Carbon Stock and Opportunity Assessment of Shorea Plantation Forests

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Abstract

Deforestation and forest degradation are common phenomenon's, especially in tropical countries worldwide. Together with industrial and transport CO_2 emissions, deforestation and forest degradation are worldwide the main reasons for the release of CO_2 into the atmosphere. Countries and organizations are reducing carbon emissions by using forests as CO_2 sinks, as formally the focus was mainly on natural forests, now forest plantations have been recognized as important carbon sinks. However every forest type, age and species composition stores a different amount of carbon, making carbon accounting methods required for accurate estimates of the potential on carbon storage of forest areas. This study focused on a variety of Shorea plantation plots in Sarawak, Malaysia and compared the biomass and total carbon stock between the plots. Furthermore this study compares the use of different allometric models for estimating biomass applicable to the study area. Methods used consisted of measuring the Diameter at Breast Height (DBH), height and Wood Density (WD) of the tree species and were used as parameters for allometric models. Above Ground Biomass (AGB), Below Ground Biomass (BGB), Coarse Woody Debris (CWD) and Litter, Soil Carbon (SC) were the different carbon pools assessed, although AGB was accurately measured, the other carbon pools have accurate literature references for carbon estimations.

The current total carbon stock varied from 215 t/ha (plot 12) to 265 t/ha (plot 4c). The difference in AGB was much greater between the plots, in some cases over 50%. The annual AGB increment ranged from 0,57 t/ha to 2,33 t/ha from the establishment year to the last assessment of 1974 and ranged from 0,82 t/ha to 3,08 t/ha from the last assessment of 1974 to the current study, these are however specifically for the Shorea species in the plots and unknown species are excluded (Unknown species are however included in the total carbon stock). Forest characteristics indicated that some plots were heavily degraded and contained large amounts of CWD, exceeding the rotation period. Some Shorea proved to be capable of long rotation periods and contained high amounts of carbon, especially in AGB (plot 4c and 5c). Important for using Shorea species as future reforestation/afforestation and forest plantations is finding the optimal rotation period, for the benefits of carbon storage, timber production and non-timber forest products (NTFP). The development of specific forest plantations carbon accounting schemes is required for monitoring and the allowance of carbon credits trading.

Keywords: Allometric equations; Biomass carbon stock; Carbon pools; Shorea species; Plantation forest

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Acronyms and Abbreviations

°C	Degree Celsius
AGB	Above ground biomass
ANOVA	Analysis of variance
BA	Basal area
BEF	Biomass expansion factor
BGB	Below ground biomass
CCB	Climate, Community & Biodiversity Standards
CDM	Clean Development Mechanism
CFS	Carbon Fix Standards
CWD	Coarse woody debris
DBH	Diameter at breast height
FAO	Forest Agriculture Organization
GPS	Global positioning system
Ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
Mm	Millimeter
MMD	Malaysian Meteorological Department
MVR	Monitoring, verification and reporting
No.	Number
NTFP	Non-timber forest products
REDD	Reduced Emissions from Deforestation and forest Degradation
SFD	Sarawak Forestry Department

SC	Soil carbon
t/ha	Tons per hectare
TRC	Timber Research Center
UNFCCC	United Nations Framework Convention on Climate Change
Vol	Volume
VCS	Voluntary Carbon Market
WD	Wood density

1. Introduction

Forests worldwide are important carbon sinks and pools, especially in tropical forests (Gorte, 2009). Tropical deforestation is estimated to have released roughly 15-25% of annual global greenhouse gas emissions. (Houghton, 2005) (Gibbs, et al., 2007). Climate change is a threat on global scale and over the last few decades this subject is getting more and more attention. Carbon-offset programs have been initiated, as part of payment for environmental services, to increase the worldwide carbon storage capacity and thereby capture the CO_2 that is released in the air by human activities (Dixon, et al., 1993). Many of these programs consist of afforestation and reforestation projects and require the biodiversity, social and climatic benefits aspects taken into account and assessed. The upcoming Reduced Emissions from Deforestation and Forest Degradation (REDD) framework will be internationally oriented and many countries are getting ready for REDD+ by implementing or improving their Monitoring, Verification and Reporting (MVR) systems (Westholm, 2010).

Tropical forest plantations can be an important sink for CO_2sequestration. The United Nations Framework Convention on Climate Change (UNFCCC) has recognized the importance of forest plantations to combat global warming and store carbon emissions (Kaul, 2010). Besides the storing capacity, forest plantations can reduce the pressure on natural forests by providing the required timber that otherwise would be extracted from natural forests (Gladstone & Thomas ledig, 1990) (Plantations2020, n.d.).

Malaysia has exploited its forestry resources and is now one of the leading countries on export of tropical timber (R. Ismail, 1995) (ITC/ITTO, 2002). The Malaysian forestry plantation program, launched in 1983, had its primary purpose to provide its countries needs on paper and timber products. Before the plantation program, these resources were imported which showed to be expensive and it would be more economical feasible to create forest plantations and provide its countries required products. However, besides its paper pulp and timber provisions, carbon storage in forest plantations proved an important benefit (R. Ismail, 1995).

The tropical forests of Borneo, including Malaysia, are dominated by the Dipterocarp family tree species. The Dipterocarp is a keystone species for Borneo and provides many economic benefits, such as quality timber and non-timber forest products (NTFP) (Seeds) (Phua, n.d.). Borneo is rapidly depleting its natural resources; deforestation is threatening the Dipterocarp species as over 50% of the Dipterocarp family is found on Borneo. Sarawak is experiencing an annual deforestation rate of 0.6% between 1990-2009 (Phua, sd); other research indicates an annual deforestation rate of 5.9% between 2000-2010 for Malaysia (Miettinen & Liew, 2011), mainly due deforestation in peatlands. At the current rate of deforestation the tropical forests of Borneo will be depleted within a few decades (Tan et al, 1987).

The knowledge on the importance of forests in militating climate change has led countries to assess their national carbon pools (Kaul et al, 2010). These assessments consist of national forest inventories to get an indication on national carbon stocks. Inventories are held on above ground biomass (AGB), below ground biomass (BGB), coarse woody debris (CWD) and litter, and soil. Combining these elements will give an estimated carbon stock of forests. To attend in (inter)national carbon-offset programs, it is required to provide an estimated, preferable accurate, carbon stock of the forests.

This research will focus on the carbon storage capacity of Dipterocarp (*Shorea spp*.) plantations in Sarawak, Malaysia. The AGB will be accurately measured and combined with literature data on BGB, dead wood and litter, and soil. Several allometric models will be used for estimating the carbon storage capacity of these forest plantations and will be compared to natural forests and forest plantations to evaluate the differences in carbon storage capacities.

1.1 BACKGROUND

Carbon dioxide is the most important anthropogenic greenhouse gas (IPCC, 2007) and the concentration of carbon dioxide has increased significantly over the last decades. Primary sources of this carbon dioxide increase are the results of burning fossil fuels and land-use change. This causes the climate the warm (global warming) with a rise in global air and ocean temperatures, widespread melting of snow and ice and the rise of sea levels (IPCC, 2007). Forest degradation and deforestation are the results of land clearing for agriculture and other land uses. Deforestation has become a common phenomenon, especially in tropical forests of developing countries. In Peninsular Malaysia the total loss of biomass was 28%, in south-east Asia, the reductions are even larger (Houghton, 1994). The UNFCCC has recognized the importance of forest degradation and deforestation and policies are emerging to stabilize and increase the world terrestrial carbon stocks. Policies are combining the important aspects that come along with reducing deforestation, such as social benefits, biodiversity preservation and nature conservation.

Terrestrial ecosystems play an important role in carbon storage and can contain up to 3 times that of atmospheric carbon (Trumper, et al., 2009). To quantify for the amounts of carbon in forests, carbon storage assessments on the different carbon pools within the biomes (Tropical forests, dry forests, temperate forests etc.) is crucial. Carbon pools commonly exist of above ground biomass (AGB), below ground biomass (BGB), coarse woody debris (CWD) and litter, and soil carbon (SC). In tropical forests and mainly in humid/wet tropical forests, most carbon is stored in the vegetation, the AGB. Vegetation in tropical forests however can vary significantly due to species and forest composition (Trumper, et al., 2009). It is therefore important to assess each carbon pool, of each forest, to make sure no under- or overestimation of the actual biomass occurs.

1.2 FOREST PLANTATIONS AND CARBON SEQUESTRATION

Forests are critical in the emission of carbon into the atmosphere. When forests are cut down, the carbon stored in the above ground and belowground biomass is released back into the atmosphere. Forests share about 17-20% of the global carbon pool (IPCC, 2007). Around 4% of the global forest area is represented by plantation forests (Trumper, et al., 2009). Forest plantations can have an important role in removing CO_2 from the atmosphere. Furthermore forest plantations can generate wood and NTFP's to either replace fossil fuels or supply the demand for timber. With the right management forest plantations can offer more carbon storage capacity (Dewar & Cannel, 1992). Here the focus can be on rotation period. The carbon storage capacity of a plantation forest also depends on the wood products. If wood products consist for example of long durable products instead of pulpwood, the CO_2 sequestered will remain in the harvested wood, allowing forest plantations to regrow wood and continue storing carbon (Mohren, et al., 2012) (ITC/ITTO, 2002).

1.3 CARBON-OFFSET FRAMEWORKS AND CLIMATE CHANGE

In order to mitigate climate and further the effects of global warming, carbon-offset programs and protocols were established. The Kyoto Protocol, an international treaty, sets the obligations for industrialized countries to reduce emissions of greenhouse gases. Under the Clean Development Mechanism (CDM), Countries can trade emissions quotas among themselves and receive credit for financing emissions reductions in developing countries. Reduced Emissions from Deforestation and forest Degradation (REDD) is a mechanism developed for countries and organizations to create financial incentives to reduce emissions on deforestation and forest degradation (Westholm, 2010). Projects such as afforestation and reforestation can provide carbon credits amongst these mechanisms which result in greenhouse gas reductions. Participating in these carbon-offset programs and mechanisms requires safeguards and rules. Both national and international programs have been developed to create carbon credits and this market is still in development.

1.4 CARBON ESTIMATION MODELS

1.4.1 REMOTE SENSING

Over the years different carbon estimation models have been developed. Several carbon estimation methods are currently available. They consist of remote sensing, using satellite imagery from space, or ground based inventories. Remote sensing is a promising method because it's relatively cheap compared to ground based inventories. Remote sensing for carbon stocks measuring is performed by optical or radar sensors, but showed to be ineffective in high biomass and closed canopy forests (Houghton, 2005). However recent airborne investigations showed that long wave-length radar and LIDAR have demonstrated to be effective in determining the AGB in temperate and tropical forest zones. Malaysia began applying remote sensing in 1961 using aerial photographs, further national inventories carried out in 1971 and 1981 used remote sensing to stratify different forest types. The national inventory in 1991-1993 used Landsat imagery to indicate the usefulness of remote sensing for forest monitoring and inventory (Piazza, 2007).

