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CARBON STOCKS IN FOREST FRAGMENTS

THE EFFECTS OF FOREST FRAGMENT SIZE AND LOGGING ON CARBON STOCKS AND TREE MORTALITY

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THE EFFECTS OF FOREST FRAGMENT SIZE AND SELECTIVE LOGGING ON CARBON STOCKS AND TREE MORTALITY IN LOWLAND DIPTEROCARP RAINFORESTS IN SABAH, MALAYSIA

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Preface

This report has been issued by the South-East Asia Rainforest Research Program (SEARRP) as part of the Socially and Environmentally Sustainable Oil palm Research (SEnSOR) project, which aims to obtain an improved understanding of the effects and implications of sustainable oil palm agriculture. This study attempts to identify possible connections between deforestation, carbon storage and tree mortality in order to achieve improved sustainable management of High Conservation Value (HCV) areas and to gain knowledge on forest fragment dynamics in general.

Abstract

The number of primary rainforests in South-East Asia is in rapid decline since many formerly continuous forests become splintered as a result of human activities like mining, agriculture and silviculture. This study examined the effects of forest fragment size and logging on the tree carbon stocks and dead biomass proportions in lowland dipterocarp forests of Sabah, a Malaysian state on Borneo. Forest inventories were completed using plots along transects in 12 forest fragments (12 – 3529 ha) with different management histories; six locations were selectively logged before fragmentation, where the other six were undisturbed pre-fragmentation. Two continuous forest sites (~8000km^2) were included and measured as a baseline for unfragmented logged forest. Using field data from 1266 trees the total tree biomass was calculated, which was then used for carbon stock estimations per forest fragment. This resulted in a high variability of carbon stocks, ranging from 13,8 t C/ha in one of the smaller unlogged fragments (120 ha) to 111,2 t C/ha in the continuous forest. Significant differences in aboveground carbon stocks were encountered when comparing the forest fragment sizes with a multiple linear regression analysis, proving that both logged and unlogged forest fragments contained significantly lower carbon stocks as their size decreased. This analysis also showed a significant difference in aboveground carbon stocks between forests that were logged and forests that had stayed undisturbed, the latter containing higher carbon stock values. Although the same analysis concluded almost no difference in dead biomass throughout the different locations, the relative dead biomass ratios compared to living biomass (range 1,0% – 30,3%) showed very clear connections for both logging impacts and fragment size. Differences in carbon stock proportions of dead wood were highly significant ($p > 0,01$) with respect to both tested factors, with increasing dead/living biomass ratios as forest fragments became smaller or logging had occurred. Findings like these are important steps towards an improved understanding of forest dynamics, especially with human-induced disturbances. The results of this study call for alterations in future forest management as creation of additional small forest fragments should be avoided, wherever possible. The parties responsible for future forest management should attempt to abstain from timber extraction or implement less intensive logging techniques (e.g. Reduced Impact Logging). Although the effect of fragmentation and logging was measured in this study, additional sampling will be invaluable for identifying more accurate carbon stock models and formulating concrete management guidelines accordingly.

Contents

1 Introduction

1.1 General information

The last few decades the South-East Asian landscapes have been drastically altered. Pristine forests have been cleared on a large scale (Kummer & Turner, 1994), leaving the continuous rainforests splintered and compartmentalized on many locations, whereas other areas still remain relatively connected and intact. The location for this study, the Malaysian state Sabah, is one of the areas that is subject to these drastic changes and therefore shows a mosaic of different landscapes with large-scale plantations, commercial logging, mining and vast untouched primary rainforests (J. E. Bryan et al., 2013; Sodhi et al., 2010).

Forests worldwide have a substantial regulating function when it comes to carbon sequestration; the storage of carbon in organic matter through photosynthesis. With current worldwide deforestation rates accounting for up to 17% of the global carbon emissions (Baccini et al., 2012), it is crucial to understand the dynamics of carbon regulating functions of forests. Forests in the tropics offer both the highest carbon density, as a result of rapid growth, and high carbon sequestration rates (Lucey et al., 2015). The tropical zone is also subject to the highest deforestation rates worldwide, thus making it the most critical focus area for natural carbon management (Brown & Lugo, 1982).

Bornean rainforests naturally contain a high level of biodiversity, although logging operations and fragmentation have been known to seriously impact forests' species compositions (Burghouts et al., 1994; Lucey et al., 2015). The native forests of Sabah are predominantly lowland dipterocarp rainforests, mainly characterized by a high abundance of trees from the *Dipterocarpaceae* family, which compose the backbone of forest structure and dynamics (Campbell & Newbery, 1993). Dipterocarp trees generally produce high density wood, thus being popular timber species as well as valuable carbon storing species, making logging history a substantial variable in carbon stock analyses (King et al., 2006). Disturbed forests have been known to contain a higher number of climbers and pioneer tree species with low wood density, as a result of higher light penetration (Burghouts et al., 1994). Forest disturbances like logging and fragmentation can also substantially affect other ecosystem services like soil preservation, water uptake and nutrient cycling, if not controlled sustainably (Acton et al., 2016; Ferraz et al., 2014).

The most prominent cause of deforestation and forest fragmentation in Malaysia is undoubtedly the increase of oil palm *(Elaeis guineensis)* cultivation (Reynolds et al., 2011). Aside from forest clearing, oil palm cultivation has been known to sometimes lead to excessive erosion, soil depletion and loss of biodiversity in its vicinity (Fitzherbert et al., 2008; D Sheil et al., 2009), factors which inevitably impact the ecosystem dynamics. An attempt to improve the sustainability of the plantations resulted in the founding of the Roundtable on Sustainable Palm Oil (RSPO), which has promoted designating and maintaining High Conservation Value (HCV) areas. These areas have regularly been adopted to form a natural buffer zone in the proximity of a plantation and prevent loss of biodiversity, while ensuring additional conversion from natural vegetation to oil palm (Edwards et al., 2010). Albeit valuable, these areas often remain merely fragments of previously vast forests as degradation has already occurred and rehabilitation is a slow process.

Fragmentation has been proven to lead to changes in microclimate, species richness and overall forest resilience. It therefore affects ecosystem dynamics and biological mechanisms like carbon sequestration and nutrient availability (W. F. Laurance et al., 2011; Yeong et al., 2016). These fragmentation-based alterations are recurrently connected to an enhanced edge effect; the influence of climatic factors on the forest's outer edges. This often leads to relatively high wind speeds, elevated sunlight intensities and rainfall penetration changes (D'Angelo et al., 2004). Even though most intense influences are confined to the outer 100m from forest edges, some effects can penetrate up to 2-3km into the forest in extreme conditions, thus heavily affecting smaller fragments (Cochrane & Laurance, 2002; W. Laurance, 2002). Considering this, the HVC areas are especially interesting sites for ecological studies.

1.2 Study importance

Problems like fragmentation and deforestation are happening on a large scale, with relatively little knowledge for improvement in nature management. Understanding forest fragment dynamics is important as a large portion of the existing forests have already been splintered and this share is likely to increase notably in the near future, with various consequences for local flora and fauna (Bennet & Saunders, 2010).

With little existing data on the exact impacts of fragmentation and logging on forest dynamics, addressing carbon stock analyses is certainly a priority. Carbon stocks do not solely encompass the fixation of greenhouse gases in organic matter, but are also often used as a health indicator for forests and regularly positively linked with biodiversity and a sound forest structure (Huston & Marland, 2003; Strassburg et al., 2010).

Researching the direct effects of forest fragmentation and logging can contribute to proper adjustments in current forest use and management. Sharing newfound insights on forest dynamics with parties responsible for land use planning, agriculture or forestry will be able to reduce or prevent environmental deterioration due to fragmentation impacts in the future.

1.3 Objective

This study aimed to assess the carbon dynamics of trees in various forest fragment sizes with different histories of human disturbance, in order to investigate whether smaller fragment sizes or higher past disturbances actually impacted the carbon stocks of the forests. The overall objective of this study was formulated accordingly:

Identify whether and how tree carbon stocks and tree mortality rates of forest fragments in an agricultural landscape are affected by fragment size and human disturbance history.

1.4 Hypotheses and research questions

Following the study objective four expected outcomes were formulated:

h1. A smaller forest fragment size leads to a reduced carbon stock per hectare in lowland dipterocarp forests

h2. Previously logged forest fragments contain lower carbon stocks than unlogged fragments of comparable size

h3. Forest fragments of a smaller size contain higher proportions of dead tree biomass compared to larger fragments

h4. The percentage of dead tree biomass is higher in previously logged forests than undisturbed forests.

In order to test the aforementioned hypotheses, the following main research questions were adopted:

r1. How are carbon stocks of lowland dipterocarp forests influenced by forest fragment size?

r2. What are the differences in carbon stocks between previously logged and unlogged forest fragments?

r3. How does forest fragment size influence the proportion of carbon contents in dead wood?

r4. What are the differences in carbon stock percentages of dead wood n logged and unlogged forest fragments?

2 Methodology

2.1 Study areas

The focus area (Sabah, Malaysia) consists of a range of forest fragments and continuous lowland dipterocarp rain forests of various sizes and different histories of human disturbance. A total of 12 forest fragments were previously selected for carbon study in HCV areas on Wilmar Ltd. plantation sites and Virgin Jungle Reserves (VJRs) of the Sabah Forestry Department (Figure 1). Inclusion of continuous forests allowed the establishment of a carbon stock and tree mortality baseline without fragmentation-caused alterations. Thus also two study sites within continuous forests of the Malua Forest Reserve were included in the field survey for data comparison purposes.

The study sites were chosen for their specific forest characteristics in order to test the variables of the research questions. Initially, the forest locations were selected on size, with fragments ranging from 12 to 3529 hectares and continuous forests of approximately 8000km^2 (see Appendix I for coordinates).

Logging history was considered for each of the study sites as a means to also include effects of logging within the forests; fragments of variable sizes were chosen with both disturbed and undisturbed management histories, a total of eight logged sites and six undisturbed sites (Table 1). The six disturbed forest fragments were selectively logged in the past decades pre-fragmentation, the remaining two sites in the continuous forests of the Malua Forest Reserve were selectively logged lastly one decade ago (2005/2006)(Reynolds et al., 2011). The undisturbed study locations had no known history of structural logging and/or other high-impact disturbances.

