in the oven at 70 °C was 8,16 g per sample. This means that on average the sample still contained 13% of its weight as moisture after sun-drying. With errors this large, sun-drying cannot be regarded as a suitable substitute for oven drying. This is especially the case in a tropical climate where the relative humidity is usually high.

	Sun-dried	**Oven at 70°C**	**Difference**	**Percentage**
Average dry weight	61.26 g	53.11 g	-8.16 g	**-13.32 %**

Appendix VIII: Description of Forest Reserve Classes in Sabah

Tables 7 and 8 show the description and total area of the different types of forest reserves that have been identified by the Sabah Forestry Department as of 2015. Chapter 2.1 (Area description) discusses the protection classes of forest fragments further.

Table 6: Description of the different classes of Forest Reserves in Sabah (Sabah Forestry Department, 2015a)**.**

Class	Type of Forest Reserve	Forest Function
Class I	Protection Forest	Forests conserved for the protection of watershed and maintenance of the stability of soil, water conservation, and other essential climatic and environmental factors. Logging is not permitted in these areas. There are currently 126 Forest Reserve of this class with a combined cover of 1,260,890.00 hectares throughout Sabah making up 35.48% of total PFR.
Class II	Commercial Forest	Forests allocated for harvesting to supply timber and other forest produce, contributing to the state's economy. Harvesting is carried out according to Sustainable Forest Management (SFM) principles. Collectively, there are 1,70,521.00 hectares of Commercial Forest Reserves in 29 locations throughout Sabah, making up 49.29% of total PFR.
Class III	Domestic Forest	The produce from this forest classification, including small amount of timber, is for the consumption of local communities only and commercial use is discouraged. Collectively, there are 4,673.00 hectares of Domestic Forest Reserves in 4 locations throughout Sabah, making up 0.13% of total PFR.
Class IV	Amenity Forest	Forests primarily for providing amenity and recreation to the local inhabitants. Recreational facilities may be provided in attractive sites, notably often along roadsides, within these reserves. Exotic tree species are sometimes planted to enhance the amenity value of these areas. Collectively, there are 11,149.17 hectares of Amenity Forest Reserves in 23 locations throughout Sabah thus making up 0.31% of total PFR.
Class V	Mangrove Forest	Forests for supplying of mangrove timber restoration and other forest produce to meet general demands and multi-uses. There are a number of varieties but the Rhizophora sp. is the most common species harvested, and the products range from fishing stakes to firewood and charcoal. Collectively, there are 280,002.27 hectares of Mangrove Forest Reserves in 23 locations throughout Sabah, making up 7.88% of total PFR. This type of forest may also be used for eco-tourism development.
Class VI	Virgin Jungle	Forests conserved intact strictly for forestry research purpose including biodiversity and genetic conservation. Logging is strictly prohibited in this type of forest reserve. Collectively, there are 106,812.32 hectares of Virgin Forest Reserves in 66 locations throughout Sabah, making up 3.01% of total PFR.
Class VII	Wildlife Reserve	Forests conserved primarily for the protection conservation and research of wildlife. The Sumatran Rhinoceros is one of the endangered wild animals list living in Wildlife Reserves. Logging is prohibited. There are currently 6 Wildlife Reserves with a combined area of 137,991 hectares making up 3.89% of total PFR.

Table 7: Number of Forest Reserves and total area in hectares per class for 2014 and 2015 (Sabah Forestry Department, 2015a)**.**

Class	Type of Forest Reserve	2014		2015	
		Approximate Area (Ha)	No. of Forest Reserves	Approximate Area (Ha)	No. of Forest Reserves
Class I	Protection Forest	1,038,890.00	109	1,260,098.00	126
Class II	Commercial Forest	2,033,183.00	29	1,750,521.00	29
Class III	Domestic Forest	4,673.00	4	4,673.00	4
Class IV	Amenity Forest	12,409.45	17	11,149.17	23
Class V	Mangrove Forest	281,374.56	23	280,002.27	23
Class VI	Virgin Jungle Forest	106,801.14	62	106,812.32	66
Class VII	Wildlife Reserve	137,735.00	5	137,991.00	6
Grand Total		3,615,066.15	249	3,551,246.76	277