1.4.2 GROUND BASED INVENTORIES

Ground based inventories are still the most accurate method to estimate biomass stocks in forests, but are expensive and time consuming (Houghton, 2005). Different allometric models have been developed to determine ABG and BGB by using parameters such as, in decreasing order of importance; DBH, height, WD and tropical forest type (dry, moist, wet) (Chave, et al., 2005). Some common existing models have been developed by (Basuki, et al., 2009; Chave, et al., 2005; Ketterings, et al., 2001; Brown, 1997) and most models have been approved by the Intergovernmental Panel on Climate Change (IPCC) and incorporated or referred to in the IPCC Good Practice Guidance for carbon measurements standards. The models prefer different parameters, some consider DBH and height as most accurate parameters (Chave, et al., 2005), while others consider DBH and WD as most accurate parameters (Basuki, et al., 2009). The most common error in biomass estimates is choosing the wrong allometric model (Chave, et al., 2004), thus comparing different allometric models with site specifics in relation to tree species is crucial.

1.5 JUSTIFICATION

There have been many researches towards carbon quantification in vegetation types, tree species and soil types. For carbon-offsets and their frameworks it is required to show a most accurate estimation of the carbon storage capacity of the project area. These will be used for the calculation of the carbon credits and that will be related to a price for which it can be sold on the carbon market. Not much research has been done towards the carbon storage capacity of forest plantations containing the Shorea species in Malaysia. Further understanding the role of forest plantations is important for carbon sequestration and the effects it has on future climate change (Kaul et al, 2010). This research will offer data that can be referenced to for future carbon-offset programs and can be used for national carbon pool estimates on forest plantations. Several Shorea species are currently under protection under the Wild Life Protection Ordinance 1990 (H.S. Lee, et al, (1997). Many of the project area forest plantation species are on this list of protection. According to a FAO report of 2002, over 4,780 ha of forest plantations of the Shorea species of the Dipterocarp family were present in Sarawak, Malaysia. A similar study to carbon storage and sequestration has been performed on Shorea species of community forests in India, by M. Kaul (2010), using a CO_2FIX model. Carbon sequestration or other payment for environmental services could provide new incentives on forest plantations and forest plantation management that would make them economically more viable, and contribute to forest conservation.

1.6 OBJECTIVES AND RESEARCH QUESTIONS

The overall objective and main research question is:

To determine the carbon storage capacity, carbon-offset possibilities and management options of Shorea forests plantations in Sarawak, Malaysia

This objective will be researched by answering the following research questions:

- What is the annual AGB increment, the current above ground biomass (AGB) and current below ground biomass (BGB) of the forests plantations containing different Shorea species in Sarawak, Malaysia?
- What is the current Coarse Woody Debris (CWD) and litter biomass of forest plantations containing different Shorea species in Sarawak, Malaysia?
- What is the soil carbon (SC) content of forest plantations containing different Shorea species in Sarawak, Malaysia?

From these research questions the results will be an estimated combined biomass of the AGB, BGB, CWD and litter, and soil. From these results the current carbon content of a Shorea forest plantation will be calculated. Besides the main objective and research question, the following questions will be researched and evaluated:

- What are possible applicable management options to increase the carbon storage capacity of the researched forest plantations?
- What (inter)national carbon-offset framework would be applicable for the research area?

1.7 LIMITATIONS

- Litter (leaves) carbon content has been estimated from literature and is not accurately measured in the field.
- SC content has been estimated from literature sources and was not accurately measured in the field.
- Data on previous research in the study area was missing or lost during the moving of the Sarawak Forestry Department (Seng, 1986), making some results difficult to analyze and compare.
- Conditions in some of the Engkabang plots were poor to very poor. For example the Shorea *splendida* plots had a significant high amount of CWD compared to the other plots.

2. Methodology; Materials and Methods

2.1 STUDY AREA

Malaysia consist of two separated regions, known as Peninsular Malaysia (West Malaysia) and the states Sabah and Sarawak located to the East, on Borneo. These regions are separated by the South China Sea. Malaysia is located 2 ° to 6 ° north of the equator (Figure 1). The study area is located at 2° north of the equator. Sarawak is generally mountainous with the highest range forming the border with Indonesia. The study area is located 20 kilometers south of the city Kuching, Sarawak.

Figure 1: Geographical map of Malaysia (indicated in Yellow). Source: www.eoearth.org

Precipitation is high in most parts of Malaysia. Kuala Lumpur receives over 2400 mm per year, Penang over 2700 mm per year, Kuching in Sarawak over 3900 mm per year (Figure 2), and Labuan in Sabah over 3500 mm per year of precipitation. Maximum rainfall in the coastal areas of Sarawak and northeast Sabah occur during January with minimal rainfall in the coastal Sarawak occurring in June or July. Rainfall is more evenly distributed through the year in inland areas of Sarawak, southern Sabah, and the central parts of Sabah. On average Kuching receives 255 days of rain each year. Being close to the equator, Malaysia has lots of sunlight and there for solar radiation. However it is rare to have a clear sky, even in drought periods. This is due cloud cover. Kuching has around 5 hours of average sunlight a day ((MMD, 2013)). Malaysia has uniformly high temperatures throughout the year. In most areas the average maximum and minimum temperature per month vary less than 2°C annually. Temperature can range daily between 5°C to 10°C near the coast and from 8° C to 12°C inland. The average temperature is between 29- 33° in Kuching. The relative humidity in Malaysia is high, ranging from 70% to 90%. Humidity varies more throughout the day than it does annually.

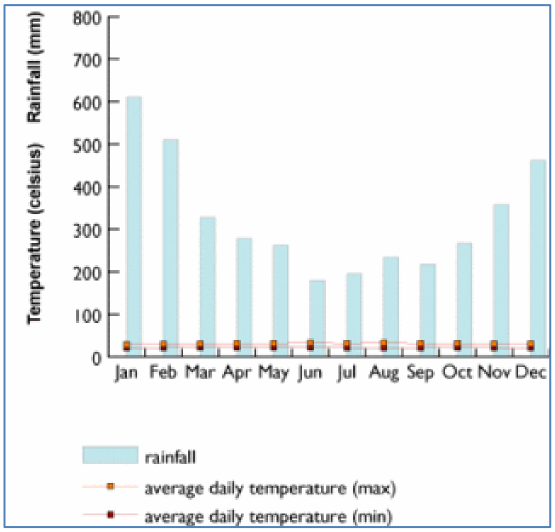


Figure 2: Average rainfall and temperature in Kuching. Source: BBC Weather

2.1.1 STATE OF SARAWAK

Sarawak became interested in forest plantations in the late 1920's and initiated trial plantations of indigenous species of the Engkabang group (*Shorea spp.),* which is an important producer of the illipe nut. After these trials no other major plantings have occurred until the Reforestation Research Program was initiated in 1965. The objective was to test fast growing exotic tree species, for reforesting land that was subject to shifting cultivation. Shifting cultivation is a major problem in Sarawak and is the cause of many damaged forests areas (FAO, 2002). The pressure for the requirement of reforestation and plantation forests was not as high for Sarawak as for Sabah or Peninsular Malaysia, because Sarawak had many productive forests left. This also caused a lack of interest in carbon-offset programs. In 2002 Sarawak had a total of 4,780 ha of the Shorea spp. planted, covering 1 third of the total planted species (FAO, 2002). Currently that number is around 11,783 ha and is covering almost half of the total planted species (Table 1).

Table 1: Species planted per hectare in Sarawak. Source: (SFD, n.d.)

Species planted	**Area (ha)**
Conifer species	58
Acacia mangium including Acacia auriculiformis and Acacia mangium x Acacia auriculiformishybrid	3,715
Shorea macrophylla & other Shorea species	11,783
Durio zibethinus	1,116
Azadirachta excelsa	617
Dryobalanops species	1,970
Calamus species (Rattans)	2,222
Other indigenous & non indigenous species	1,615
Total	23,096

2.1.2 SELECTION OF FOREST PLANTATIONS

In the Semengoh Forest Reserve, a plantation area was established in the period 1927 to 1940 with a variety of Shorea species (Engkabang group). Around 19 hectares were planted in Semengoh Forest Reserve. Although the purpose of establishment of some of these plantations were unknown (S.S. Tan, 1987), the overall goal was to establish these plantation plots for research on the illipe nut production by applying different management techniques , such as 'improvement felling', 'removal of overtopping trees' or 'thinning'. These Shorea plots were measured at frequent intervals (Table 2). The planted Shorea species are indigenous species to Malaysia and Borneo and are known, besides for the Illipe nut production, for their high quality timber (Meranti timber). These Engkabang plots were selected for this research because of the available data on previous research and maintenance on the plots. Research on the carbon content of Engkabang plots could result in options for payment for environmental services, which would make Engkabang plantations economically viable in combination with Illipe nut and timber production. A total of 8 plots with 6 different Shorea species were selected from the Semengoh Forest plantation. Plot 7c is intercropped with Belian species (*Eusideroxylon zwageri)*. More information on the plots specifically and the history can be found in research from S.S. Tan, 1987.

Table 2: Engkabang plot information and growth measurements data. Data from research by S.S. Tan, 1987.

Sample Plot	Species (Engkabang)	Plot size (ha)	Year of establishment	Growth measurement (year)
4B	E. bintang (Shorea splendida)	0.11	1926	1969, 1972, 1973, 1974
4C	E. gading (Shorea hemsleyana)	2.19	1935	1969, 1972, 1973, 1974
5C	E. langgai bukit (Shorea pinanga)	0.81	1935	1969, 1972, 1973, 1974
7C	E. jantung (Shorea macrophylla)	1.62	1936	1969, 1974
9	E. bintang (Shorea splendida)	1.34	1939	1972, 1973
12	E. asu (Shorea palembanica)	0.81	1940	1969, 1972, 1973, 1974
13	E. bintang (Shorea splendida)	0.81	1940	1969, 1972, 1973, 1974
14	E. rusa (Shorea stenoptera)	0.97	1940	1969, 1972, 1973, 1974

2.2 FIELD SAMPLING

2.2.1 LOCATION OF THE SAMPLE PLOTS

No coordinate data was available on the location of the plots. Many plots were indicated by a sign but boundaries have been overgrown throughout the years and the plots were hard to distinguish from each other. Corners of the plots were regularly marked with wooden pegs and tags, but were often heavily degraded or were missing. A Global Positioning System (GPS) was used to mark the boundaries and corners of the plots. Old maps of the plantation were obtained from the Sarawak Forestry Department for an indication of the plots (Annex II).

2.2.2 SAMPLING AND MEASUREMENTS

For the inventory all the trees with a DBH of >=5 were measured as this is considered *Good Practice* (IPCC, 2006) and a nested sampling approach was applied. The Engkabang plots were 100% inventoried for the DBH of >=30. With the use of rope and compass the lines were set out in each plot at every 20 meter distance to make an accurate inventory. Within the 100% inventory the Shorea species were distinguished from unknown species by iron name tags and the Shorea species were planted in rows, making identification reliable. Subplots were randomly placed within the Engkabang plots for trees with a DBH of >= 5 to <30. Each Engkabang plot had enough sub-plots to inventory at least 10% of each plot. The sub-plots consisted of 20 by 20 meters (0.04 ha). The plots were randomly placed by using ArcMap and the 'Create Random Point' tool within the program. These points were then placed within the GPS and located in the field. For DBH measurements a diameter tape was used and for height measurements a clinometer was frequently used at initial estimates at each plot for verification and accurate height values. Two heights were inventoried, the base crown height is used for biomass estimations and commercial height is used for timber volume calculations. Furthermore notes on vegetation status and soil information were collected at each plot. 'Quality' information of the trees has been categorized into four classes: 1 = Straight stem, 2 = slightly/moderately crooked, 3 = crooked/unusable for timber and 4 = dead standing wood. Remark information consisted mostly of the presence of lianas in the plots. Table 3 summarizes the elements measured in the plots and sub-plots.