Table 1 Summary of the fourteen study locations per forest type, forest size and logging history

Site	Area (ha)	Location
High Conservation Value areas		**| Logged**
1. Jatu	12	Rekahalus plantation
2. Meranti	30	Rekahalus plantation
3. Yong Peng	57	Sabahmas plantation
4. Rekasar	85	Rekahalus plantation
5. Sabassar	88	Sabahmas plantation
6. Water Catchment	120	Rekahalus plantation
Virgin Jungle Reserves		**| Unlogged**
7. Sapi A	45	Sapi Plantation
8. Keruak	220	Sukau
9. Materis	250	Kota Kinabatangan
10. Sapi C	500	Sapi Plantation
11. Ulu Sapa Payau	720	Telupid
12. Lungmanis	3529	Beluran
Continuous forest		**| Logged**
13. Malua A	∞	Malua Forest Reserve
14. Malua B	∞	Malua Forest Reserve

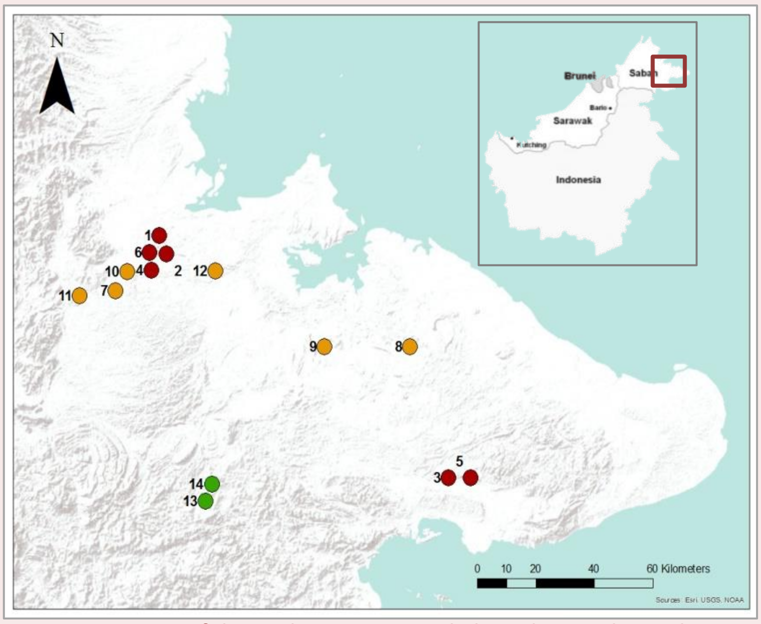

Figure 1 Locations of the study 14 areas in Sabah, Malaysia. The study areas were divided in HCV areas (red), VJR (yellow) and continuous forest (green).

2.1.1 High Conservation Value areas

The six previously logged forest fragments were located within the two oil palm plantations of Rekahalus (5352 ha) and Sabahmas (10447 ha), both operated by PPB Oil Palms Berhad (part of the Wilmar International Ltd. Group). The forest fragments were previously part of state-owned logging concessions, which were last selectively logged in the years 1985 (Rekahalus) and 1991 (Sabahmas)(Awang Ali et al., 2011; Yeong et al., 2016). After the logging a large fraction of the areas were systematically converted to plantations.

The remaining forest patches within Sabahmas received a High Conservation Value (HCV) status in 1991, and remain state owned land. The two locations visited for this study had a total area of 57 and 88 hectares and were mainly located on areas that were unfit for agricultural cultivation. The fragments are thus consistently found on hills and ridges.

The Rekahalus forest fragments were instated as HCV areas in 1995 and were either also found on locations unsuitable for oil palms or sites with otherwise important ecological functions (Awang Ali et al., 2011). A total of four study locations were found on this plantation of which three hill forests (12, 30 & 85ha) and a water catchment area (120ha).

2.1.2 Virgin Jungle Reserves

The six relatively undisturbed forest fragments in this study were located in virgin jungle reserves (VJRs). These reserves usually contain primary rainforest, which has been fragmented over the years, mainly by the expansion of surrounding plantations. VJRs have a conservation status and thus only serve educational, academic and ecological purposes, as hunting and logging is prohibited throughout the entire area (Mannan & Awang, 1997). Despite the ban on timber extraction, it is plausible that small scale illegal logging still occurred in the past decade (Yeong et al., 2016).

Two reserves were located in the vicinity of the Kinabatangan River, known for its high abundance in wildlife. Keruak VJR and Materis VJR encompassed an area of 220 and 250 hectares and were often reclassified throughout the 20th century. Where the reserves were originally classified as conservation forest in 1930, the status changed thrice (1947, 1954 and 1984), causing logging, hunting and non-timber forest product (NTFP) harvesting to be allowed sporadically. These changes in management and status have arguably had its effect on forest structure which can possibly still be detected (CAIMS, 2005a, 2005c).

Another pair of VJRs was located within the former Sungai Sapi Forest Reserve. With areas of 45 and 500 hectares they are but remnants from a previously larger forest complex of 362km^2 (CAIMS, 2005d). The reserve was officially instated as conservation forest in 1958, but lost this status twenty years later, which prompted a large scale deforestation of the reserve. In 1984 the remaining untouched forest fragments, now enclosed by plantations, were reinstated as a protection zone.

The remaining two sites are located within the Ulu Sapa Payau VJR and Lungmanis VJR, which are the largest measured fragments in this study, with areas of 720 and 3529 hectares. The Lungmanis VJR was originally part of the Segaluid-Lokan Forest Reserve, which was partially destroyed by wildfires in 1983 and subsequently locally replaced with agricultural plantations (CAIMS, 2005b). The remaining fragments received their conservation status a year after that. Even though background information was scarce, the history of the Ulu Sapa Payau VJR was assumed similar to the abovementioned reserves with no intensive logging having occurred in the past half century (CAIMS, 2005e).

2.1.3 Malua Forest Reserve

Two measurement locations in an unfragmented forest were chosen to serve as a carbon stock baseline. The study sites were located within the Malua Forest Reserve, with a total size of 340km^2, but encompassed in a continuous forest landscape of approximately 8000km^2. The size of this reserve negates any edge effects that might affect the smaller fragments, but the forest still shows signs of commercial exploitation as Malua Forest Reserve has had the most recent logging operation, albeit extensive, compared to the other sites in this study.

The Malua Forest Reserve has long been a commercial logging forest, but has not been subject to clear-cutting practices. The last two substantial logging operations were executed in 1980 and 2005-2006, the first being a selective logging (DBH ≥60cm) and the latter being a Reduced Impact Logging (RIL) with only minor disturbances to forest ecology (Healey et al., 2000; Reynolds et al., 2011). The reserve received a protection status in 2013, therefore prohibiting timber extraction for the coming years.

2.2 Study design

2.2.1 Forest inventory

Collection of carbon stock data has had a long history of different standards and various experimental methods. Classic methods of estimation mostly involve forest inventories for biomass measurements, where modern techniques allow broad carbon stock estimation using remote sensing software to analyze satellite imagery or LiDAR aerial images (Patenaude et al., 2005). Although digital carbon stock analyses are undeniably more time-efficient for large study areas, the accuracy of the data is often debated and generally considered inferior to on-site observations and measurements (Goetz & Dubayah, 2011).

As this study required delicate data measurement on relatively confined study sites (12 – 3529 ha), field observation was chosen as the most reliable method for acquiring carbon stock data. The information was gathered exclusively by conducting forest inventories, which involved measuring tree data from both living and dead trees.

2.2.2 Plot design

At each of the 14 study sites a transect line was established, with two to five measurement plots – depending on fragment size – at 200m intervals (see appendix II). Where possible, a buffer of 100m was taken from the forest edges to reduce data distortion as a result of inordinate forest edge effects. The field design for this study used rectangular plots of 20 x 50 meters, with two identical sub-plots of 20 x 10 meters on both ends of the main plot for more precise measurements (Figure 2). If the terrain proved either impassable or unsuitable for this layout, either a smaller plot of 20 x 20 meters was used or the plot was moved 100 meters further along the transect. Details per plot are provided in Appendix I.

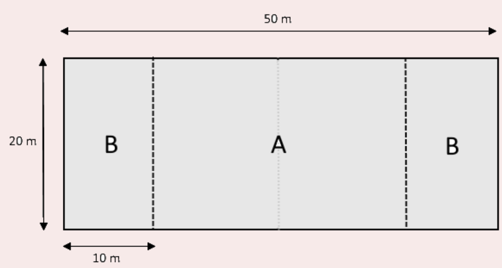

Figure 2 Measurement plot design; Trees with DBH >25 cm measured in main plot A (20 x 50m); trees with DBH >10 are measured in two sub-plots B (20 x 10m).

2.3 Field procedure

Carbon stock analyses generally include many forest components, such as climber species, undergrowth, litter and organic soil material, the measured data from this study were confined to biomass calculations from living and dead trees. Although inclusion of other carbon pools would improve the overall accuracy of the results, it would also be massively time consuming. By limiting the measurements to arboreal carbon, it allows efficient data gathering, while still addressing the largest source of carbon within the forests (Saner et al., 2012). Carbon studies often suggest monitoring biomass increment, by incorporating multiple visits for resampling over time (Clark et al., 2001). The results of this study, however, were retrieved from single-measurement observations, which was more productive given the limited timeframe.

2.3.1 Living biomass

The essential portion of the measurements consists of living tree data. The trees located within the plots were measured for their stem width using girthing tape at diameter breast height (DBH). For wood density and species composition data, the trees would need to be identified to at least genus-level by a professional local research assistant. Lastly, the total tree height (crown height) was either estimated or measured by clinometer for the biomass calculations. In many cases the species were unidentified in the field and added to a herbarium for species determination in the laboratory. For unknown tree species a default density value of 0,612 g/cm^3 was used, based on the average of the species that were identified, as suggested by Saner (2012).

In the main plot only trees with a diameter above 30 centimeters were measured, while trees with a girth exceeding 10cm were included in the two sub-plots. Diameters below 10 centimeters were not measured as this category often only makes up for less than 10% of the total biomass in mature forests. Moreover, the required data collection for smaller diameters is more time consuming due to a higher tree density and species determination issues (Brown, 2002).

For a thorough analysis of carbon stocks in trees, belowground biomass needed to be accounted for as well. Yet, given the short amount of time and means, no dedicated measurements were conducted in this study. Following Niiyama et al. (2010) a belowground/aboveground biomass ratio of 0.18 for primary dipterocarp forests was adopted, although there was no reliable way to predict this ratio for secondary forests in various stages of degradation. Therefore, to avoid inaccurate calculations based on assumptions, belowground biomass was not included in the statistical analyses and was solely used for total carbon stock calculations.

2.3.2 Dead biomass

To analyze tree mortality with respect to forest fragment size it was important to include dead standing trees, in order to calculate the total dead biomass in trees. The mortality data was then applied as a means to estimate proportions of sequestrated carbon in dead wood.

Following the procedure for living trees, standing dead trees with a DBH starting from 25cm were measured, while dead trees between 10cm and 25cm DBH were also registered in the sub-plots. As recounts were not included in this study, an estimate was made whether or not the tree had been dead for more than 1 year, based on the visible state of decomposition. Fallen trees were measured if their diameter exceeded 25cm and the tree center (at DBH) was originally based or located within the plot. A tree was excluded from the survey if it was standing outside the plot while still alive, but rather had fallen inside it afterwards.

2.4 Data analysis

2.4.1 Biomass calculations

After completion of the field work the data were used to calculate the total biomass per plot, which consequently allowed for conversion to carbon stocks. This calculation depends on parameters like wood density and local characteristics, which were adopted from existing databases and literature (Encyclopedia of Life, 2016; World Agroforestry, 2016). Different wood densities were adopted for each specific tree species identified during the forest inventory (Appendix III). A default average wood density value of 0.612 g/cm^3 was calculated with the known densities of encountered species (Slik et al., 2008), which was adopted in cases where trees could not be identified or wood density data were absent.

