

## Total carbon sequestration during an entire rotation period of oil palm in northern Borneo

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# Abbreviations

AGB = Above ground biomass

BGB = Below ground biomass

C = Carbon

CWD = Coarse woody debris

FFB = Fresh fruit bunches

SSB = Sabah Softwood Berhad

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# Abstract

Considerable amounts of carbon (C) has been lost from tropical forests as a result of continuous conversion of tropical forests into oil palm plantations. Therefore, a better understanding of the C budget and potential sequestration rate in oil palm plantations and how it compares to natural forests is needed. Which is crucial in order to provide a more reasonable C credit payment to limit the widespread land conversion of tropical forests to oil palm plantations. In this thesis, I quantified the amount of C in both above- and belowground pools, which included: aboveground oil palms, stumps, senesced fawns, fine litter, coarse woody debris, roots and soil over an entire rotation period of oil palm. I established 12 plots of similar conditions within a chrono sequence of oil palm, spanning from recently planted plantations <1 year old to a 22 year old plantation. Using this approach, I was able to calculate the carbon sequestration rate during an entire rotation period of oil palm as well as assess changes in different carbon pools. I estimated that 160-ton C ha<sup>-1</sup> is lost when converting a secondary forest in Sabah Borneo to oil palm plantations. However, I found that rate of C sequestration (ton C ha<sup>-1</sup> yr<sup>-1</sup>) in oil palm is considerably higher than C sequestration in primary and secondary tropical forests. Aboveground oil palm and soil C are the two major C pools in oil palm plantation, yet it is changes in aboveground oil palm during the rotation period that is responsible for the high C sequestration rate. I also estimated an economic profit of 37,333 USD during a rotation period based on data from the production of fresh fruit bodies. Comparing the profit to the difference in C sequestration between natural forests and oil palm plantation I calculated a C credit payment of 54-96 USD ton<sup>-1</sup> CO<sub>2</sub> that would be need to conserve carbon in tropical forests while at the same time provide the same economic revenue as oil palm production , which is considerably higher than the current price for C. Thus, if we want to limit the conversion of tropical forest to oil palm plantations the current C credit payment is not enough and addition payments for other ecosystem services (i..e biodiversity and water quality) are needed.



# Abstrakt

En betydande mängd kol har försvunnit från tropiska skogar som ett resultat av kontinuerlig konvertering av tropiska skogar till oljepalmsplantage. På grund av detta behövs en bättre förståelse för kollager och potentiell kolbindning i oljepalmsplantage samt hur det skiljer sig från naturlig skog. Vilket är väsentlig för att skapa ett mer resonabelt pris på kolkrediter för att begränsa konverteringen av skog till oljepalmsplantage. I denna uppsatts har jag kvantifierat mängden kollager i både ovan och under mark, vilket inkluderade oljepalmer, stubbar, avskurna oljepalmslöv, förna, död ved, rötter och jord under en hel rotation av första generations oljepalm. Jag etablerade 12 ytor med likande förhållanden med en krono sekvens av oljepalm, från nyligen planterat <1 år till 22år gammal plantage. Med hjälp av detta kunde jag räkna ut kolbindningen under en hel rotation av oljepalm samt uppskatta förändringar i de olika kollagren. Jag uppskattar att 160-ton kol  $\text{ha}^{-1}$  försvinner när en sekundär skog i Sabah Borneo konverteras till oljepalmsplantage. Dock så fann jag att kolbindningen i oljepalmsplantage är betydligt högre än i primär och sekundär skog. Kol i oljepalmerna och jorden är de två största kollagren i oljepalmsplantage, men det är förändringar i oljepalmerna som driver kolbindningen. Jag uppskattar en ekonomisk vinst på 37,333 USD under en rotationsperiod baserat på fruktproduktionen. Genom att jämföra vinsten emot skillnaden i kolbindning och lager för sekundär samt primär skog så uppskattar jag att priset på kolkrediter ska vara 54-96 USD  $\text{ton}^{-1} \text{CO}_2$  för att bevara kollagren i tropisk skog men ge samma ekonomiska vinst som oljepalmsplantage, vilket är betydligt högre än det nuvarande priset. Således om vi vill begränsa konverteringen av tropiska skogar till oljepalmsplantage så räcker inte det med de nuvarande kolkrediterna, utan ytterligare betalning för andra ekosystemstjänster (ex. biodiversitet och vattenkvalitet) behövs.