Table 3: The elements measured in the plots and sub-plots, see annex I for an example of the field forms.

DBH range >=5 - <30 (sub-plot)	**DBH range >30 (plot)**
Diameter Breast Height (1.3 meter)	Diameter Breast Height (1.3 meter)
Height (Base Crown Height)	Height (Base Crown Height)
Tree Species	Height (Commercial Height)
	Tree Species
	Quality
	Remark

2.3 ESTIMATION OF CARBON STOCKS IN BIOMASS

2.3.1 ABOVE GROUND BIOMASS

AGB consist of trees, including branches, twigs, leafs and fruits, but also shrubs and herbs. AGB accounts for 70% to 90% of forests biomass, of which most is in trees (Houghton, et al., 2009), hence the importance of accurate estimations of this carbon pool. Trees less than 10 cm contribute little to the AGB pool, but not including <10 will underestimate the AGB biomass (Chave, et al., 2001). The focus in this research is preliminary on tree biomass with a DBH of >=5 cm, as this is the minimum DBH recommended for measuring according to the IPCC Good Practice Guidance, 2003. ABG can be calculated by two approaches, the direct and indirect approach (IPCC, 2003), described below. Both approaches will be applied and compared in this research.

Direct approach

Allometric models apply a relation between different parameters (DBH), WD, height, tropical forest type, ecological zone). These parameters are however not always available, therefore allometric equations have different models in cases where parameters are missing. Height is a variable often missing and is difficult to accurately measure in closed canopy tropical forests due to low visibility, tree distinction and tree architecture (Chave, et al., 2005; Basuki, et al., 2009). In plantation forestry height is frequently measured but this data is often inaccessible or not published. Since tropical forests can contain around 300 different tree species per hectare, species specific relation models were difficult to establish, therefor mixed species models have been developed (Chave, et al., 2005). Research by Basuki, et al., 2009 was performed for allometric models development in Kalimantan, Indonesia on lowland Dipterocarp forests. Results from that research developed allometric models for several large genus groups in Dipterocarp forests; *Dipterocarpus, Hopea, Palaquium* and *Shorea*. The allometric model developed by Basuki, et al. 2009, with genus specific parameters, is the most applicable for Shorea plantation forests, because of its relevance to a similar forest area/type and species composition, but other allometric models will be applied to the same data set. The allometric equation from Basuki, et al. 2009, with DBH, WD and Shorea specific parameters, is as follows:

$$\ln(AGB) = -1{,}533+2{,}294*\ln(DBH)+ 0{,}56*\ln(WD)$$

Where:

- AGB = Above Ground biomass in kg
- DBH = Diameter at Breast Height (1.3m)
- WD = Wood Density is the volume-weighted average wood density, tons of oven-dry matter per m^3 of green volume

Indirect Approach

The indirect approach bases the AGB on volume, data often available for commercial plantations. This approach is mentioned in the IPCC Good Practice Guidance, 2003 and is based on the equation from Brown, 1997. This approach is applicable for plantation forests because of a single-species composition; the characteristics (species, age, WD) of trees are often similar throughout the stand. Variables required for ABG based on volume are Biomass Expansion Factor (BEF) and WD. The BEF variable takes stumps, branches, twigs and leafs into account for calculating the biomass (IPCC, 2006). For this research the BEF default value will be used for broadleaved tropical forests as described by Brown, 1997. BEF has two values, either 1.74 or 2.66. If biomass of inventoried volume (BV) is >190 the BEF is 1.74. Below <190 the BEF value is 2.66. The equations are as follows:

$$\text{Above Ground Biomass (Tons of dry matter/ha)} = \text{Commercial tree volume} * \text{WD} * \text{BEF}$$

Where:

- Commercial tree volume, m^3 /ha
- Wood Density (WD) is the volume-weighted average wood density, tons of oven-dry matter per m^3 of green volume
- BEF = biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of commercial volume), dimensionless.

$$\text{BV (tons per ha)} = \text{Tree Volume} * \text{WD}$$

Where

- Tree Volume is in m^3 per ha
- Wood Density (WD) is the volume-weighted average wood density, tons of oven-dry matter per m3 of green volume

Table 4: Allometric equations with model numbers and different parameters used in this research; *AGB = Above ground biomass, WD = Wood density, DBH = Diameter at breast height*. For future reference model numbers are indicated by 1, 2 or 3.

Source	Model no.	Allometric equation	Study area/region
Basuki, et al. 2009	1	ln(AGB) = 2,193+2,371*ln(DBH)	Lowland mixed Dipterocarp forests, Kalimantan, Indonesia
	2	ln(AGB) = -1,533+2,294*ln(DBH)+ 0,56*ln(WD)	Lowland mixed Dipterocarp forests, Kalimantan, Indonesia
	3	ln(AGB) = -2,758+2,178*ln(DBH)+ 0,463*ln(H)	Lowland mixed Dipterocarp forests, Kalimantan, Indonesia
Chave, et al. 2005	1	AGB = WD*Exp(-1,499+(2,148*ln(DBH)) +(0,207*ln(DBH)^^{2})-(0,0281*ln(DBH)^^{3}))	Moist Tropical Forests
	2	AGB = Exp(-2,997+ln(WD)*(DBH^^{2})*H	Moist Tropical Forests
Chave, et al, 2001	1	AGB = Exp(-2+2,42*ln(DBH))	Moist Tropical Forests
Chave, et al, 2008	1	AGB = WD*Exp(1,499+2,148*ln(DBH)+ 0,207*ln(DBH)^2-0,0281*ln(DBH)^3)	
Brown, et al. 1997	1	AGB = 42,69-12,8*DBH+1,242*DBH^^{2}	Moist Tropical Forests
	2	AGB = Exp(-2,134+2,53*ln(DBH))	Moist Tropical Forests
Kettering, et al. 2001	1	AGB = 0,066*(DBH)^2,59	Mixed secondary forests, Indonesia
	2	AGB = 0,11*WD*DBH$^{\wedge 2+0,7}$	Amazon, Brazil
Kenzo, et al, 2009	1	AGB = 0,0829*DBH^^{2,43}	Secondary forest, Sarawak, Malaysia

Wood density

WD or wood specific gravity is an important factor for tree carbon content calculations and leads to more accurate results (Chave, et al., 2005). WD is defined as the oven dry mass divided by fresh volume (living biomass) (Verwer & van der Meer, 2010). WD values are collected by destructive sampling methods, where wood samples are taken from trees and oven dried (103 C˚) in order to predict WD values. A common source of error among WD inventories is that WD varies at parts of the stem. Inventories should measure the trunk, middle stem and base of the crown for average wood; not doing so will result in over-estimation (Basuki, et al., 2009). This is nearly impossible to perform in every study site or carbon stock assessment, since its time consuming, expensive and destructive for the trees. Wood densities can vary amongst forest types, age, growing condition, stand density and climate (IPCC, 2003). Therefore global data bases have been created that contain the WD of tree species including information at what location the samples have been measured. This global WD data base might not always contain the WD of every species; this could be improved by taking regional samples or existing information on wood densities. According to IPCC 2003 Good Practice Guidance, it's considered wise to derive wood densities from the study sites, next to plot locations, to get accurate measurements on wood densities. But regional sampling might not always collect sufficient data, in contrary to global data sets which usually have a larger sampling data set. When calculating carbon stocks, global data sets should be used as standard variables, instead of regional or local sampling data sets (Flores & Coomes, 2011), unless local data sets have a large sample size. For this research, the WD values of the global data base compiled by Zanne, et al. 2009 in combination with the local WD values will be applied. If species WD values are missing, the species family name values will be derived instead. Local WD values were derived from the Timber Research Center, in Sarawak, Malaysia (Table 5). Because dead wood has a different (often lower) WD values than living trees, a different WD value will be used for dead wood. Since local data on WD values on dead wood was not available, a WD value of 0.5 g/cm$^{\wedge 3}$ is often used for reference for dead wood as described by Delaney, et al., 1998. However, since most Shorea species in this study have a lower WD than 0.5 g/cm$^{\wedge 3}$, the WD values of each species used for estimating AGB will be applied for CWD as well and a slight overestimation of carbon might occur.

Table 5: Average WD and sample size listed per species per region. ***Wood density values used in this research*****. TRC= Timber Research Center (located in Sarawak).**

Species (*Shorea*)	Average Wood density (g/cm$^{\wedge 3}$)	Sample size (n of trees)	Region	Source
S. splendida	0,550*	-	Asia (tropical)	Brown, 1997; FAO
S. hemsleyana	0,650* -	129 -	South-East Asia (tropical) -	Zanne, et al. 2009
S. pinanga	0,363 0,390*	466 47	South-East Asia (tropical) Malaysia, Sarawak	Zanne, et al. 2009 TRC
S. macrophylla	0,320 0,350*	119 33	South-East Asia (tropical) Malaysia, Sarawak	Zanne, et al. 2009 TRC
S. palembanica	0,453* 0,470	332 10	South-East Asia (tropical) Malaysia, Sarawak	Zanne, et al. 2009 TRC
S. stenoptera	0,330* 0,440	296 12	South-East Asia (tropical) Malaysia, Sarawak	Zanne, et al. 2009 TRC
Eusideroxylon zwageri	0,787*	520	South-East Asia (tropical)	Zanne, et al. 2009
Unknown	0,519*	-	South-East Asia (tropical)	Average taken from Shorea species

2.3.2 BELOWGROUND BIOMASS

The BGB can be defined as the biomass of living coarse and fine roots of trees (Verwer & van der Meer, 2010). Data collection for BGB is often performed by the excavation of trees and measuring the roots and calculating carbon content. Since this methodology is destructive and time consuming to measure, allometric models for BGB have been developed. These allometric equations related DBH to BGB. A study by Niiyama, et al., 2010, performed in Peninsular Malaysia, determined that the biomass-partitioning ratio of the BGB/ABG was 0.18 (18%). Niiyama, et al., 2010 research was applied on Dipterocarp tropical forests and is also applicable for old growth Dipterocarp tropical forests. A study by Sierra, et al., 2007 determined that the BGB in primary forests consisted of 10% of the total biomass. Several allometric models for BGB have been developed (Niiyama, et al., 2010; Kenzo, et al., 2009; Sierra, et al., 2007), but not all are applicable to this research area. The allometric equations summarized in table 6 will be compared to each other; the allometric equation used in this research is developed by Niiyama, et al., 2010 and is as follows:

$BGB_{\text{(Coarse roots)}} = 0.023*DBH\hat{}^{2,59}$

Where:

- $BGB_{\text{(Coarse roots)}}$ = Below Ground Biomass in kg
- DBH = Diameter at Breast Height (1.3m)

Table 6: Allometric equations for BGB; BGB = Below ground biomass, DBH = Diameter at breast height.