For this step, the above ground biomass (AGB) per tree needed to be calculated. Following Chave et al. (2005), the formula for moist forests – with annual rainfall between 1500-3500mm – was adopted;

$AGB = 0.112 \times (\rho \times D^2 \times H)^{0.916}$ *where;*

AGB = above ground biomass (kg)
ρ = wood density (g/cm^3)
D = diameter at breast height (cm)
H = total tree height (m)

2.4.2 Carbon stock estimations

When the above ground biomass of the trees had been calculated the values were converted to carbon stocks. This calculation required carbon content (*c*) of the encountered trees, therefore the mean fraction of 47.1% for tropical angiosperm trees will be adopted, as indicated by Thomas et al. (2012).

$C_t = AGB \times c$ *where;*

C_t = total carbon content (kg C)
AGB = above ground biomass (kg)
c = carbon fraction (%)

2.4.3 Tree mortality and dead biomass ratio

At this stage also dead tree biomass and carbon were calculated per dead tree encountered (<1 year). When the carbon contents of the dead trees were summed per plot, these values were extrapolated to hectares. Newbery et al. (1999) found a baseline mortality rate of 1.47% per annum within the Danum Valley reserve (DBH ≥10cm and <50cm). With this information a comparison was made between tree mortality in forest fragments and continuous forests. Additionally, dead tree biomass percentages could be compared between forest fragments and different management histories to check whether the dead/living biomass ratio was impacted.

2.4.4 Statistics

After the carbon stock and mortality calculations, the data needed to be analyzed for possible relations. Statistical analyses were executed with IBM SPSS Statistics (v22.0) and Microsoft Excel (2010) to prove whether or not the height of the present carbon stock, tree mortality and level of fragmentation were connected in logged and unlogged areas.

Regular data pairing was not possible, since none of the sizes of the logged and unlogged fragments were the identical, therefore the data needed to be analyzed for regression instead. First the data were checked for normality and variance. Afterwards, the data needed to be checked for correlation between carbon stock and fragment size, as well as the forests' carbon contents and logging history. The same method was also applied to the measured dead trees, where the dead carbon stocks and the proportions of dead/living biomass were examined per fragment area and logging history. The analyses used mostly consisted of multiple linear regression analyses, followed by additional t-tests and Analysis Of Variance (ANOVA) tests.

Lastly, the combination of the factors in a multiple linear regression needed to be investigated for collinearity in order to ensure that neither of the independent factors influenced each other significantly while testing for correlation.

3 Results

The field data were retrieved over the course of eight weeks of forest monitoring during the months June and July of 2016. On the 14 predetermined unique locations a total of 46 plots were constructed, fully covering an area of 3,46 km2 in which 1266 unique trees were measured. Of all the visited plot locations, 35 plots contained trees that presumably died less than a year ago, providing a total number of 132 dead trees. The main results will be discussed below and additionally obtained vegetation data (species compositions, main causes of tree mortality, etc.) will be included as appendices (see Appendix IV).

3.1 Forest analysis

3.1.1 Forest inventory

The data shown in Table 2 contains the raw average data for each of the fourteen visited locations. The calculated values for trees per hectare were divided in two categories, trees between 10 and 25 cm diameter and trees exceeding 25 cm DBH, since the latter usually contains the dominant portion of the aboveground biomass within a forest.

On each of the 14 locations the transect line was followed to measure at least two up until five plots, depending on the forest fragment size. The only occasion where the protocol could not be followed as initially planned was in the water catchment high conservation value area. Being the largest logged forest fragment, this area should have allowed for five measuring plots. This unfortunately had to be reduced to two plots due to intensive climber cutting management, which caused the vegetation to be heavily disturbed and therefore nearly inaccessible. The recent climber cutting operation has negatively impacted the forest structure (Tamby, pers. comm., 2016), which is visible in the measured data, such as the lower number of trees per hectare, lower canopy height and the reduced average tree diameter. For the analyses concerning fragment size, this location was excluded. Nonetheless, for all tests involving disturbance influence the site was included in the analysis.

Throughout the three different forest types, there appeared to be practically no differences in the average diameters of the trees with 21,1cm and 25,1cm average DBH in the logged and unlogged fragments and 26,6cm DBH in the continuous forests.

The canopy height and number of larger trees (DBH ≥25cm) in the fragmented forests were seemingly impacted by their size, compared to the continuous forests. Despite the fact that Malua Reserve was the most recently logged location, it still averaged 173 large trees per hectare, as compared to 112 and 134 N/ha in the logged and unlogged forest fragments, a 23-36% difference respectively.

Due to the difference in resource management in and surrounding the fragments (discussed in chapter 4.1.2), the relatively small HCV areas clearly contained the roughest terrain (average slope of 34%), as compared to only half the gradient in the VJR sites (average slope of 17%).

Table 2 Forest inventory information of the 12 forest unlogged and logged fragments and 2 continuous forest sites in Sabah

	Area (ha)	Plots	N/ha		Average DBH (cm)	Average tree height (m)	Slope (%)	Logged
			> 10 DBH <25	>25 cm DBH				
High Conservation Value areas								
Jatu	12	2	437,5	162,5	22	8,7	45	yes
Meranti	30	2	462,5	125	19,5	8,2	44	yes
Yong Peng	57	3	433,3	96,7	21,4	8,4	40	yes
Rekasar	85	3	608,3	133,3	22,6	11,0	20	yes
Sabassar	88	3	491,1	76,6	21,7	8,9	44	yes
Water Catchment	120	2	250	75	19,6	6,3	14	yes
Virgin Jungle Reserves								
Sapi A	45	2	400	87,5	17,9	7,2	34	no
Keruak	220	3	350	133,3	28,2	11,6	18	no
Materis	250	3	341,7	193,3	24,7	11,3	6	no
Sapi C	500	4	375	120	27,4	11,3	11	no
Ulu Sapa Payau	720	4	406,3	137,5	25,8	8,9	11	no
Lungmanis	3529	5	350	132	26,4	8,5	24	no
Continuous forest								
Malua A	∞	5	505	188	26,2	14,7	32	yes
Malua B	∞	5	445	158	26,9	13,8	24	yes

3.1.2 Biomass and carbon stock calculations

As dictated by Chave et al. (2005) and Thomas et al. (2012), the aboveground tree biomass and carbon stock conversions and belowground biomass conversion factors were applied to the tree data from the forest inventories. Subsequently carbon stocks were calculated per separate plot and location. Extrapolation of these values to tons (1000kg) of stored carbon per hectare allowed a fair comparison between the different study areas (Table 3; Table 4). Tree biomass and carbon stock values per separate plot are provided in Appendix V.

Table 3 Average (aboveground + belowground) tree biomass and carbon stock values per hectare for each of the three forest types assessed in this study

Forest Type	Average Biomass (t/ha)		Average Carbon Stock (t C/ha)
	10> DBH <25	>25 cm DBH	
High Conservation Value areas	34,8	74,2	51,3
Virgin Jungle Reserves	28,2	146,1	82,1
Continuous forests	49,8	209,5	122,1

As stated in the previous paragraph, the water catchment HCV area was heavily disturbed, which inevitably led to a reduced amount of aboveground biomass and therefore caused the lowest encountered carbon stock per hectare (13,82 t C/ha).

One of the plots in Jatu, the smallest logged fragment, appeared to have an unusually high carbon stock per hectare (169,1 t C/ha), compared to the second plot in that location (32,6 t C/ha) and the other HCV areas (avg. 41,3 t C/ha). The plot contained a high number of large trees, as well as the steepest average gradient (45%). This suggests that while the rest of the fragment was previously logged, this plot might have been excluded from timber extraction, possibly due to the rough terrain. Due to this uncertainty, this specific plot was left out in the analyses dedicated to logging. No plots were excluded for the statistical tests solely concerning fragment size or both size and logging.

Across the three different forest types the continuous forest contained the highest average carbon stock per hectare (122,1 t C/ha), followed by the unlogged VJRs (82,1 t C/ha) and the lowest values were found in the smallest logged fragments (51,3 t C/ha).

Table 4 Average tree biomass (for both small and larger DBH) and carbon stock calculations for each of the 14 study sites

	Area (ha)	Biomass (t/ha)		Carbon Stock (t C/ha)	Logged
		10> DBH <25	>25 cm DBH		
High Conservation Value areas					
Jatu	12	33,6	181,1	101,1	Yes
Meranti	30	29,7	47,3	36,3	Yes
Yong Peng	57	31,0	37,2	32,1	Yes
Rekasar	85	55,8	91,3	69,3	Yes
Sabassar	88	40,7	71,3	52,8	Yes
Water Catchment	120	17,6	17,0	16,3	Yes
Virgin Jungle Reserves					
Sapi A	45	23,0	36,2	27,9	No
Keruak	220	31,6	167,2	93,6	No
Materis	250	25,9	213,0	112,5	No
Sapi C	500	34,7	137,8	81,2	No
Ulu Sapa Payau	720	29,9	102,3	62,2	No
Lungmanis	3529	24,4	220,4	115,3	No
Continuous forest					
Malua A	∞	54,3	224,1	131,2	Yes
Malua B	∞	45,2	194,9	113,1	Yes

For the statistical analyses only the aboveground biomass is used, as no dedicated belowground measurements were conducted (as discussed in Chapter 2.3.1).

3.2 Fragmentation and disturbance impact on carbon stock

By using the calculated aboveground carbon stocks per location, the data were analyzed for correlation. Multiple linear regression analyses had to be conducted in order to test the predetermined hypotheses. No data transformation was applied for these analyses and no data measurements were excluded for these regressions.

The two trend lines in the scatterplot (Figure 3) were based on 11,4% (unlogged) and 32,0% (logged) of the data. A multiple linear regression analysis, (stepwise model) shows a significant correlation between forest fragment size and carbon stock of aboveground tree biomass (R^2 = 0,143 / p = 0,01). Taking potential collinearity into account, carbon stocks proved to be significantly lower in logged compared to unlogged forests (R^2 = 0,222 / p = 0,042). Full test results are included in Appendix VI.A.

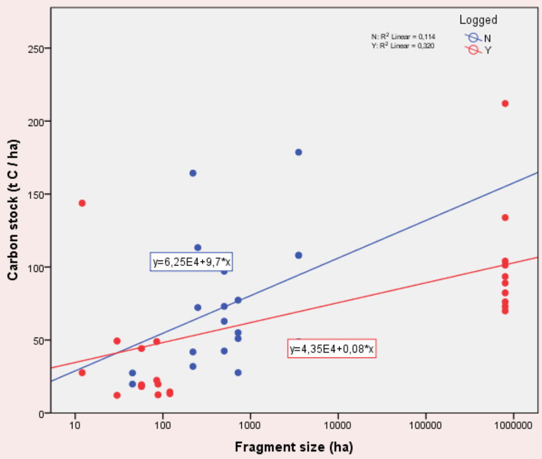

Figure 3 Scatterplot showing two regression lines for carbon stocks in both logged (green) and unlogged (blue) forest fragments of various sizes.

3.2.1 Logging impacts

The collinearity diagnostics from the linear regression analysis, as discussed in the previous paragraph, showed no significant intercorrelation (Appendix VI.A) between forest fragment size and its logging history. With these results, the influence of logging history was checked separately with a t-test, without accounting for fragment size. All measurement plots were included, except for one site in the Jatu HCV area of which the logging history is quite uncertain and was therefore considered an outlier.