Appendix IX: Map of Forest Reserves in Sabah, Malaysia

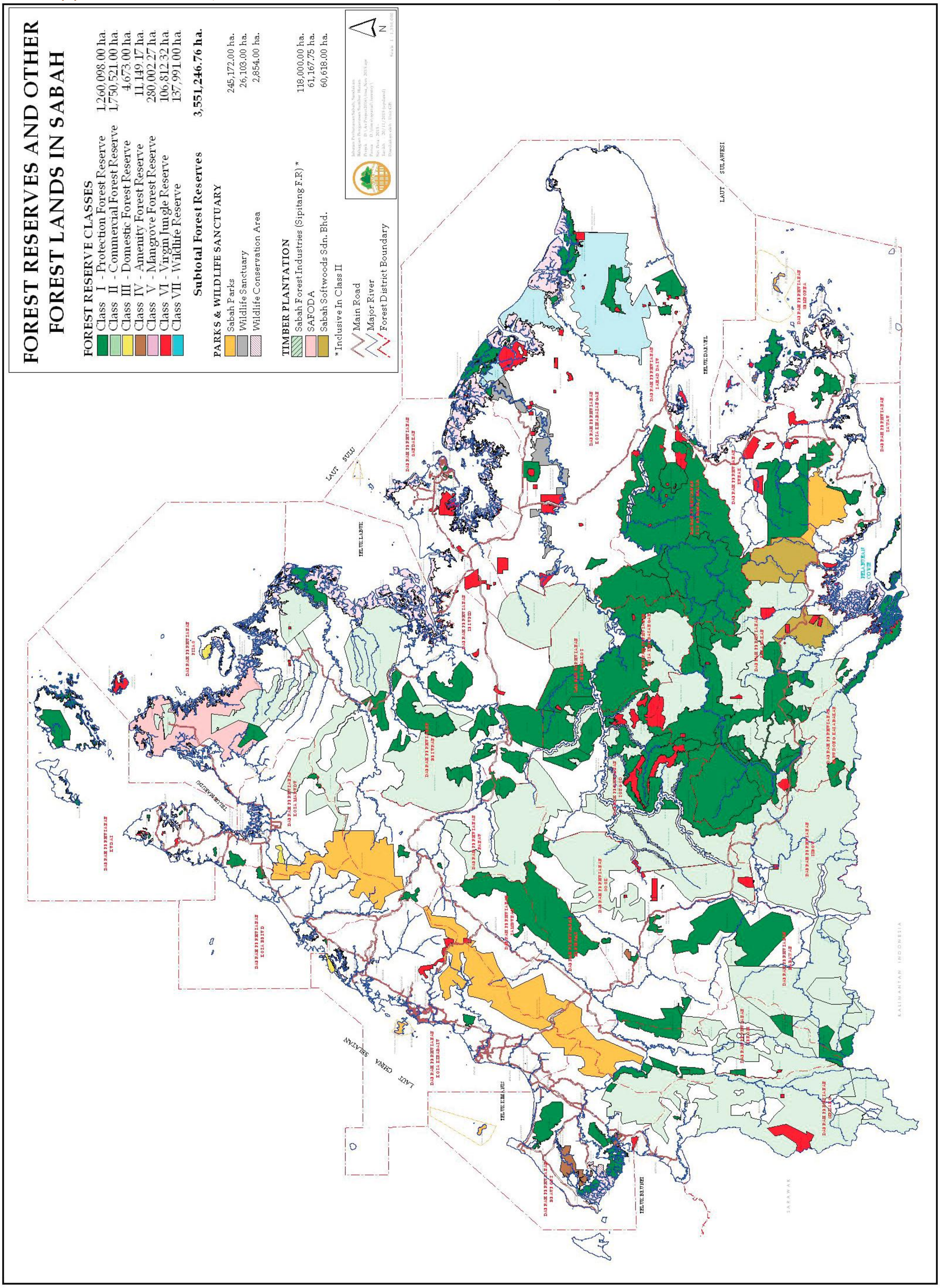

Figure 11: Map of Forest Reserves in Sabah: Malua Forest Reserve and other Class I areas are depicted in dark green, and Virgin Jungle Reserves (Class VI) are depicted in red (Sabah Forestry Department, 2015a)**.**