Source	Allometric equation	Study area
Niiyama, et al., 2010	$BGB_{\text{(Coarse roots)}} = 0.023*DBH\hat{}^{2,59}$	Primary lowland Dipterocarp forests, Pasoh, Malaysia
Kenzo, et al., 2009	$BGB = 0.0214*DBH\hat{}^{2.33}$	Secondary forests, Sarawak, Malaysia
Niiyama, et al., 2005	$BGB = 0.02186*DBH\hat{}^{2.487}$	Primary lowland Dipterocarp forests, Pasoh, Malaysia

2.3.3 COARSE WOODY DEBRIS AND LITTER BIOMASS

CWD consists of large pieces of standing and fallen dead wood. The CWD carbon pool plays significant roles in the ecological processes, such as nutrient cycling. Depending on ecological zone, forest type, stage of succession, land-use history and management practices, the CWD carbon pool can contain significant carbon contents (Clark, et al., 2002) and is therefore an important carbon pool to include. The CWD can be divided in two components; dead standing wood and dead lying wood. Together with litter biomass, the CWD data collection is described below:

Dead standing wood

Dead standing trees biomass data is collected and calculated according the same allometric models as living trees. The difference in dead standing trees is that they often lack branches and twigs, depending on the stage of decomposition, and biomass reductions should be taken accordingly (IPCC, 2003). This research notes dead standing trees as part of the field inventory and DBH and height will be measured. For data analysis, dead standing trees will use the equations of DBH + height by Basuki, 2009, (model 3), otherwise an overestimation of the actual biomass will occur.

Dead lying wood

Dead lying wood was not inventoried in this research. However the potential of carbon stored in dead lying wood can be similar to dead stand wood. Dead lying wood is often inventoried by the use of transects, depending on the size of the plots. For an estimation of the lying dead wood, a percentage of 39% to 58% of the standing dead wood will be taken, as 42% to 61% of the total carbon in CWD was standing dead wood (Delaney, et al., 1998). These percentage values taken for lying dead wood should be considered as a rough estimate and not accurate, since research on these values were performed in Venezuela and might be different in forest plantations or other ecological zones.

Litter

Several elements make up the litter carbon pool. The litter types consist of leaves, small wood fragments (usually <2 cm), flowers and fruits, and trash. Litter decomposition is influenced by several factors, consisting of site environmental conditions (climate), litter quality and soil biota. In the Semengoh Forest Reserve (study area), the decomposition rate is relatively slow due to a low P concentration and high acid insoluble residue concentration (Hirobe, et al., 2004). Methods for litter collection is commonly performed by litter traps in small sample plots (1 m^2) and measured over time (monthly/periodically). In the Semengoh Forest Reserve there has been litter trap research by J. Sabang, et al., (unpublished data). This study was not focused on the plantation forests, but on the natural Dipterocarp forests of Semengoh, including a variety of Shorea species (Hirobe, et al., 2004). The results from that study and similar studies will be used to indicate litter biomass in Shorea plantation forests.

2.3.4 SOIL DATA

Soil maps have been derived from the Sarawak Forestry Department. Although sufficient soil data could be collected from these soil maps, no further carbon data was found and could be linked to these soil groups. Further literature data on carbon in soils that are related to the study area will provide an average carbon content per ha.

2.3.5 ESTIMATION OF CARBON STOCKS

The biomass carbon stock was calculated by assuming that the carbon content is 50% of the total biomass, as described in the IPCC and thus considered *Good Practice* (IPCC, 2006).

2.4 DATA ANALYSIS

Data collected on the field forms were converted to Microsoft Excel and are analyzed in Microsoft Access. For mapping of the study area ArcMap and Basecamp (Program that linked the coordinate data in the GPS and allowed it to be converted to ArcMap) were used. Plot 4b is excluded from analysis because of its small sample size (0.11) and possible inaccurate results. Species that were common in several plots are not combined for the reason that management options carried over years might have influenced the growth of the species. Therefore management options might be important for future references (Although these are often unknown).

2.5 STATISTICAL TESTING

For statistical analysis an ANOVA-One tailed test is performed between the means of the diameters and biomass (Basuki, 2009 model 2) of the groups. The test should indicate if there is a significant difference between the groups. Significant differences are indicated by unlikely or statistically significant ($P<0,05$), unlikely or statistically highly significant ($P<0,01$) and extremely unlikely or statistically very highly significant ($P<0,001$). No Tukey test could be performed due the uneven samples between the groups; a Tukey test indicates between which groups there is a significant difference, because not all the groups might differ significantly from each other.

3. Results

3.1 PROPERTIES OF FOREST STAND

The basal area in m2 (BA_m2), volume in m^3 (Vol_m^3) and number of trees per hectare (N_ha) are listed in Table 7. For these calculations the base crown height values are used. This is the volume that can be converted into biomass, it is important to realize that this is not the commercial volume. The different diameter classes, species and dead trees are incorporated in the table and have been summed up for a total value. The classes are as follows: <30 cm DBH, <30 cm DBH dead trees, >=30 cm DBH for Shorea species, >=30 cm DBH Shorea dead trees, >=30 cm DBH unknown species. For complete data on the different DBH classes see annex V.

Table 7: The plot numbers with Basal Area (Ba_m2), volume (Vol_m^3) and number of trees (No_ha) for all the trees >=5 cm DBH.

Plot no.	BA_m^2	Vol_m^3	No_ha
4c	32,05	381,90	1384
5c	26,03	340,25	833
7c	22,12	283,30	398
9	26,06	190,20	1255
12	23,60	263,18	1154
13	24,46	194,75	518
14	26,27	253,78	860

The density of the trees for most plots varied significantly (Figure 3). For the small diameters (>=5 - <30 cm), Plot 4c and 9 had over a 1000 small diameters trees per hectare. Whereas plot 7c and 13 had almost 2.5 times lower density values for the smaller diameter trees. A similar result for the diameter class 30-54 cm, where plot 7c and 13 again have a low density compared to other plots. Most likely this is the result of the high amount of dead standing trees within these plots, mainly Shorea macrophylla (plot 7c) and Shorea splendida (plot 9 and 13) were severely degraded.

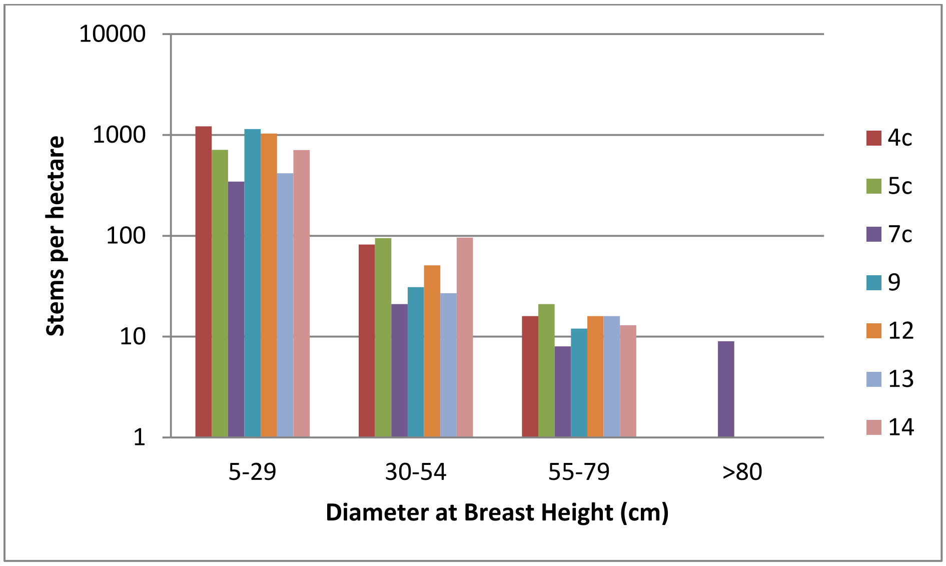


Figure 3: The total number of trees per hectare in different diameter classes. Data is in logarithm scale, for complete data see Annex III.

3.2 CARBON STOCKS IN DIFFERENT POOLS

3.2.1 ABOVE GROUND BIOMASS

Direct approach

The data was applied to all allometric models applicable to the research area and is simulated in figure 4. A clear difference can be distinguished between the allometric models. The AGB differed highly significant between the plots (ANOVA: F=23,8, p<0,001). Kettering_2, Brown_2 have a much larger DBH–biomass relation than most other models. Kenzo_1 and Basuki models have almost twice as low DBH – biomass relation than the top models. Kenzo_1 model is applied on secondary forests, which could explain why the low DBH – biomass relation occurs.

The total AGB biomass per allometric equation and model are simulated in figure 5. In this scenario each allometric model has the specific parameters for each Shorea species, giving an accurate estimation of the AGB stocks per plot. Shown is that both Brown models (model 1 and 2) reflect the highest AGB estimates. Other allometric models show a variation between the plots, on occasions topping other models and at other times with results below the comparing models in different plots (e.g. Chave,2001_1 comparing plot 14 with other plots).

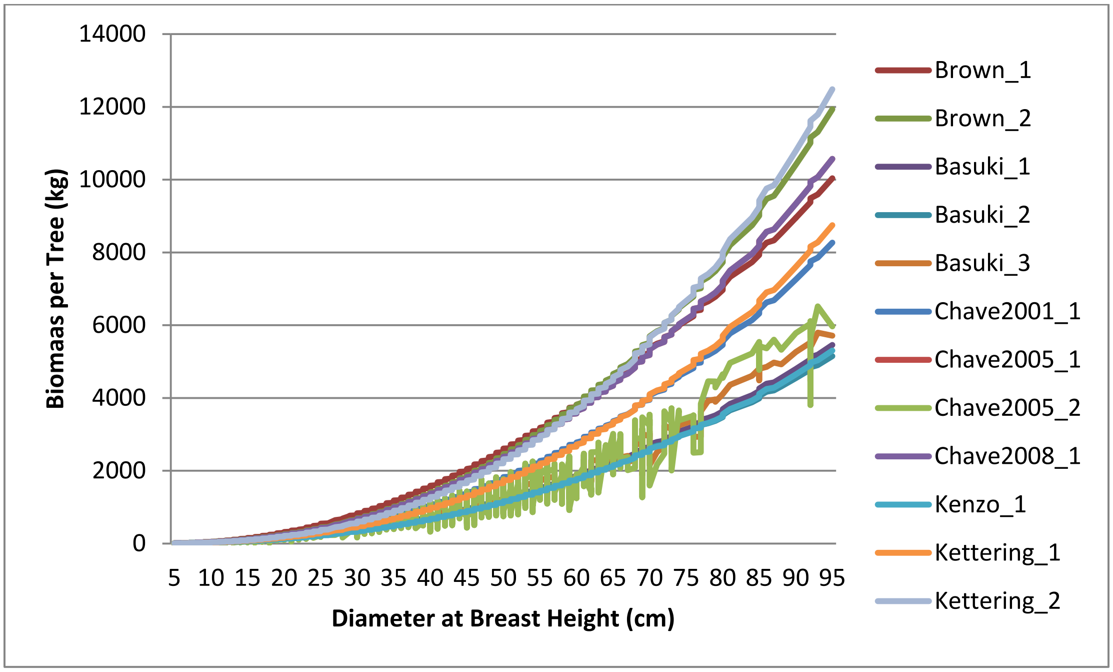


Figure 4: Living AGB simulated and compared by different allometric models with a biomass per tree in relation to DBH.