Following Yeong (Yeong et al., 2016), additional tests were executed to check for differences between three forest types, instead of merely two. For these tests forest size was ignored, except for the selection of continuous forest as a separate group. The three selected groups were the logged HCV areas, the unlogged VJR and the logged continuous forest (CF). A single factor ANOVA test suggested a significant difference ($p < 0.01$) between the groups (See Appendix VI.B). Individual ANOVA tests for all three groups combined pointed out significant differences between both logged & unlogged fragments and unlogged fragments & continuous forests (Table 5).

Table 5 Single factor ANOVA results, showing correlation between carbon stocks and logging in each of three different measured forest types. HCV = High Conservation Value Area (logged), VJR = Virgin Jungle Reserve (unlogged), CF = Continuous Forest (logged). Significant differences are highlighted in green.

	HCV - VJR	VJR - CF	HCV - CF
P - value	0,043	0,082	0,002

3.2.2 Fragmentation impacts

If logging history were to be ignored, then only fragmentation impacts will be analyzed. In this case, the only viable way of analyzing correlation is by checking linear regression, since the number of measurements per fragment size was relatively low. In this analysis all plots were included except the water catchment measurements, as recent human disturbances heavily impacted the natural vegetation and forest structure, thus bearing low carbon stocks.

A linear regression line analysis showed an R-squared value of 0.197, meaning that roughly 20% of the data could confidently be confirmed following this linear formula (Figure 4). This does not meet the usual standards of confidence, however there was no evidence this has impeded the accuracy of the overall results. No data abnormality was found and homoscedasticity levels were on expected levels. The analysis showed a positive trend and proved a significant difference in carbon stock, as the forest size increases ($R^2 = 0.134$ / $p = 0.015$). The full test results are found in Appendix VI.C.

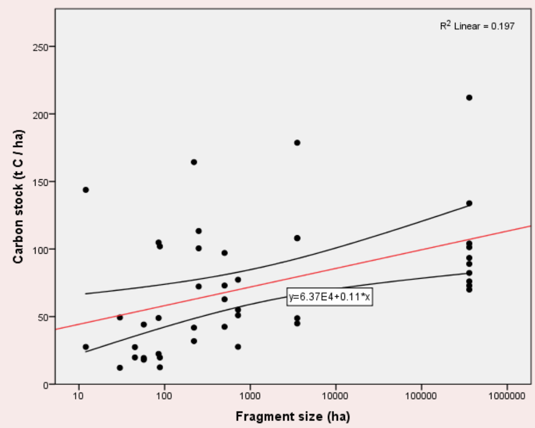

Figure 4 Linear regression displaying the correlation between forest fragment size and carbon stock of aboveground tree biomass (DBH >10cm). Dotted line = 95% confidence limit, R-square = 0.132, p = 0.015

3.3 Fragmentation impact on tree mortality

All 46 measured plots were checked for dead trees, of which the times of death were estimated. Based on these estimations all trees presumed dead for less than one year were measured and used for carbon stock calculations (Table 6).

Table 6 Dead biomass calculations (for both small and larger DBH) and tree mortality rates within the 16 study locations. Collected data were confined to recently dead trees (<1 year)

	Area (ha)	Plots	Dead trees (N/ha)	Tree Mortality (%)	Dead biomass (t/ha)		Carbon pool (%)
					10> DBH <25	DBH >25	
High Conservation Value areas							
Jatu	12	2	63	10,42	1.59	0	0.87
Meranti	30	2	200	34,04	9.86	9.94	30.28
Yong Peng	57	3	65	14,81	9.20	9.61	15.05
Rekasar	85	3	117	15,32	0.94	7.67	9.06
Sabassar	88	3	43	8,86	1.85	1.84	12.54
Water Catchment	120	2	63	17,86	2.93	5.15	13.96
Virgin Jungle Reserves							
Sapi A	45	2	75	15,38	1.75	5.10	4.06
Keruak	220	3	27	6,10	1.35	1.77	1.50
Materis	250	3	50	8,33	1.94	0	0.96
Sapi C	500	4	30	5,56	2.31	0	4.59
Ulu Sapa Payau	720	4	44	8,55	0.98	9.15	6.91
Lungmanis	3529	5	35	6,80	1.18	2.27	3.08
Continuous forest							
Malua A	∞	5	91	10,75	4.77	4.04	3.73
Malua B	∞	5	38	5,95	1.13	2.44	1.75

When a multiple linear regression analysis (Enter model) was executed (Appendix VI.D), no significant differences were detected between the amount of dead biomass and fragment size ($R^2 = 0.09$ / $p = 0.209$) or between dead biomass and logging impacts ($R^2 = 0.06$ / $p = 0.113$). So although a downward trend line is visible, the correlation is too weak to actually allocate these effects to the tested factors, instead of random influences.

3.3.1 Proportion of dead biomass per location

In order to get a better insight in the tree mortality statistics, the standing dead carbon stock was compared to the living standing carbon stock in that study area, thus calculating the percentage of dead biomass per hectare.

The scatterplot on the right (Figure 5) shows a stronger trend than the previous figure, with substantially higher confidence levels to determine the trend line. A multiple linear regression (Enter model) shows highly significant results (Appendix VI.E). The percentage of dead biomass was highly correlated to both the effects of logging ($R^2 = 0.213$ / $p = 0.007$) as well as to forest fragment size ($R^2 = 0.193$ / $p = 0.005$).

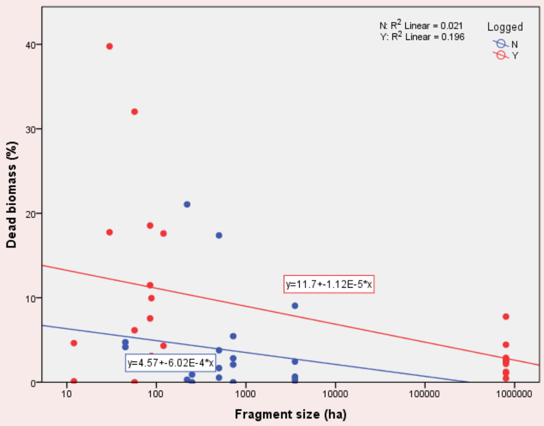

Figure 5 Scatterplot with trendlines showing the strong correlation between the percentage of dead biomass in logged and unlogged forest fragments of different sizes.

4 Discussion

4.1 Study findings

4.1.1 Influence of logging history and forest fragment size on carbon stocks

In the previous chapter, tests were performed to identify correlations of both logging and fragment size on carbon stocks of living trees (DBH ≥10 cm) within lowland dipterocarp rainforests. The most suitable way to test these influences was by conducting a linear regression analysis where both factors were included simultaneously. This analysis tries to determine a reliable trend line from the measured data to predict how high carbon stocks in different fragment sizes with different disturbance histories would be. The scatterplot in chapter 3 (Figure 3) shows two linear regression lines which both indicate a positive trend, meaning that both logged and unlogged forest patches were positively correlated with forest fragment size. The unlogged forests seem to have a slightly stronger rise in carbon stock as the forest size increased, compared to the logged forests. A multiple linear regression test, with stepwise modeling, proved the two factors to be significantly correlated to carbon stocks in living trees, therefore confirming the first two hypotheses (see Chapter 1.3).

The carbon stocks of the observed forests were proven to be significantly higher (R^2 = 0,143 / p = 0,01) in larger fragments sizes than smaller ones, as was expected when comparing these results to similar fragmentation studies in the amazon rainforest (W. F. Laurance et al., 2007; Numata et al., 2010). Numata et al (2010) found that smaller forest patches often contained significantly lower amounts of tree biomass than larger ones. This comparison is somewhat skewed as these results also included the outer forest edges, where this study avoids extreme edge effects by excluding the first 100 m of the forest fragments as hyperdynamism is often encountered in the forest edges (W. Laurance, 2002).

Logging history was also proven to be a significant driving factor (R^2 = 0,222 / p = 0,042) for reduced tree biomass and living carbon stocks in the forest fragments. The forest fragments that were logged contained significantly lower amounts of carbon per hectare – a 41% decrease – as compared to the unlogged forest patches, even after collinearity and influences of varying fragments sizes were taken into account. This corroborates with the findings of Bryan (2010) where aboveground biomass rates were found to be up to 37% lower in forests with Reduced Impact Logging (RIL), which is supposedly less intrusive than the selective logging that occurred in the fragments of this study (J. Bryan et al., 2010).

Additional single factor ANOVA tests were executed to check the validity of the regression analyses and to check for intergroup variety in carbon stocks between logged fragments, unlogged fragments and continuous forest (with RIL). Significant differences were confirmed between the logged and unlogged fragments (p = 0,043) and logged fragments and the RIL-logged Malua Forest Reserve (p = 0,002). However, the ANOVA test could not prove a significant difference between the unlogged fragments and the continuous forest (p = 0,082). Although significance would be expected here, the p-value did approach the significance level of 95%, showing a trend that could possibly be proven with additional measurements. It is also plausible that a significant difference was not found due to the influence of the forest fragment size, which was entirely omitted in these tests.

4.1.2 Influence of logging and fragmentation on tree mortality and dead aboveground biomass

To test the remaining hypotheses (h3, h4; see Chapter 1.4) dead trees with diameters larger than 10cm at breast height were also measured, in order to check for tree mortality and dead biomass in different forest fragments. A reliable estimate of annual tree mortality rates usually requires multiple measurements over time, which was unfortunately not possible given the limited timeframe for this study. Instead, an estimation of time of death was made by two independent observers to verify whether a tree had died in the past year. This method is undeniably less accurate than remeasurements (Douglas Sheil et al., 1995), which is also evident when looking at the calculated tree mortality rates (see Table 6). Annual tree mortality rates were estimated up to 44,3% in Meranti (plot M3), which is highly unlikely and surely seems to be an overestimation. These percentages also make no distinction between large or small diameters, a factor which is more crucial than simple quantity of dead trees. However, as throughout the field survey the observations were made by the same people, the deviation is likely to be consistent over all plots, which still allows a fair comparison between different sites, fragment sizes and logging history. Standing dead wood calculations within the Malua Forest Reserve (3,57 – 8,83 t C/ha) were similar to those found in previous studies by Saner (2012) (8.7 ± 3.5 t C/ha).

The first multiple linear regressions analysis (Enter model), was conducted in a similar manner as the living tree data; the standing dead biomass per hectare was calculated per plot and analyzed for correlation with respect to fragment size and logging history. No significant differences were found between the different forest types (R^2 = 0.09 / p = 0.209) or logged and unlogged forest (R^2 = 0.06 / p = 0.113). These results are similar to previous studies in continuous lowland dipterocarp forests, which failed to find any significant differences in dead carbon pools between logged and unlogged forests (Saner et al., 2012).

More interesting though, was to check how the percentage of dead biomass compared to living biomass differed between locations. A scatterplot (Figure 3) showed substantially stronger negative trends than the first dead biomass analysis. Another multiple linear regression analysis (Enter model) showed highly significant correlation between dead biomass percentage and logging (R^2 = 0.213 / p = 0.007). This disproves the null-hypothesis ($h_0$3) and shows that forest fragments contain lower proportions of dead wood as their sizes increase. The correlation with forest fragment size was proven highly significant as well with a p-value of 0,005 (R^2 = 0,193). Logged forest fragments are therefore very likely to contain substantially higher percentages of dead biomass compared to untouched forest fragments of comparable size, thus confirming the fourth hypothesis.

4.2 Comparative results on carbon stocks and tree mortality

As mentioned in Chapter 3.3 and 4.1, the found tree mortality rates were unusually high and very variable with mortality percentages ranging from 0 – 44,3%. Some measurement plots did not contain any dead trees, which causes problems when average mortality and dead trees per hectare are calculated and extrapolated. An increase in sample size will reduce the influence of outliers on the overall results when observing trees.

Newbery et al. (1999) found a baseline mortality rate for healthy lowland dipterocarp rainforest of 1,47% (DBH ≥10cm and <50cm) in the Danum Valley Reserve, a continuous unlogged forest in Sabah. Although no continuous unlogged forests were included in this study, the Malua Forest Reserve should at least approach similar values. However, the data show an average tree mortality of 8,0%, a rate which is considered catastrophic from an ecological perspective (Lugo & Scatena, 1996). The real situation though, is much less severe and it is highly unlikely that the measured forest patches were to completely die in the following 3 to 15 years. The tree mortality data were based on assumptions in the field, as the time of death was estimated, which is fairly difficult without proper repeated monitoring. Apparently the field observation caused a considerate overestimation with respect to the age of the dead trees. The dead tree biomass proportions, however, can still be deduced from the measurements as the deviation is most likely stable throughout all the observations.

Little is known of carbon stock dynamics of trees in forest fragments, so consequently no reliable carbon data could be used for comparison with this study. Saner et al. (2012) did a study on carbon stocks and fluxes in the continuous Malua Reserve, which concluded 91,6 and 16,5 tons of carbon per hectare, for above- and belowground stocks respectively. This is similar to the carbon stocks found in this study where averages of 103,5 t C/ha for aboveground carbon and 18,6 t C/ha were calculated in the Malua Reserve. This proves that, at least for the continuous forest, the field measurements provide accurate results with respect to carbon stock calculations.

The forest inventories of this study were conducted simultaneously with two similar surveys, both concerned carbon stocks in forest fragments, but with foci on lianas and litter, rather than trees (Beaujon, 2016; De Winter, 2016). The climber cut water catchment HVC area was excluded from the other studies. Figure 6 shows that each of the three studies encountered similar outliers, especially in the smallest fragment 'Jatu' (12ha) and the Ulu Sapa Payau VJR (720ha). The combined carbon stocks of the four measured factors in Malua (119,2 - 137,7 t C/ha) slightly exceed the maximum values (114,2 t C/ha) found earlier by different studies, although probably no specific climber measurements were included in those calculations (Saner et al., 2012).

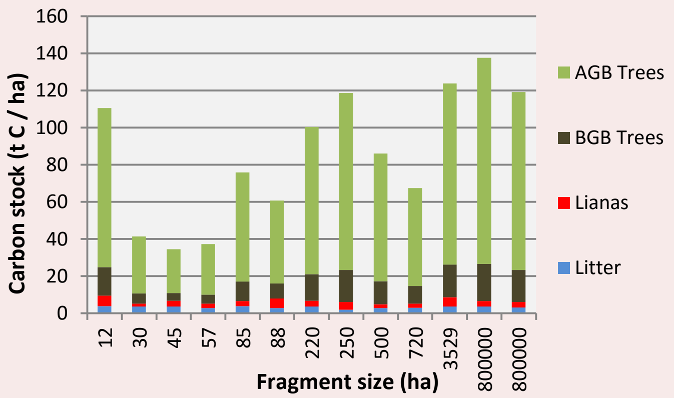

Figure 6 Combined carbon stocks of leaf litter, lianas, above- and belowground biomass of trees within forest fragments of various sizes. Liana and litter data were extracted from (Beaujon, 2016; De Winter, 2016)

4.3 Methodological limitations

4.3.1 Data quantity

The results were retrieved from data of 14 different locations, including 12 forest fragments. The forest fragments were preselected from previous studies, with logged and unlogged forests of various sizes. The only unpaired locations were the two continuous forest sites located within the Malua forest reserve, which did not have an unlogged counterpart due to the limited timeframe. The absence of continuous undisturbed forest data makes it impossible to include a reliable carbon stock baseline for the unlogged forest fragments.

Generally, the most common way of determining carbon storage is by measuring biomass increment over time through revisits of the study locations (Clark et al., 2001). The short duration of this study, however, did not allow revisits of the measurement plots. Although single measurements certainly allow for accurate biomass measurements, it does reduce the reliability of the data for future management purposes, as the annual biomass increment can only be estimated, instead of calculated.

Following Brown (2002), the data from the 20 x 50 meter plots was limited to trees with a DBH of >10 cm, since including lower diameters would be more time consuming. Under undisturbed circumstances the total biomass in the trees with <10 cm DBH should be less that 10% of the total carbon stock. However, in some previously logged or otherwise disturbed locations it could have been valuable to measure the smaller trees as well, as these sites were heavily disturbed and the proportion of lower diameters classes was larger than the higher ones. As a means to determine the value of inclusion of lower diameters in future observations every tree with DBH >1cm was measured in plots M3 and LV1 (see Appendix I). These locations were chosen for their relatively high quantity of small diameter trees as well as a low number of larger trees. Biomass calculations showed that the biomass proportions of the trees with <10 cm DBH were high, containing 21,6% and 14,9% of total aboveground biomass respectively. Therefore, these cases show that including diameters <10 cm would have definitely led to improved figures when converting the measured trees to carbon stocks.

4.3.2 Data quality

The research locations were selected with two different variables: fragment size and management history. Despite the fact that the sites were chosen carefully to minimize external influences, the results are undeniably distorted by other environmental factors.

Although every measuring plot was located within lowland rainforest, however it did not directly lead to one uniform vegetation composition. The forest fragments at Sabahmas and Jatu mainly consisted of ridge forest vegetation, which inevitably contained a vastly different vegetation structure than the larger fragments and continuous forests in relatively leveled areas. With these substantial differences in forest ecology it is debatable whether the carbon stock comparison between the various sites is fair.

Five out of six of the previously logged forest fragments were located within an oil palm landscape. Large-scale agricultural plantations have been proven to heavily influence microclimatic factors and ecological processes in the surrounding forests (Awang Ali et al., 2011; W. F. Laurance et al., 2011). This means that even though the inter-plantation locations are comparable, this could give complications for the comparison to the fragments and continuous forest locations that were not subject to the same influences.

The chosen sites within the disturbed forests were all selectively logged between 1985 and 2001. Even though the period since the last logging is known, it is not definite that the logging intensity was comparable. Differences in vegetation structure between, for example, the Jatu and Meranti HCV areas were substantial, with higher average tree heights and larger average diameters in the latter. These factors suggest different logging intensities in different forest fragments.

The biomass calculations in this study were deduced from wood densities, based on the identified trees within the measuring plots. However, in many cases (36,1%) the specific tree species could not be identified. In these cases a sample would be taken where possible. In cases that sampling was impossible an average wood density based on the identified species would be taken. It is likely that this average value was biased towards pioneer species, since the taken samples would mostly be taken from lower diameter trees. Therefore it is possible that the biomass of unidentified emergent trees was systematically underestimated by this selection bias.

4.3.3 Methodological procedure

The biomass and carbon stock calculations were based on an allometric system designed by Chave (2005), which has been widely applied in similar studies focused on aboveground biomass (Saner et al., 2012). Different allometric models have been developed in the last few years, often based on this system, but with minor to substantial alterations in the biomass regressions (Basuki et al., 2009). Even though these systems are generally used less, they are not necessarily inferior, as some have stated that the existing models often lead to overestimations in aboveground biomass calculations (Basuki et al., 2009). Since this report solely deals with newly gathered data, the exact allometric system does not influence the comparison between measurement plots. However, when comparing these carbon stock data to other studies, a different allometric system could lead to significantly different numbers.

The results from this study mainly consist of linear regression analyses, which are powerful tools for indicating correlation between factors on a continuous scale. However, for this study a non-linear scale would be expected to give more reliable results, as carbon stocks are likely to have an optimum value and would not increase infinitely with forest size as fragmentation effects wear off and become negligible. As the number of samples was relatively small (N = 46), no accurate non-linear regression could be determined, especially due to missing baseline data for the unlogged forests and missing intermediate data to fill the gaps between the smaller fragments and the continuous forests. Additional data could surely resolve this issue and improve the reliability of the trendlines that were displayed in the previous chapter.

5 Conclusions and recommendations

5.1 Conclusions and implications for forest management

This study shows that both fragment size and logging history have a significant impact on the aboveground carbon stocks of trees in the lowland rainforests of Sabah, Malaysia. Moreover, tree mortality analyses show that the fraction of dead tree biomass increased substantially as forest size declined and/or timber extraction had taken place. Although fragmentation is currently practically unavoidable while agricultural monocultures dominate the landscape, it is most crucial that the associated consequences are identified. As carbon storage is increasingly used as a means of forest preservation to negate the effects of global climate change, it is necessary to consider the carbon dynamics of the remaining forests. The future of the current rainforests is unsure if forest fragmentation persists on a similar scale. As forests become smaller the tree mortality rises, which creates a highly unstable forest structure that is less capable of handling external fluctuations in wind, temperature and other climatic factors. For future management of HCV areas and forest reserves in South-East Asia, especially in and around large-scale plantations, it is important to avoid the creation of new small forest fragments as forest structure and dynamics are heavily impacted. If carbon storage is indeed deemed an important indicator for forest management on the long term, it is also vital to abstain from timber extraction or focus on implementation of less intrusive harvesting measures (e.g. RIL) and/or intensive enrichment planting for higher carbon sequestration per hectare.

It is hard to pinpoint a specific threshold for logging intensity or optimal forest fragment size with respect to carbon stocks or tree mortality in lowland dipterocarp rainforests, as the found correlations were proven on a linear scale. Future studies can quite possibly provide more accurate insight in the specific carbon stock dynamics, knowledge that could improve future management considerably.

5.2 Recommendations for future studies

Despite the fact that this study managed to identify significant effects of forest fragment size and logging on the existing living carbon stock in trees, it is certain that additional data sampling would be highly useful. The results showed a high degree of variance, which could be (partially) negated either by measuring more plots or adding additional study sites with different fragment sizes. Thus, supplementary data could either help test and strengthen the results from this study, which would further improve the understanding of forest fragment dynamics.

The current set of plots in this study did not allow for proper paired data sampling, which impacts the number of viable analyses for the logging impacts. Potential follow-up research or future research on similar topics could benefit substantially from other measuring sites with at least reasonably comparable sizes, as far as a comparison between logged and unlogged is concerned. Another addition that could prove useful for future studies is the examination of edge-effects in forest fragments, which were not included in this study.