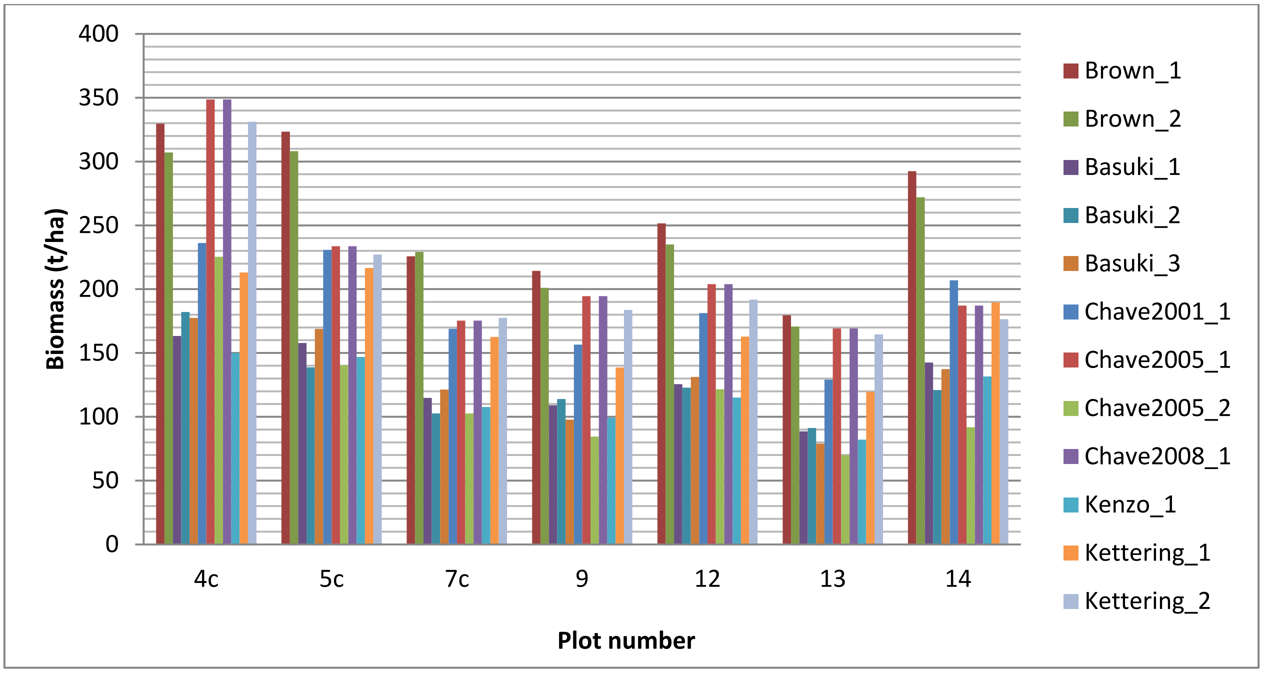
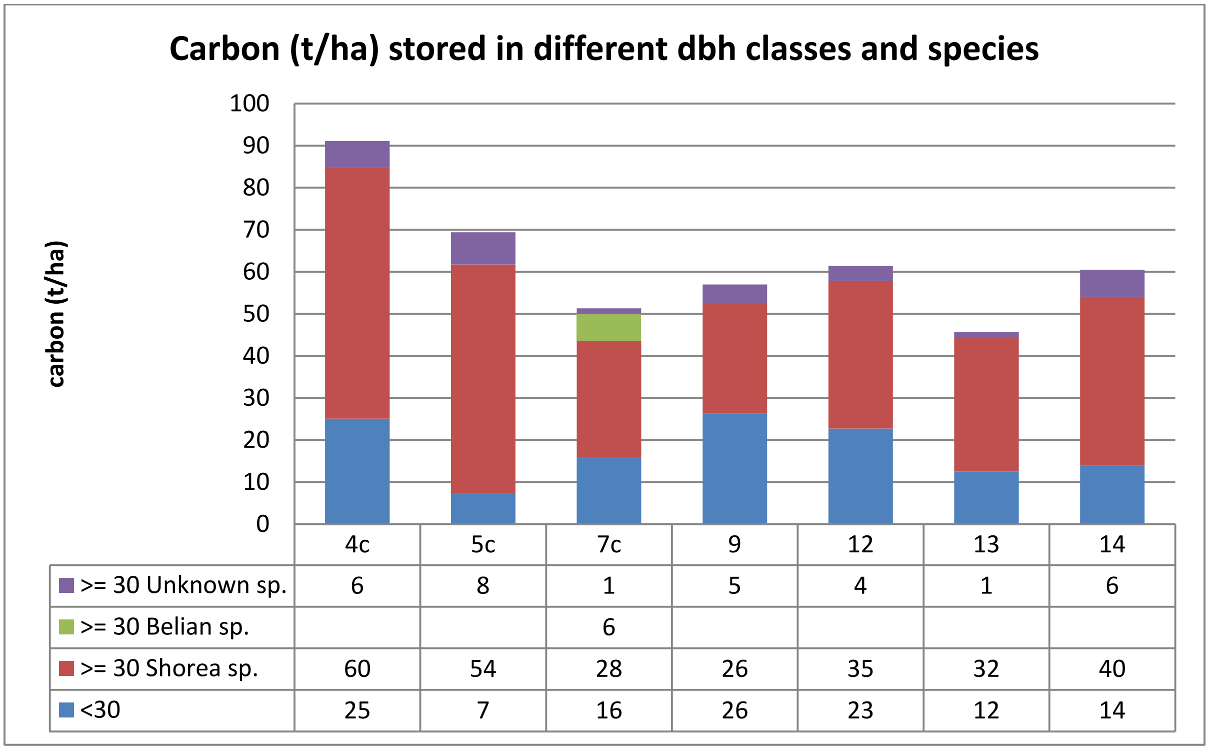


Figure 5: biomass (t/ha) for each allometric model and plot. Data in values are listed in Annex VI

The carbon (t/ha) stored in the AGB is distributed among species and DBH classes (Figure 6). For all the plots the Shorea species contributed to the highest carbon storage and for most plots the <30 DBH class stored secondly the most carbon. Plot 9 had an equal amount of carbon stored in Shorea species as in the <30 DBH class of unknown species. Overall the unknown species of the DBH class >=30 contributed little to the AGB.



	4c	5c	7c	9	12	13	14
🟪 >= 30 Unknown sp.	6	8	1	5	4	1	6
🟩 >= 30 Belian sp.			6				
🟥 >= 30 Shorea sp.	60	54	28	26	35	32	40
🟦 <30	25	7	16	26	23	12	14

Figure 6: Carbon content distribution (t/ha) of the AGB per DBH classes and species, based on the allometric model of Basuki_2.

Indirect approach

The indirect approach used the volume, WD and BEF values to calculate biomass per hectare for each plot (Table 9). Dead standing wood was not incorporated into the calculations, the values listed in Table 8 are living AGB. However it should be noticed that unknown species have been given the same WD value as the Shorea species of that specific plot, giving it a slight overestimation of the actual biomass. This indirect approach is however just simulating how the biomass and carbon levels might vary from the direct approach. It shows that the carbon content is slightly higher than the allometric models developed by Brown, 1997.

Table 8: AGB and carbon levels listed in t/ha per plot, based on the model by Brown, 1997 and IPCC

Plot no.	AGB (t/ha)	Carbon (t/ha)
4c	399	200
5c	347	174
7c	203	102
9	227	113
12	304	152
13	185	93
14	210	105

Annual AGB increment

The annual AGB increments ranged from 0.57 t/ha (plot 4c) to 2.33 t/ha (plot 13) from the year of establishment to 1974. For the time period of 1974 to 2013 the annual AGB increment ranged from 0.82 t/ha (plot 13) and 3.08 t/ha (plot 4c). The annual AGB increments are listed in table 9, for complete data see annex VII.

Table 9: Annual AGB increments from year of establishment to 1974 and from 1974 to 2013 in t/ha.

Plot no.	AGB (t/ha) in 1974	annual AGB increment from establishment - 1974 (t/ha)	AGB (t/ha) in 2013	annual AGB increment from 1974- 2013 (t/ha)
4c	22	0,57	120	3,08
5c	45	1,16	108	2,77
7c	64	1,74	56	1,44
9	41	1,13	52	1,33
12	34	1,01	70	1,79
13	79	2,33	32	0,82
14	42	1,44	40	1,03

3.2.2 Below Ground Biomass

The allometric models used for BGB assessment are simulated and compared in figure 7. A clear difference can be distinguished between the allometric models. Niiyama's model from 2010, the allometric model used in this research, has the highest DBH-biomass relation.

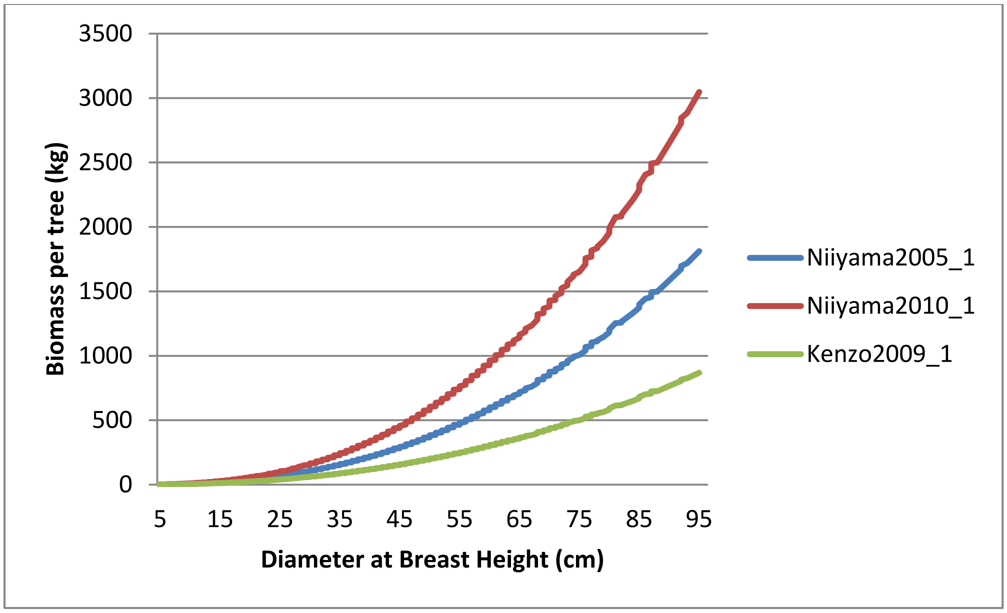


Figure 7: Different allometric models compared on DBH-biomass relation for BGB.

Data limitations on BGB are that the dead trees are excluded from biomass calculations, since dead and decaying wood might have a different amount of BGB. The data used and combined in the calculations of this research are listed in table 10.

Table 10: BGB and carbon (t/ha) for the different DBH classes and species based on the allometric model of Niiyama, 2010.