Some changes would also be recommended for the methodological part of future studies. The 20x50 m plots used in this study often proved difficult to measure with respect to terrain, especially in the smaller forest fragments. A revised plot layout of 20x20 m was therefore sometimes adopted and validated this method as an equally capable means of executing a reliable forest inventory, while saving time in the field. This allows for more plots or additional measurements (e.g. including DBH <10 cm) within the same timeframe. Tree identification was troublesome due to a lack of local floristic knowledge within the field team, which inevitably led to a reduced accuracy as wood density data often had to be estimated, instead of measured. No doubt a local tree spotter or botanist would have been able to provide more reliable results in the field.

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Signed, Sake Alkema

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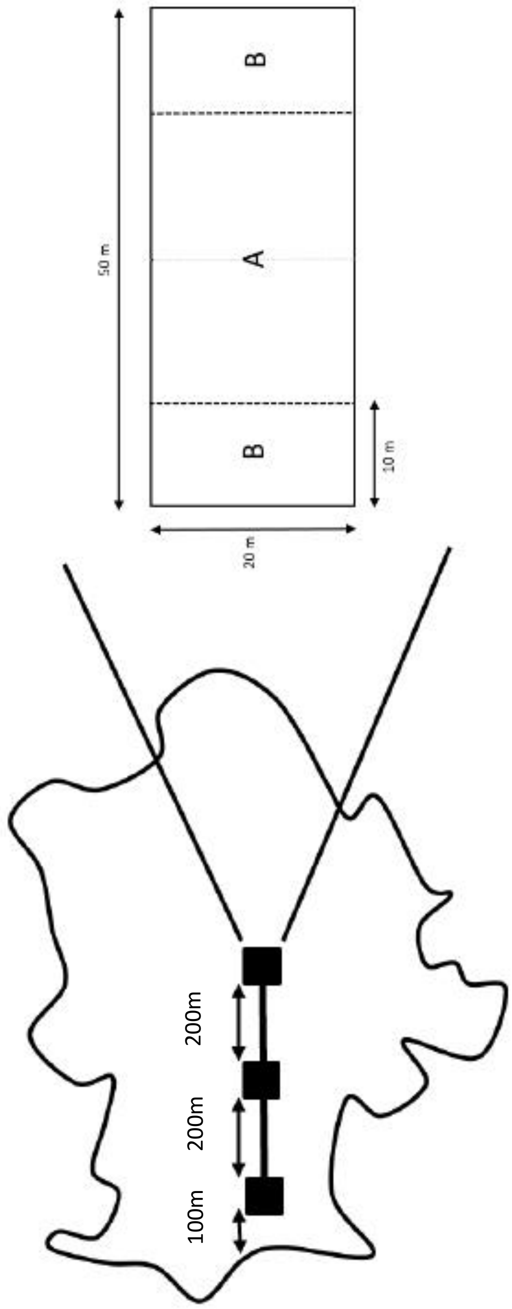
8 Appendices

Appendix I: Measurement plot information and location

Site	Location	Area (ha)	Plot	Coordinate	Logged	Fragmented
Malua A - Near SBE	Malua Forest Reserve	800.000	MA1	N5° 05.718' E117° 39.994'	Yes	No
Malua A - Near SBE	Malua Forest Reserve	800.000	MA4	N5° 05.517' E117° 40.011'	Yes	No
Malua A - Near SBE	Malua Forest Reserve	800.000	MA6	N5° 05.434' E117° 40.017'	Yes	No
Malua A - Near SBE	Malua Forest Reserve	800.000	MA8	N5° 05.333' E117° 40.045'	Yes	No
Malua A - Near SBE	Malua Forest Reserve	800.000	MA10	N5° 05.226' E117° 40.061'	Yes	No
Malua B - Gate	Malua Forest Reserve	800.000	MB1	N5° 07.141' E117° 40.497'	Yes	No
Malua B - Gate	Malua Forest Reserve	800.000	MB3	N5° 07.131' E117° 40.396'	Yes	No
Malua B - Gate	Malua Forest Reserve	800.000	MB5	N5° 07.160' E117° 40.296'	Yes	No
Malua B - Gate	Malua Forest Reserve	800.000	MB7	N5° 07.250' E117° 40.233'	Yes	No
Malua B - Gate	Malua Forest Reserve	800.000	MB9	N5° 07.325' E117° 40.159'	Yes	No
Lungmanis Virgin Jungle Reserve	Sandakan	3529	LV1	N5° 43.510' E117° 41.139'	No	Yes
Lungmanis Virgin Jungle Reserve	Sandakan	3529	LV3	N5° 43.577' E117° 41.098'	No	Yes
Lungmanis Virgin Jungle Reserve	Sandakan	3529	LV4	N5° 43.619' E117° 41.066'	No	Yes
Lungmanis Virgin Jungle Reserve	Sandakan	3529	LV5	N5° 43.657' E117° 41.039'	No	Yes
Lungmanis Virgin Jungle Reserve	Sandakan	3529	LV6	N5° 43.695' E117° 41.032'	No	Yes
Ulu Sapa Payau Virgin Jungle Reserve	Telupid	720	UV2	N5° 39.591' E117° 15.947'	No	Yes
Ulu Sapa Payau Virgin Jungle Reserve	Telupid	720	UV4	N5° 39.501' E117° 15.883'	No	Yes
Ulu Sapa Payau Virgin Jungle Reserve	Telupid	720	UV6	N5° 39.472' E117° 15.819'	No	Yes
Ulu Sapa Payau Virgin Jungle Reserve	Telupid	720	UV8	N5° 39.414' E117° 15.754'	No	Yes
Sapi C Virgin Jungle Reserve	Beluran	500	SC1	N5° 43.478' E117° 24.724'	No	Yes
Sapi C Virgin Jungle Reserve	Beluran	500	SC3	N5° 43.572' E117° 24.700'	No	Yes
Sapi C Virgin Jungle Reserve	Beluran	500	SC5	N5° 43.667' E117° 24.637'	No	Yes
Sapi C Virgin Jungle Reserve	Beluran	500	SC7	N5° 43.754' E117° 24.640'	No	Yes
Materis Virgin Jungle Reserve	Sukau, Kinabatangan	250	MV1	N5° 30.731' E118° 01.284'	No	Yes
Materis Virgin Jungle Reserve	Sukau, Kinabatangan	250	MV4	N5° 30.724' E118° 01.162'	No	Yes
Materis Virgin Jungle Reserve	Sukau, Kinabatangan	250	MV6	N5° 30.737' E118° 01.055'	No	Yes
Keruak Virgin Jungle Reserve	Sukau, Kinabatangan	220	KV1	N5° 30.665' E118° 17.106'	No	Yes
Keruak Virgin Jungle Reserve	Sukau, Kinabatangan	220	KV4	N5° 30.755' E118° 17.019'	No	Yes
Keruak Virgin Jungle Reserve	Sukau, Kinabatangan	220	KV6	N5° 30.838' E118° 16.953'	No	Yes
Water Catchment	Rekahalus Plantation	120	WC1	N5° 46.496' E117° 28.837'	Yes	Yes
Water Catchment	Rekahalus Plantation	120	WC3	N5° 46.425' E117° 28.857'	Yes	Yes
Sabasar	Sabahmas Plantation	88	SB3	N5° 08.357' E118° 26.602'	Yes	Yes
Sabasar	Sabahmas Plantation	88	SB4	N5° 08.359' E118° 26.646'	Yes	Yes
Sabasar	Sabahmas Plantation	88	SB7	N5° 08.444' E118° 26.651'	Yes	Yes
Rekasar	Rekahalus Plantation	85	R1	N5° 47.864' E117° 30.085'	Yes	Yes
Rekasar	Rekahalus Plantation	85	R3	N5° 47.903' E117° 29.996'	Yes	Yes
Rekasar	Rekahalus Plantation	85	R4	N5° 47.908' E117° 29.941'	Yes	Yes
Yong Peng	Sabahmas Plantation	57	Yp2	N5° 08.103' E118° 25.621'	Yes	Yes
Yong Peng	Sabahmas Plantation	57	YP6	N5° 08.401' E118° 25.549'	Yes	Yes
Yong Peng	Sabahmas Plantation	57	YP7	N5° 08.317' E118° 25.561'	Yes	Yes
Sapi A Virgin Jungle Reserve	Beluran	45	SA1	N5° 41.812' E117° 24.155'	No	Yes
Sapi A Virgin Jungle Reserve	Beluran	45	SA3	N5° 41.758' E117° 24.100'	No	Yes
Meranti	Rekahalus Plantation	30	M1	N5° 47.056' E117° 30.012'	Yes	Yes
Meranti	Rekahalus Plantation	30	M3	N5° 47.065' E117° 30.088'	Yes	Yes
Jatu	Rekahalus Plantation	12	J1	N5° 43.870' E117° 29.169'	Yes	Yes
Jatu	Rekahalus Plantation	12	J3	N5° 43.938' E117° 29.075'	Yes	Yes

Appendix II: Transect line and plot placement schematics

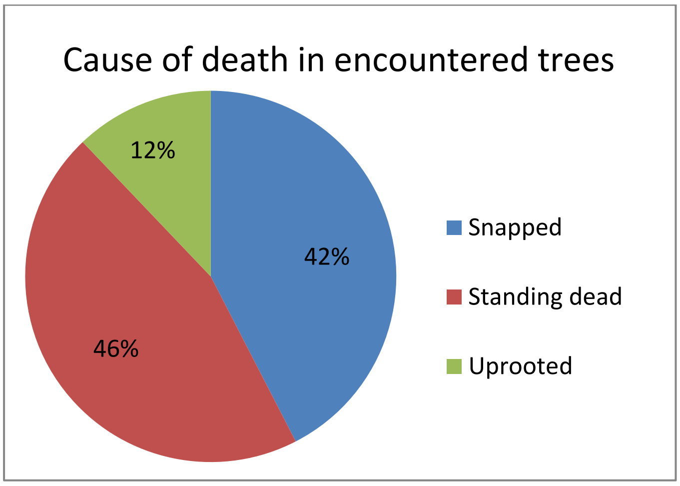


Appendix III: Encountered tree species list

ID	Scientific name	Taxonomic family	Genus	Density (g/cm3)	Source
ts1	Shorea leptoderma	Dipterocarpaceae	Shorea	0,632	http://db.worldagroforestry.org//wd/genus/Shorea
ts2	Teijsmanniodendron holophyllon	Lamiaceae	Teijsmanniodendron	0,658	http://db.worldagroforestry.org//wd/genus/Teijsmanniodendron
ts3	Macaranga tanarius	Euphorbiaceae	Macaranga	0,455	http://eol.org/pages/1155237/overview
ts4	Unknown non-Dipterocarp			0,612	
ts5	Unknown non-Dipterocarp			0,612	
ts6	Unknown non-Dipterocarp			0,612	
ts7	Ficus septica	Moraceae	Ficus	0,42	http://eol.org/pages/2906822/overview
ts8	Meiogyne virgata	Anonaceae	Meiogyne	0,75	http://db.worldagroforestry.org//wd/genus/Meiogyne
ts9	Meiogyne virgata	Anonaceae	Meiogyne	0,75	http://db.worldagroforestry.org//wd/genus/Meiogyne
ts10	Cynometra elmeri	Fabaceae	Cynometra	0,841	http://db.worldagroforestry.org//wd/genus/Cynometra
ts11	Pterospermum javanicum	Malvaceae	Pterospermum	0,4	http://eol.org/pages/6862451/overview
ts12	Streblus sp.	Moraceae	Streblus	0,755	http://db.worldagroforestry.org//wd/genus/Streblus
ts13	Hydnocarpus anomala	Achariaceae	Hydnocarpus	0,671	http://db.worldagroforestry.org//wd/genus/Hydnocarpus
ts14	Hydnocarpus sp.	Achariaceae	Hydnocarpus	0,671	http://db.worldagroforestry.org//wd/genus/Hydnocarpus
ts15	Paranephelium xestophyllum	Sapindaceae	Paranephelium	0,81	http://eol.org/pages/5631000/overview
ts16	Unknown non-Dipterocarp			0,612	
ts17	Unknown non-Dipterocarp			0,612	
ts18	Dendrocnide elliptica	Urticaceae	Dendrocnide	0,62	Tropical Wood Density Index Appendix 1
ts19	Brownlowia peltate	Malvaceae	Brownlowia	0,6	Tropical Wood Density Index Appendix 1
ts20	Mallotus peltatus	Euphorbiaceae	Mallotus	0,47	http://eol.org/pages/1154797/overview
ts21	Chisocheton sp.	Meliaceae	Chisocheton	0,548	http://db.worldagroforestry.org//wd/genus/Chisocheton
ts22	Beilschmiedia sp.	Lauraceae	Beilschmiedia	0,584	http://db.worldagroforestry.org//wd/genus/Beilschmiedia
ts23	Ardisia macrophylla	Myrsinaceae	Ardisia	0,51	http://eol.org/pages/5499772/overview
ts24	Diospyros sp.	Ebenaceae	Diospyros	0,758	http://db.worldagroforestry.org//wd/genus/Diospyros
ts25	Koilodepas longifolium	Euphorbiaceae	Koilodepas	0,99	Tropical Wood Density Index Appendix 1
ts26	Mallotus penangensis	Euphorbiaceae	Mallotus	0,545	http://eol.org/pages/1154796/overview
ts27	Drypetes longifolia	Putranjivaceae	Drypetes	0,62	http://eol.org/pages/1145743/overview
ts28	Polyalthia cauliflora	Anonaceae	Polyalthia	0,589	http://db.worldagroforestry.org//wd/genus/Polyalthia
ts29	Pterenandra coerulenscens	Melastomataceae	Pterenandra	0,57	http://eol.org/pages/5442752/overview
ts30	Cleistanthus hirsutipetalus	Phyllantaceae	Cleistanthus	0,666	http://db.worldagroforestry.org//wd/genus/Cleistanthus
ts31	Shorea parvifolia	Dipterocarpaceae	Shorea	0,56	Tropical Wood Density Index Appendix 1
ts32	Antidesma sp.	Phyllantaceae	Antidesma	0,715	http://db.worldagroforestry.org//wd/genus/Antidesma
ts33	Gironniera nervosa	Cannabaceae	Gironniera	0,45	http://eol.org/pages/5722371/overview
ts34	Chisocheton sp. 2	Meliaceae	Chisocheton	0,548	http://db.worldagroforestry.org//wd/genus/Chisocheton
ts35	Aporosa sp.	Phyllantaceae	Aporosa	0,683	http://db.worldagroforestry.org//wd/genus/Aporosa
ts36	Lindera sp.	Lauraceae	Lindera	0,516	http://db.worldagroforestry.org//wd/genus/Lindera
ts37	Mallotus stipularis	Euphorbiaceae	Mallotus	0,6	Tropical Wood Density Index Appendix 1
ts38	Mallotus wrayi	Euphorbiaceae	Mallotus	0,557	http://db.worldagroforestry.org//wd/genus/Mallotus
ts39	Gnochidion sp.	Phyllantaceae	Gnochidion	0,607	http://db.worldagroforestry.org//wd/genus/Glochidion
ts40	Mallotus sp.	Euphorbiaceae	Mallotus	0,557	http://db.worldagroforestry.org//wd/genus/Mallotus
ts41	Mallotus sp.	Euphorbiaceae	Mallotus	0,557	http://db.worldagroforestry.org//wd/genus/Mallotus
ts42	Santiria sp.	Burseraceae	Santiria	0,642	http://db.worldagroforestry.org//wd/genus/Santiria
ts43	Orophea	Anonaceae	Orophea	0,76	http://db.worldagroforestry.org//wd/genus/Orophea
ts44	Chisocheton sp.	Anonaceae	Chisocheton	0,547	http://db.worldagroforestry.org//wd/genus/Chisocheton
ts45	Shorea leprosula	Dipterocarpaceae	Shorea	0,44	http://eol.org/pages/5712641/overview
ts46	Polyalthia sp.	Anonaceae	Polyalthia	0,589	http://db.worldagroforestry.org//wd/genus/Polyalthia
ts47	Madhuca sp.	Sapotaceae	Madhuca	0,715	http://db.worldagroforestry.org//wd/genus/Madhuca
ts48	Mesua sp.	Calophyllaceae	Mesua	0,781	http://db.worldagroforestry.org//wd/genus/Mesua
ts49	Aporosa frutescens	Phyllantaceae	Aporosa	0,683	http://db.worldagroforestry.org//wd/genus/Aporosa
ts50	Mangifera sp.	Anacardiaceae	Mangifera	0,599	http://db.worldagroforestry.org//wd/genus/Mangifera
ts51	Jackiopsis sp.	Rubiaceae	Jackiopsis	0,86	http://db.worldagroforestry.org//wd/genus/Jackiopsis
ts52	Shorea macrophylla	Dipterocarpaceae	Shorea	0,32	http://eol.org/pages/5712655/overview
ts53	Urophyllum sp.	Rubiaceae	Urophyllum	0,48	http://db.worldagroforestry.org//wd/genus/Urophyllum
ts54	Pterygota sp.	Malvaceae	Pterygota	0,58	*www.srs.fs.usda.gov/pubs/gtr/gtr_so088.pdf*
ts55	Aporosa nitida	Phyllantaceae	Aporosa	0,683	http://db.worldagroforestry.org//wd/genus/Aporosa
ts56	Croton caudatus	Euphorbiaceae	Croton	0,525	http://db.worldagroforestry.org//wd/genus/Croton
ts57	Eusideroxylon zwageri	Lauraceae	Eusideroxylon	0,84	http://eol.org/pages/483590/overview
ts58	Croton argyratus	Euphorbiaceae	Croton	0,691	http://db.worldagroforestry.org//wd/species/Croton_argyratus
ts59	Macaranga sp.	Euphorbiaceae	Macaranga	0,404	http://db.worldagroforestry.org//wd/species/Macaranga
ts60	Shorea johorensis	Dipterocarpaceae	Shorea	0,448	http://db.worldagroforestry.org//wd/genus/Shorea
ts61	Macaranga personii	Euphorbiaceae	Macaranga	0,404	http://db.worldagroforestry.org//wd/species/Macaranga
ts62	Unknown non-Dipterocarp			0,612	
ts63	Hopea nervosa	Dipterocarpaceae	Hopea	0,63	http://eol.org/pages/5712411/overview
ts64	Hopea nutans	Dipterocarpaceae	Hopea	0,933	http://db.worldagroforestry.org//wd/species/Hopea_nutans
ts65	Ficus sp.	Moraceae	Ficus	0,441	http://db.worldagroforestry.org//wd/genus/Ficus
ts66	Eucalyptus sp.	Myrtaceae	Eucalyptus	0,828	http://db.worldagroforestry.org//wd/genus/Eucalyptus
ts67	Shorea sp.	Dipterocarpaceae	Shorea	0,632	http://db.worldagroforestry.org//wd/genus/Shorea
ts68	Unknown non-Dipterocarp	Anonaceae		0,612	
ts69	Eusideroxylon zwageri	Lauraceae	Euseridoxylon	0,84	http://eol.org/pages/483590/overview
ts70	Macaranga gigantea	Euphorbiaceae	Macaranga	0,32	http://db.worldagroforestry.org//wd/species/Macaranga
ts71	Macaranga hypoleuka	Euphorbiaceae	Macaranga	0,298	http://db.worldagroforestry.org//wd/species/Macaranga

Appendix IV: Forest inventory graphs and tables

IV.A Cause of death in the dead trees (<1 year) that were encountered in the forest fragments



IV.B Family distribution of the identified trees throughout all the study sites

Taxonomic family	Quantity
Dipterocarpaceae	278
Euphorbiaceae	168
Anonaceae	62
Moraceae	50
Phyllantaceae	32
Rubiaceae	21
Meliaceae	19
Melastomataceae	19
Myrsinaceae	11
Malvaceae	9
Lauraceae	9
Calophyllaceae	8
Anacardiaceae	8
Ebenaceae	7
Lamiaceae	7
Myrtaceae	4
Sapindaceae	4
Cannabaceae	4
Sapotaceae	4
Fabaceae	3
Burseraceae	3
Urticaceae	2
Achariaceae	2
Putranjivaceae	1

IV.C Family distribution of the identified trees for each of the three forest types

Taxonomic family	Quantity	Percentage
High Conservation Value areas (logged)		
Dipterocarpaceae	47	22.3%
Moraceae	38	18.0%
Anonaceae	27	12.8%
Euphorbiaceae	25	11.8%
Rubiaceae	20	9.5%
Virgin Jungle Reserves (unlogged)		
Dipterocarpaceae	186	59.2%
Anonaceae	31	9.9%
Euphorbiaceae	30	9.6%
Phyllantaceae	18	5.7%
Moraceae	9	2.9%
Continuous forest (logged)		
Euphorbiaceae	113	53.8%
Dipterocarpaceae	45	21.4%
Meliaceae	12	5.7%
Phyllantaceae	8	3.8%
Melastomataceae	7	3.3%

IV.D Number of identified tree species for each of the 14 visited study sites

Site	Area	Species identified
High Conservation Value areas		
Jatu	12	8
Meranti	30	9
Yeong Peng	57	6
Rekasar	85	18
Sabasar	88	14
Water Catchment	120	12
Virgin Jungle Reserves		
Sapi_A	45	12
Keruak	220	12
Materis	250	16
Sapi C	500	12
Ulu Sapa Payau	720	14
Lungmanis	3529	21
Continuous forest		
Malua A	∞	22
Malua B	∞	23