		Plot no.						
		4c	**5c**	**7c**	**9**	**12**	**13**	**14**
DBH Class	<30	17,02	4,70	11,84	18,14	15,57	8,94	9,41
	>=30 Shorea species	51,73	62,93	39,05	25,87	37,92	31,54	50,97
	>=30 Unknown species	5,19	7,84	1,13	4,30	3,25	1,17	5,69
	Total biomass (t/ha)	73,93	75,47	52,02	48,31	56,75	41,65	66,07
	Total carbon (t/ha)	**37**	**38**	**26**	**24**	**28**	**21**	**33**

3.2.3 Coarse Woody Debris and Litter

Two applicable research data results are listed in Table 11, both performed in Sarawak. Litter research and results performed in the Semengoh Forest Reserve by J. Sabang (Sabang, et al., 2005) will be used to indicate litter biomass for this research. Values from that research were mainly on leaves and resulted in an 8.6 t/ha of leaf litter in mixed Dipterocarp forests in the Semengoh Forest Reserve.

Table 11: Litter biomass data of applicable research results.

Source	Litter biomass (In tons of dry matter/ha)	Litter carbon content (t/ha)	Forest type	Study area
Proctor, et al., 1983	8.8	4,4	Dipterocarp forest	Gunung Mulu National Park, Sarawak, Malaysia
J. Sabang, et al. Unpublished data	8.6 (Leaves only)	4,3	Dipterocarp forests (including Shorea sp.)	Semengoh Forest Reserve, Sarawak, Malaysia

Dead standing wood and dead lying wood biomass are presented in table 12 for each plot. The lying dead wood is related to the standing dead wood biomass, increasing the total carbon pool of CWD when the dead standing biomass is high. Plot 13 (*Shorea splendida*), 7c (*Shorea Macrophylla*) and 9 (*Shorea splendida*) have the highest dead standing wood, which can be confirmed from field notations. Dead standing wood was not found in unknown species in the diameter class of >=30 cm DBH. For an indication on the distribution of dead standing wood in different species and DBH classes, see annex V.

Table 12: Dead standing wood and lying dead wood biomass (t/ha) and carbon content (t/ha) per plot, using the allometric model by Basuki_3 (DBH and height as parameters).

Plot no.	Standing dead wood biomass (t/ha)	Carbon content standing dead wood (t/ha)	Lying dead wood biomass (t/ha)	Carbon content lying dead wood (average t/ha)	Total carbon in CWD (t/ha)
4c	18,1	9,0	7 - 10	8,5	**17,5**
5c	4,5	2,2	1,7 - 2,6	2,2	**4,4**
7c	39,7	19,9	15,5 - 23	19,3	**39,2**
9	27,7	13,9	10,8 - 16,1	13,5	**27,4**
12	7,2	3,6	2,8 - 4,2	3,5	**7,1**
13	49,9	24,9	19,5 - 28,9	24,2	**49,1**
14	9,9	5,0	3,9 - 5,8	4,9	**9,8**

3.2.4 SOIL

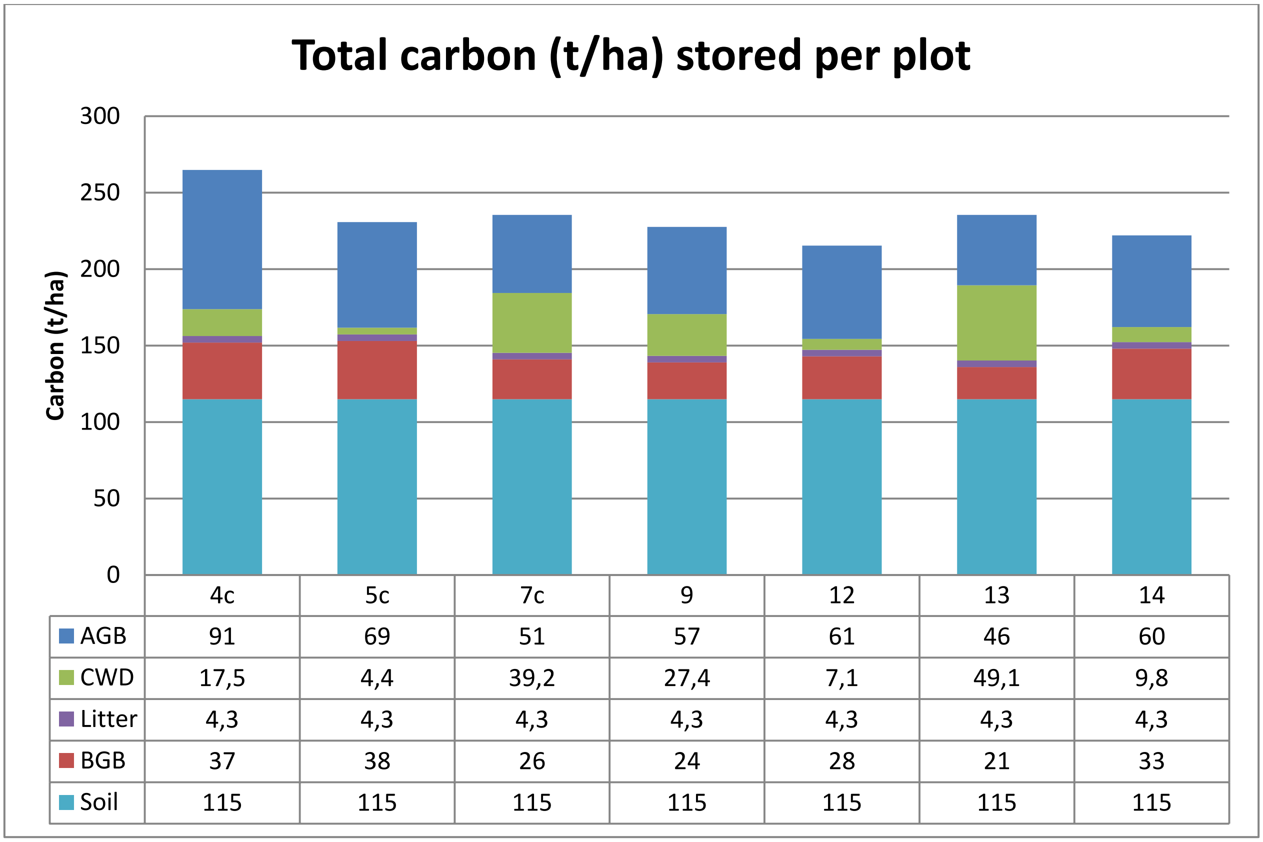
The soil of all the Engkabang plots in the Semengoh Forest Reserve can be classified as alluvial soil (S.S. Tan, 1987). Soils maps have been derived from the Sarawak Forestry Department (Annex IV), however no further research on SC storage that was specifically for the Semengoh Forest Reserve area was found. Therefor the soil data used in this research in generalized, and will indicate the SC capacity of a soil groups. According to IPCC values, tropical soils store around 136 t/ha. A more accurate estimate is summarized by Soepadmo, 1993 on data by Proctor et al., 1983, with specific soil estimates of the Sarawak region, Malaysia (Table 13). The study area is located on alluvial soils (S.S. Tan, 1987), giving it a average of 230 t of organic matter. Carbon content is 50% of soil organic carbon (Soepadmo, 1993), which results in a 115 t/ha of carbon.

Table 13: Soil organic matter and carbon storage in different forest types located in Sarawak, Malaysia. Data by: (Soepadmo, 1993).

Study area	Forest type	Organic Matter storage (t/ha)	Carbon storage (t/ha)	Source
Sarawak, Malaysia	Lowland Rain Forest on alluvial soil	210-250	105-125	Proctor et al., 1983
Sarawak, Malaysia	Lowland Dipterocarp forest	650	325	Proctor et al., 1983

3.2.5 TOTAL CARBON STOCK

The current total carbon stock in the different plots are as follows; 4c = 265 t/ha, 5c = 231 t/ha, 7c = 235 t/ha, 9 = 228 t/ha, 12 = 215 t/ha, 13 = 235 t/ha, 14 = 222 t/ha. Figure 8 stacks the different carbon pools together. Plot 4c (*Shorea hemsleyana*), has the highest carbon storage capacity. Most likely this is the result of high WD values and a healthy state of the forest (low amount of CWD). Although plots 7c and 13 (*Shorea macrophylla and Shorea splendida*) have a high amount of CWD, yet still contain a high amount of carbon. A slight overestimation did occur due the lack of accurate WD values on dead and decaying wood, giving plots with a high amount of CWD, an overestimation of carbon.



	4c	5c	7c	9	12	13	14
🟦 AGB	91	69	51	57	61	46	60
🟩 CWD	17,5	4,4	39,2	27,4	7,1	49,1	9,8
🟪 Litter	4,3	4,3	4,3	4,3	4,3	4,3	4,3
🟥 BGB	37	38	26	24	28	21	33
🟦 Soil	115	115	115	115	115	115	115

Figure 8: Stacked graph of the carbon (t/ha) for the different carbon pools per plot.

4. Discussion

4.1 CARBON STOCKS IN SHOREA PLANTATION FORESTS

The potential of forests and plantation forests to sequester and store carbon depends on a variety of factors, such as forest type, age (Pregitzer & Euskirchen, 2004) of the forest and size of the trees. Other influences are also applicable that contribute to a carbon stock, such as environmental aspects (rainfall, temperature, ecological zone). Furthermore, the Shorea plantation plots are located on highly fertile soils and have a high amount of rainfall (S.S. Tan, 1987), which influences growth patterns, and the growth rate of the same species might differ significantly on other ecological zones/soil types.

The difference in carbon stock of the Engkabang plots are related to differences in WD, DBH, height and tree density. Some of the Engkabang plots showed a high amount of CWD and low trees per hectare, yet still contain similar carbon values (plots 7c, 9 and 13). Plot 4c (*Shorea hemsleyana*) had the highest WD value (0.65) and was considered a healthy plantation forest with a low amount of CWD. This plot also had almost double the AGB than most other plots. It is important to note that CWD factors used the same WD value as living biomass, giving it an overestimation of carbon. Therefore plots with a high amount of CWD would most likely have lower carbon content. The biomass and annual AGB increment for most plots can be related to the increase amount of CWD. For plot 4c however, data used from previous research showed different than expected. Mentioned in research from S.S. Tan, 1987, plot 4c had an average of 40 trees per hectare between the year of establishment and the last assessment (1974), while this research indicates that currently the trees per hectare are almost double (84 per ha). This also explains the high annual AGB increment from plot 4c (3.08 t/ha), while other plots are significantly lower in that specific timeframe.

4.2 CARBON STOCKS IN THE DIFFERENT FOREST PLANTATIONS AND FOREST TYPES

There are a limited number of studies on carbon stocks of Malaysia Dipterocarp forests (DiRocco, 2012). AGB stock estimates in this study (AGB 92-182 t/ha) were similar to those mentioned in the IPCC, 2003 for forest plantations in Asia (AGB 130-180 t/ha) (IPCC, 2003). Important is to know that the annual AGB increment in this study was solely on the Shorea species in the plots, excluding unknown species, so data could be compared to previous research. Natural forests produced a much higher amount of AGB (180-280 t/ha) than the results of this research. It is unknown what plantations types are listed in the IPCC, possibility could be that most of these plantations consist of fast growing exotic species for the paper pulp industry, such as *Eucalyptus* species. Other Shorea community- and natural forests, mainly Shorea *robusta* (Singh, et al., 2009) (Magar, 2012), located in Nepal and the Himalayan area, showed a much higher biomass level, but information (age, species composition, management) was often lacking and access to these researches was restricted, furthermore, most research was focused on a specific carbon pool. Other natural Dipterocarp forests stored a total carbon content of 258 t/ha (Lasco, et al., 2006) and 208.8 t/ha (DiRocco, 2012), which are values within the range of the current total carbon stock of the studied plantation plots. The annual AGB increment in this study compared to IPCC, 2003 data, resulted to be rather low. This could however be the result of no (clear) management practices on the plots in this study, whereas the plots mentioned in the IPCC could have had management practices to increase biomass (mainly for timber production enhancement), such as thinning and/or fertilizer applications. Research on selectively logged natural Dipterocarp forests in Sabah resulted in a total carbon stock of 167.9 t/ha (Saner, et al., 2012), which was almost 40 to 90 t/ha lower than this research (215-265 t/ha). For more data on forest types, biomass storage and annual AGB increments see annex VII.