Appendix V: Biomass and carbon stocks per hectare for each plot

Site	Area	ID-Plot	Biomass/ha (>10 DBH <25)	Biomass/ha (>25cm DBH)	Carbon stock/ha	Logged
Jatu	12	J3	46.085,56	12.524,33	27.605,26	Y
Jatu	12	J1	10.907,29	294.357,97	143.779,94	Y
Keruak_Virgin_Jungle_Reserve	220	KV3	30.622,98	37.092,83	31.894,14	N
Keruak_Virgin_Jungle_Reserve	220	KV1	19.698,46	69.094,01	41.821,25	N
Keruak_Virgin_Jungle_Reserve	220	KV6	29.983,24	318.906,83	164.327,22	N
Lungmanis_Virgin_Jungle_Reserve	3529	LV1	15.973,58	79.447,38	44.943,27	N
Lungmanis_Virgin_Jungle_Reserve	3529	LV5	18.296,35	85.319,86	48.803,23	N
Lungmanis_Virgin_Jungle_Reserve	3529	LV3	18.985,13	210.219,62	107.955,44	N
Lungmanis_Virgin_Jungle_Reserve	3529	LV6	37.374,92	192.216,52	108.137,56	N
Lungmanis_Virgin_Jungle_Reserve	3529	LV4	12.675,47	366.581,66	178.630,11	N
Malua_A_Near_SBE	800000	MA1	11.440,01	143.391,92	72.925,84	Y
Malua_A_Near_SBE	800000	MA4	45.733,35	115.838,04	76.100,12	Y
Malua_A_Near_SBE	800000	MA8	68.713,03	129.696,72	93.450,99	Y
Malua_A_Near_SBE	800000	MA6	62.940,91	152.097,60	101.283,14	Y
Malua_A_Near_SBE	800000	MA10	41.455,38	408.722,29	212.033,68	Y
Malua_B-Gate	800000	MB9	20.370,20	128.210,74	69.981,62	Y
Malua_B-Gate	800000	MB7	23.219,98	151.529,67	82.307,09	Y
Malua_B-Gate	800000	MB5	46.188,41	142.779,62	89.003,94	Y
Malua_B-Gate	800000	MB3	30.208,19	190.747,64	104.070,20	Y
Malua_B-Gate	800000	MB1	71.517,41	212.764,17	133.896,62	Y
Materis_Virgin_Jungle_Reserve	250	MV1	13.811,26	139.566,39	72.240,88	N
Materis_Virgin_Jungle_Reserve	250	MV4	29.933,94	183.566,54	100.558,73	N
Materis_Virgin_Jungle_Reserve	250	MV6	22.201,32	218.349,52	113.299,44	N
Meranti	30	M3	13.468,89	12.239,06	12.108,45	Y
Meranti	30	M1	36.894,88	67.856,08	49.337,70	Y
Rekasar	85	R4	31.746,13	15.837,80	22.412,03	Y
Rekasar	85	R3	44.524,81	59.386,45	48.942,21	Y
Rekasar	85	R1	65.711,41	156.865,31	104.833,64	Y
Sabasar	88	SB4	23.266,46	3.202,19	12.466,73	Y
Sabasar	88	SB3	32.755,75	9.087,06	19.707,96	Y
Sabasar	88	SB7	47.503,25	168.975,51	101.961,49	Y
Sapi_A_Virgin_Jungle_Reserve	45	SA3	10.982,42	31.037,63	19.791,45	N
Sapi_A_Virgin_Jungle_Reserve	45	SA1	27.922,04	30.289,75	27.417,75	N
Sapi_C_Virgin_Jungle_Reserve	500	SC3	50.238,77	39.946,89	42.477,45	N
Sapi_C_Virgin_Jungle_Reserve	500	SC1	25.392,74	107.991,64	62.824,04	N
Sapi_C_Virgin_Jungle_Reserve	500	SC7	18.169,46	136.845,02	73.011,82	N
Sapi_C_Virgin_Jungle_Reserve	500	SC5	23.940,20	182.202,69	97.093,30	N
Ulu_Sapa_Payau_Virgin_Jungle_Reserve	720	U2	26.654,92	32.030,77	27.640,96	N
Ulu_Sapa_Payau_Virgin_Jungle_Reserve	720	U4	23.305,94	84.960,30	50.993,40	N
Ulu_Sapa_Payau_Virgin_Jungle_Reserve	720	U8	31.112,41	85.751,32	55.042,81	N
Ulu_Sapa_Payau_Virgin_Jungle_Reserve	720	U6	20.204,04	143.906,67	77.296,15	N
Water_Catchment	120	WC3	12.968,17	15.086,50	13.213,75	Y
Water_Catchment	120	WC1	16.933,81	13.704,42	14.430,61	Y
Yeong_Peng	57	YP6	31.624,94	6.809,07	18.102,42	Y
Yeong_Peng	57	YP7	16.107,18	25.000,61	19.361,77	Y
Yeong_Peng	57	YP2	31.099,10	62.640,38	44.151,30	Y

Appendix VI: Statistical tests

VI.A Multiple regression fragment size and logging:

Model Summary[c]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.378[a]	.143	.124	44041.478699349410000	
2	.472[b]	.222	.186	42434.960321933366000	1.954

a. Predictors: (Constant), Area

b. Predictors: (Constant), Area, Cut

c. Dependent Variable: Carbon stock/ha

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	14244110891.371	1	14244110891.371	7.344	.010[b]
	Residual	85344681225.111	44	1939651846.025		
	Total	99588792116.482	45			
2	Regression	22157580242.948	2	11078790121.474	6.152	.004[c]
	Residual	77431211873.535	43	1800725857.524		
	Total	99588792116.482	45			

a. Dependent Variable: Carbon stock/ha

b. Predictors: (Constant), Area

c. Predictors: (Constant), Area, Cut

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	60940.354	7354.466		8.286	.000		
	Area	.119	.044	.378	2.710	.010	1.000	1.000
2	(Constant)	43416.616	10958.610		3.962	.000		
	Area	.167	.048	.533	3.474	.001	.769	1.300
	Cut	-30020.701	14320.599	-.321	-2.096	.042	.769	1.300

a. Dependent Variable: Carbon stock/ha

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Area	Cut
1	1	1.469	1.000	.27	.27	
	2	.531	1.664	.73	.73	
2	1	1.825	1.000	.09	.05	.08
	2	.996	1.354	.00	.41	.14
	3	.179	3.189	.91	.54	.79

a. Dependent Variable: Carbon stock/ha

VI.B T-test and ANOVA tests on logging impact on carbon stocks

t-Test: Two-Sample Assuming Equal Variances

	Logged	*Unlogged*
Mean	67498.74	73628.59
Variance	2.56E+09	1.89E+09
Observations	25	21
Pooled Variance	2.25E+09	
Hypothesized Mean Difference	0	
df	44	
t Stat	-0.43622	
P(T<=t) one-tail	0.332404	
t Critical one-tail	1.68023	
P(T<=t) two-tail	0.664808	
t Critical two-tail	2.015368	

F-Test Two-Sample for Variances

	Logged	*Unlogged*
Mean	67498.74	73628.59
Variance	2.56E+09	1.89E+09
Observations	25	21
df	24	20
F	1.35433	
P(F<=f) one-tail	0.247364	
F Critical one-tail	2.082454	

Anova All Groups

Groups	*Count*	*Sum*	*Average*	*Variance*
LF	15	652415.2	43494.35	1.68E+09
UF	21	1546200	73628.59	1.89E+09
CF	10	1035053	103505.3	1.81E+09

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.2E+10	2	1.1E+10	6.109318	0.004620934	3.214480328
Within Groups	7.76E+10	43	1.8E+09			
Total	9.96E+10	45				

Anova LF - UF

Groups	*Count*	*Sum*	*Average*	*Variance*
LF	15	652415.2	43494.35	1.68E+09
UF	21	1546200	73628.59	1.89E+09

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.95E+09	1	7.95E+09	4.408909	0.043247733	4.130017746
Within Groups	6.13E+10	34	1.8E+09			
Total	6.92E+10	35				

Anova UF - CF

Groups	*Count*	*Sum*	*Average*	*Variance*
UF	21	1546200	73628.59	1.89E+09
CF	10	1035053	103505.3	1.81E+09

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.05E+09	1	6.05E+09	3.244313	0.082079328	4.182964289
Within Groups	5.41E+10	29	1.86E+09			
Total	6.01E+10	30				

Anova LF - CF						
Groups	*Count*	*Sum*	*Average*	*Variance*		
LF	15	652415.2	43494.35	1.68E+09		
CF	10	1035053	103505.3	1.81E+09		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.16E+10	1	2.16E+10	12.49337	0.001772008	4.279344309
Within Groups	3.98E+10	23	1.73E+09			
Total	6.14E+10	24				

VI.C Linear regression analysis forest fragment size and carbon stocks (excluded water catchment)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.364[a]	.132	.112	43817.471683783246000	1.814

a. Predictors: (Constant), Area
b. Dependent Variable: Carbon stock/ha

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	12280485137.216	1	12280485137.216	6.396	.015[b]
	Residual	80638774639.884	42	1919970824.759		
	Total	92919259777.101	43			

a. Dependent Variable: Carbon stock/ha
b. Predictors: (Constant), Area

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	63723.192	7529.902		8.463	.000		
	Area	.111	.044	.364	2.529	.015	1.000	1.000

a. Dependent Variable: Carbon stock/ha

VI.D Multiple regression analysis fragment size and logging on dead carbon stocks

Model Summary[c]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.237[a]	.056	.035	3877.596272614378000	
2	.301[b]	.090	.048	3850.159251370676000	1.961

a. Predictors: (Constant), Cut
b. Predictors: (Constant), Cut, Area
c. Dependent Variable: Carbon (dead)/ha

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	39259366.593	1	39259366.593	2.611	.113[b]
	Residual	661573125.549	44	15035752.853		
	Total	700832492.142	45			
2	Regression	63412262.923	2	31706131.461	2.139	.130[c]
	Residual	637420229.219	43	14823726.261		
	Total	700832492.142	45			

a. Dependent Variable: Carbon (dead)/ha
b. Predictors: (Constant), Cut
c. Predictors: (Constant), Cut, Area

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	2262.674	846.161		2.674	.010		
	Cut	-1854.688	1147.788	-.237	-1.616	.113	1.000	1.000
2	(Constant)	2265.543	840.177		2.697	.010		
	Cut	-2654.529	1300.569	-.339	-2.041	.047	.768	1.302
	Area	-.003	.002	-.212	-1.276	.209	.768	1.302

a. Dependent Variable: Carbon (dead)/ha

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Cut	Area
1	1	1.737	1.000	.13	.13	
	2	.263	2.571	.87	.87	
2	1	2.231	1.000	.07	.06	.08
	2	.542	2.029	.30	.01	.69
	3	.226	3.140	.63	.93	.23

a. Dependent Variable: Carbon (dead)/ha

VI.E Multiple linear regression: dead biomass percentage vs. logging history and fragment size

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.459[a]	.211	.174	7.727889877672465	2.142

a. Predictors: (Constant), Cut, Area
b. Dependent Variable: Dead %

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	685.813	2	342.907	5.742	.006[b]
	Residual	2567.972	43	59.720		
	Total	3253.785	45			

a. Dependent Variable: Dead %
b. Predictors: (Constant), Cut, Area

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	3.894	1.686		2.309	.026		
	Area	-1.119E-5	.000	-.439	-2.837	.007	.768	1.302
	Cut	-7.808	2.610	-.462	-2.991	.005	.768	1.302

a. Dependent Variable: Dead %

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Area	Cut
1	1	2.231	1.000	.07	.08	.06
	2	.542	2.029	.30	.69	.01
	3	.226	3.140	.63	.23	.93

a. Dependent Variable: Dead %