4.3 MANAGEMENT OPTIONS AND INFLUENCES ON CARBON STORAGE

Results from other studies on carbon stock and carbon stock enhancement in Shorea community forests indicate that carbon stock increases with management duration of forests (Magar, 2012). A similar study on carbon stocks of European forests also indicated an increase in carbon stock with an increase in management and rotation period (Kaipainen, et al., 2004). The Verified Carbon Standard (VCS) also mentions that forests projects can enhance carbon stocks with an increase in management duration and developed specific methodologies. This study clearly indicates that some of the plots are in a continues degrading process, the annual AGB increment and basal area of the trees support that hypothesis. The species that are degrading are fast growing species with a low WD value, such as Shorea *macrophylla* (plot 7c) and Shorea *splendida* (plot 9 & 12). These species have a high amount of dead standing and dead lying wood, which although benefits the CWD carbon pool, it has a negative impact on the timber production. It should be taken into account when using these Shorea species for timber production and carbon storage, that the management duration should be optimal, and that these are lower than the age at what most of these plots are currently (now +/- 80 years). Other plots such as Shorea *hemsleyana* have a higher WD value and grow slower, which can be indicated by the average diameter. These species can have a longer management and rotation period for optimal carbon storage and still provide high quality timber at the end of the rotation period. However it is important to point out that a low WD value does not necessarily mean that the species is fast growing and contains a lot of CWD. Shorea *pinanga* has a WD value of 0.39 and is still in a productive state (plantation forest) with a low amount of CWD.

Besides management rotation, other management options can be applied to increase specific carbon pools and thus the total carbon stock. From visual field sightings on climbers, the plots contained climber species such as lianas, resulting in damaged trees and affecting the growth rate. Research indicates the carbon stocks in tropical forests decreases with liana density (Durán & Gianoli, 2013). Although lianas do store carbon, climbers will negatively affect the growth rate of trees and thus the AGB and carbon stock. Applying liberation management on the trees and free the tree species from climbers will improve the growth rate. Enrichment planting also shows promising results, planting a diversity of species instead of monocultures provides social, ecological and environmental benefits (Paquette, et al., 2009), which in turn allows access to carbon schemes and provide more carbon credits or higher values carbon credits. For planting of Shorea species, it’s recommended not to plant under a canopy, as this clearly retards growth. The same research indicates there are good prospects for line planning of Dipterocarps (including Shorea species) (Ådjers, et al., 1995). No relation to growth rate and carbon has been discussed in Ådjers, et al., 1995 research, but increased growth rate should increase biomass and carbon. Gap liberation is a viable management option that is economically feasible as well; a clear difference in volume for red meranti (high value timber group) showed volumes of 90 m^3 in liberated gaps and 36 m^3

in untreated areas (Kuusipalo, et al., 1997). Under certain circumstances, managed forests can store and sequestrate more carbon than unmanaged or natural forests (Dewar & Cannel, 1992).

4.4 THE IMPORTANCE OF APPLYING THE RIGHT ALLOMETRIC MODELS

Looking at the carbon content (t/ha) of the different allometric models, there is a clear difference between the carbon values (Annex VIII). Some allometric equations and related models (Brown, Chave, Kettering) can have over twice as much biomass/carbon (t/ha) as other allometric equations (Basuki, Kenzo). This research indicates the importance of choosing the correct allometric model, as choosing the wrong model is a common error amongst AGB estimates (Chave, et al., 2004). Local specific parameters show to be important for carbon estimates. In this research the model with DBH and WD parameters was used, developed by Basuki, et al. 2009 in Kalimantan on Dipterocarp forests, including parameters for Shorea species.

4.5 PROSPECTS ON CARBON-OFFSET SCHEMES

There are two carbon markets, the compliance and the voluntary programs. Examples of compliance schemes are the Kyoto Protocol and the European Union's Emissions Trading Scheme. Over the last few decades there has been a strong development on different carbon standards, mainly on the Voluntary Carbon Market (VCS). REDD+ is still under development and therefore there is no specific guideline set out for this standard. Malaysia's status on REDD+ is still ongoing and is being attempted to implementing and making Malaysia REDD+ ready. However, one can prepare REDD+ project readiness by using Voluntary standards, which has a more developed REDD+ standard for VCS projects. These are usually a combination of existing standards, usually incorporated into step by step guides. Voluntary standards that are quite common are the Climate, Community & Biodiversity Standards (CCBS), Plan Vivo System and Carbon Fix Standards (CFS). All of these standards have a more or less common goal; protect biodiversity, help local communities, poverty alleviation and conserve forest areas or reforest deforested or degraded areas.

Currently the definition on what is divined as 'forest plantation' are rather vague, where even oil palm plantations are eligible for carbon sequestration schemes such as REDD+. In Sarawak, the local people have showed interest and acceptance of REDD+ in the form of rubber plantation scheme (Phua, n.d.). Countries are currently developing national carbon schemes and including plantation forests are aspects of these schemes, examples are Australia (Plantations2020, n.d.). To apply for carbon schemes, the main questions remain the same, are the forest plantations additional (as such, what would have happened to the planted area without the plantation?) and permanence (how long do the trees have to stay in the ground?). Another important aspect is whether harvested timber will be considered a carbon emission, even though research indicates that carbon remains stored in the harvested products, for their final product duration (Mohren, et al., 2012) (Plantations2020, n.d.) (ITC/ITTO, 2002). Up to date (2013) it is hard to indicate the readiness for forest plantations to join carbon schemes, options are for Malaysia to develop specific national carbon schemes, however recognized by international standards for carbon credit trading.

5. Conclusion

The current total carbon stock varied with the different plots and Shorea species of the plantation forest. Comparing different allometric models showed a remarkable difference in carbon stock, sometimes with differences over 50% in biomass. It indicates the importance of using the correct allometric models for biomass estimates, for this research the allometric model developed by Basuki, 2009, with WD and DBH parameters was considered the most applicable and accurate. The current total carbon stock varied from 215 t/ha (plot 12) to 265 t/ha (plot 4c). The difference in AGB was much greater between the plots, in some cases over 50%. The results support that high WD value species (*Shorea hemsleyana*) can take longer management/rotation duration because they are often slow growing. Results also support however that low WD species not necessarily require a short rotation period (*Shorea pinanga*). The annual AGB increment ranged from 0.57 t/ha to 2.33 t/ha from the establishment year to the last assessment of 1974 and ranged from 0.82 t/ha to 3.08 t/ha from the last assessment of 1974 to the current study, these are however specifically for the Shorea species in the plots. The high amount of CWD debris indicates that most plots exceed their management duration. With the right management and especially management rotation, the studied Shorea species can make a contribution to carbon storage, reducing CO_2 concentrations in the atmosphere, and still provide the high quality timber and NTFP's. Therefor these Shorea species can be planted for reforestation/afforestation projects or plantation forests for timber products, to reduce deforestation and forest degradation. Clear guidelines need to be created for plantation forests to join carbon schemes, for assessing leakage and additionally of the plantation forests.

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Appendices

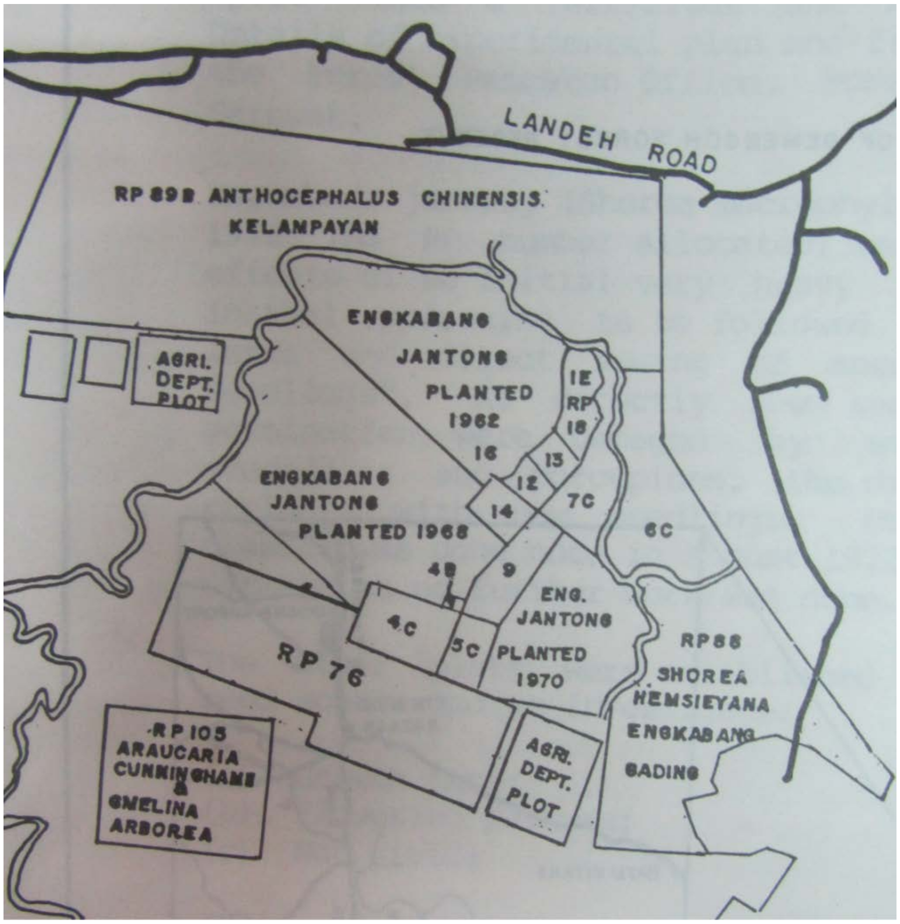
ANNEX I: Example field forms for >=30 cm DBH

Plot number:	Date:
Plot size:	Coordinates:
Shorea species:	Team leader:
Soil type: (structure, wet/dry, humus)	Quality: 1,2,3,4

Diam. class: >=30 cm

Tree nr.	Name	Diam.	Height	Quality	Remark

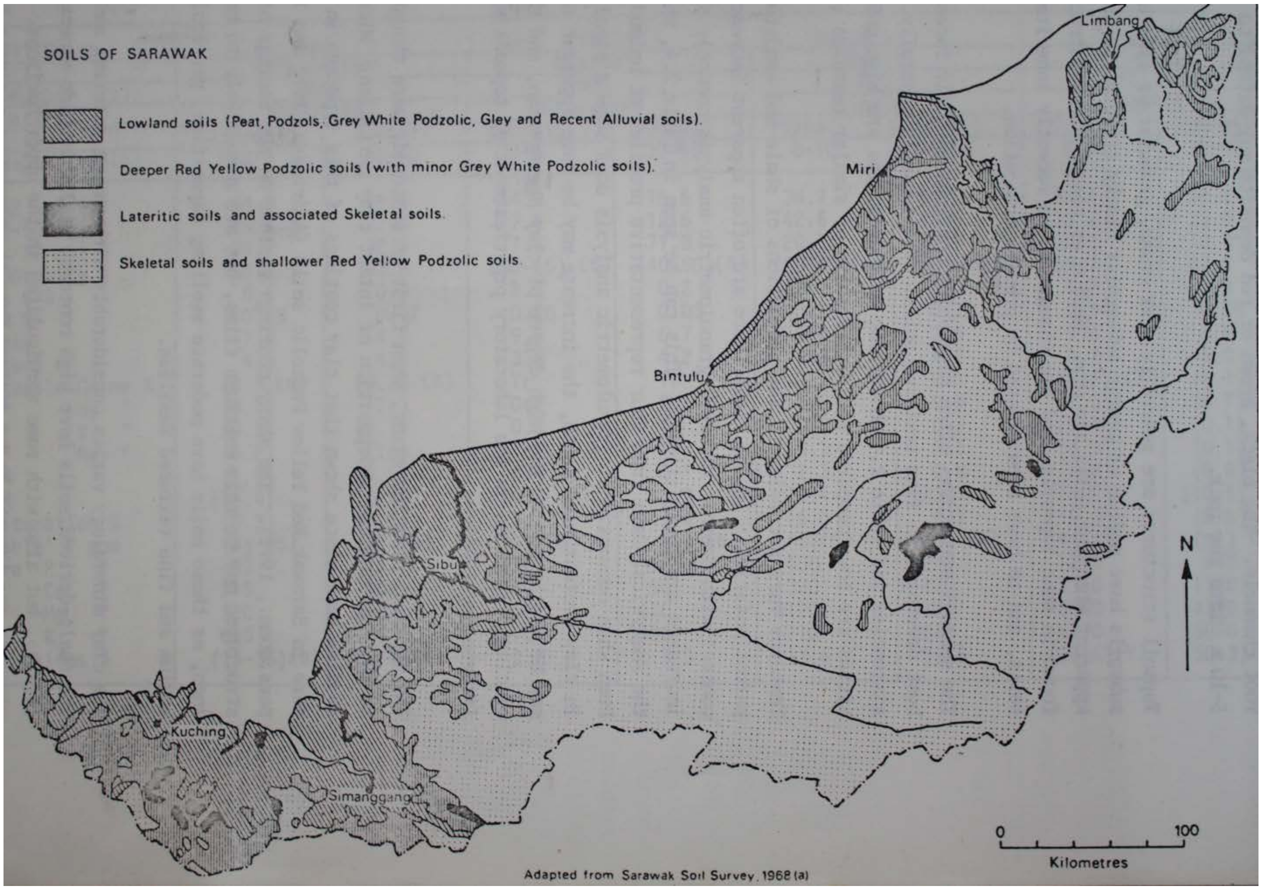
ANNEX II: Location of the plantation plots, indicated by plot number.



ANNEX III: Total number of trees per hectare for the different plots in DBH classes

DBH	*Plot number*							
	4b	**4c**	**5c**	**7c**	**9**	**12**	**13**	**14**
5-29	700	1217	710	345	1144	1033	417	708
30-54	118	82	95	21	31	51	27	96
55-79	27	16	21	8	12	16	16	13
>=80	0	0	1	9	1	0	0	1

ANNEX IV: Soil map of Sarawak. The study area is indicated by Kuching in the southwest corner. The soil type is lowland soils, with red yellow Podzolic soils and alluvial soils.



Adapted from Sarawak Soil Survey, 1968 (a)

ANNEX V: Forest properties, showing the different DBH classes with Basal area, Volume and number of trees per hectare for the different plots.

	Plot no.								
	4c			**5c**			**7c**		
DBH class	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*
<30	11,06	74,59	1217	3,52	16,49	710	6,39	47,68	345
<30 dead	0,50	1,54	46	0,00	0,00	0	0,06	0,20	10
>=30 Shorea	15,68	251,03	84	19,19	282,60	107	9,06	165,17	19
>=30 Belian	0	0	0	0	0	0	1,63	19,29	15
>=30 Shorea dead	3,03	27,43	23	1,10	5,33	6	6,17	65,03	20
>= Unknown	1,79	27,31	15	2,23	35,84	10	0,42	5,23	4
Total	**32,05**	**381,90**	**1384**	**26,03**	**340,25**	**833**	**23,75**	**302,59**	**414**

	Plot no.								
	9			**12**			**13**		
DBH class	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*
<30	11,47	66,25	1144	9,93	63,52	1033	5,22	31,38	417
<30 dead	0,29	0,86	38	0,40	1,12	50	0,54	3,02	8
>=30 Shorea	7,29	71,61	31	11,23	170,23	56	8,92	88,98	38
>=30 Shorea dead	5,55	34,32	31	0,88	11,21	4	9,32	65,16	49
>= Unknown	1,46	17,16	12	1,17	17,11	11	0,45	6,22	5
Total	**26,06**	**190,20**	**1255**	**23,60**	**263,18**	**1154**	**24,46**	**194,75**	**518**

	Plot no.		
	14		
DBH class	*BA_m*^{2}	*Vol_m*^{3}	*N_ha*
<30	6,14	31,15	708
<30 dead	0,26	2,08	25
>=30 Shorea	15,57	182,35	87
>=30 Shorea dead	2,13	11,92	16
>= Unknown	2,17	26,27	24
Total	**26,27**	**253,78**	**860**

ANNEX VI: Biomass and carbon in t/ha for each allometric model and plot number.

		Allometric models					
		Brown_1		*Brown_2*		*Basuki_1*	
		Biomass (t/ha)	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**
Plot no.	***4c***	330	165	307	154	163	82
	5c	323	162	308	154	158	79
	7c	226	113	229	115	115	57
	9	214	107	201	101	109	55
	12	252	126	235	118	126	63
	13	180	90	171	85	89	44
	14	292	146	272	136	143	71

		Allometric models					
		Basuki_2		*Basuki_3*		*Chave2001_1*	
		Biomass (t/ha)	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**
Plot no.	***4c***	182	91	177	89	236	118
	5c	139	69	169	84	231	115
	7c	103	51	121	61	169	84
	9	114	57	98	49	157	78
	12	123	61	131	66	181	91
	13	91	46	79	39	129	65
	14	121	60	137	69	207	103

		Allometric models					
		Chave2005_1		*Chave2005_2*		*Chave2008_1*	
		Biomass (t/ha)	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**
Plot no.	***4c***	349	174	225	113	349	174
	5c	234	117	140	70	234	117
	7c	175	88	103	51	175	88
	9	195	97	84	42	195	97
	12	204	102	122	61	204	102
	13	169	85	70	35	169	85
	14	187	94	92	46	187	94

		Allometric models					
		Kenzo_1		*Kettering_1*		*Kettering_2*	
		Biomass (t/ha)	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**	**Biomass (t/ha)**	**Carbon (t/ha)**
Plot no.	***4c***	150	75	213	107	331	166
	5c	147	73	217	108	227	114
	7c	108	54	163	81	177	89
	9	99	50	139	69	184	92
	12	115	58	163	81	192	96
	13	82	41	120	60	165	82
	14	132	66	190	95	176	88

ANNEX VII: Annual AGB increments (kg/ha & t/ha) and BA (m^2/ha) from year of establishment to 1974 and from 1974 to 2013

Plot no.	Year of establishment to year of last assessment	Age of plot between last assessment	No. of stems per ha. in 1974	Average Diameter (cm) in 1974	biomass (kg/ha)	biomass (t/ha)	annual AGB increment from establishment - 1974 (t/ha)	Basal area (m2/ha) in 1974
4c	1935 - 1974	39	40	32,71	20239,29	22,31	0,57	12,99
5c	1935 -1974	39	120	31,35	41378,33	45,61	1,16	9,25
7c	1936 -1974	38	74	46,1	58165,61	64,12	1,74	12,37
9	1936 -1974	37	89	31,62	37943,05	41,83	1,13	6,97
12	1940 -1974	34	77	32,56	31494,18	34,72	1,01	6,37
13	1940 -1974	34	137	34,75	72527,14	79,95	2,33	12,99
14	1940 -1974	34	139	29,78	38796,49	42,77	1,44	9,7

Plot no.	1974 assessment to 2013 assessment	Age of plot between last assessment	No. of stems per ha. in 2013	Average Diameter (cm) in 2013	biomass (kg/ha)	biomass (t/ha)	annual AGB increment from 1974- 2013 (t/ha)	Basal area (m2/ha) in 2013
4c	1974-2013	39	84	47,96	108862,17	120	3,08	15,68
5c	1974-2013	39	107	46,54	97975,95	108	2,77	19,19
7c	1974-2013	39	19	76,29	50802,35	56	1,44	9,06
9	1974-2013	39	31	53,95	47173,61	52	1,33	7,29
12	1974-2013	39	56	49,65	63502,93	70	1,79	11,23
13	1974-2013	39	38	53,17	29029,91	32	0,82	8,92
14	1974-2013	39	87	46,84	36287,39	40	1,03	15,57

ANNEX **VIII:** Comparison data on carbon/biomass stocks (t/ha) and annual biomass increments (t/ha) of different forest types.

Continent/ Country	Forest type	biomass (t/ha)	biomass in carbon (t/ha)	Annual biomass increment (t/ha)	Total carbon (t/ha)	Source
Sarawak, Malaysia	Shorea species, tropical plantation forest	92 – 182 (AGB)	46 – 91 (AGB)	(<39 y) 0,57 - 2,33 (>39 y) 0,82 – 3,08	215 - 265	This study
Nepal	*Shorea* forests	203,32	101,66	-	-	(Shrestha, 2009)
Central Himalayan	*Shorea robusta* old growth	-	-	-	379	(Rana, et al., 2010)
Central Himalayan	*Shorea robusta* new growth	-	-	-	242	(Rana, et al., 2010)
Central Himalaya	*Shorea robusta* forests	408	204	-	-	(Singh, et al., 2009)
Nepal	community managed Hill *Shorea robusta forests*	-	108-148	-	-	(Magar, 2012)
Nepal	Hill *Shorea* Forests	217	97,86	2,6	-	(Baral, et al., n.d.)
Asia (tropical moist forest)	Broadleaf forests plantation	180 (AGB)	90 (AGB)	8	-	(IPCC, 2003)
Asia (tropical rainforest)	Broadleaf forests plantation	130 (AGB)	65 (AGB)	5	-	(IPCC, 2003)
Asia (tropical moist forest)	Natural forests	180 (AGB)	90 (AGB)	(<20 y) 9 (>20 y) 2	-	(IPCC, 2003)
Asia (tropical rainforest)	Natural forests	280 (AGB)	140 (AGB)	(<20 y) 7 (>20 y) 2	-	(IPCC, 2003)
Sabah, Malaysia	Dipterocarp forests	-	91,9 (AGB)	-	167,9	(Saner, et al., 2012)
South east Asia (Phillipines)	Natural Dipterocarp forests				258	(Lasco, et al. 2006)
Peninsular Malaysia	Upper hill Dipterocarp forest				208.8	(DiRocco, 2012)