# Introduction

Oil palm is one of the world's most rapidly increasing crops (Naylor 2016) with *ca.* 0.3 million hectares of tropical forests being converted into oil palm plantations each year (Henders, Persson, & Kastner, 2015). Oil palm, *Elaeis guineensis*, is grown on over 20 million hectares of land (FAO, 2018) and most oil palm plantations are currently found on what used to be lowland tropical rainforests in Malaysia and Indonesia; one of the most biologically diverse terrestrial ecosystems on Earth (Corley & Tinker, 2008; Corvalan, Hales, & McMichael, 2005). In Malaysia, 2.4 million hectare were converted into oil palm plantations between 1900 and 2005 (Malaysian palm oil board, 2018a) resulting in the loss of at least one million hectares of tropical forest (Koh & Wilcove, 2008). Despite this rapid growth of oil palm plantations there is still *ca.* 250 million hectares of land suitable for conversion into oil palm at a global scale (Pirker, Mosnier, Kraxner, Havlík, & Obersteiner, 2016) and it is projected that oil palm plantations will continue to expand as long there is a global demand for oil palm products (Carter, Finley, Fry, Jackson, & Willis, 2007). Such widespread conversion of tropical forests into large scale oil palm plantation stresses the need for a better understanding of the consequences this land use change has on ecosystem services.

Most research on oil palm to date has primarily focused on food and related health, whereas only a small amount of research (< 2% since 1970) has focused on environmental issues (Turner, Snaddon, Fayle, & Foster, 2008). Oil palms are very homogeneous in age and structure and often lack a diverse understory plant community, which in turn might help explain why oil palm plantations support less biodiversity than natural forests and other tree plantations (Fitzherbert et al. 2008). Additionally, it is estimated that land use change is responsible for 12-20% of the human induced C dioxide (CO<sub>2</sub>) emissions to the atmosphere, where the tropical region is the most prominent (Randerson, 2009). Thus, converting tropical forests into oil palm plantations could have large, negative effects on biodiversity and other ecosystems services.

One important ecosystem service is C sequestration, yet only a few studies have assessed the C budget in oil palm plantations. Previous studies have shown that C sequestration in oil palm plantations can range from 3 to 13 ton of C per year (Kongsager, Napier, & Mertz, 2013; Lamade & Bouillet, 2005; Thenkabail et al. 2004). However, majority of these studies have only quantified aboveground C, while ignoring other C pools in the C budget, namely belowground C. Moreover, previous studies have often been done in mature oil palm plantations where C sequestration is determined by simply dividing the amount of aboveground C by the age of the plantation. Although this approach provides rough estimates of C sequestration, it provides little information about changes in different C pools, especially belowground C pools, during an entire rotation period of oil palm, which in turn limits our mechanistic understanding of total C sequestration in oil palm plantations.

Oil palm is an extremely high yielding crop, producing roughly nine times more vegetable oils per area than other competing crops (Meijaard, 2018). The harvesting of fresh fruit bunches (FFB) begins during the second year after planting and is done continuously until the plantation is harvested at roughly 25 years (Sheil et al. 2009). In addition to the production of palm oil, timber cut for the conversion to oil palm plantations is usually sold thereby providing another source of economic revenue (Wahid & Simeh, 2009). The early income from timber sales, high yields and continuous harvesting makes oil palm very profitable, ranging from 3,835–9,630 USD ha<sup>-1</sup> year<sup>-1</sup> in net present value (Butler, Koh, & Ghazoul, 2009). Thus, for countries with rural poverty, oil palm plantations are frequently viewed as a possible way for economic development (Ayodele, 2010; Gatto, Wollni, Asnawi, & Qaim, 2017). Payment of C

credits (i.e., through REDD+) for conservation has also been proposed as a way to provide economic revenue in many developing countries while at the same time mitigate forest degradation and deforestation (Kindermann et al. 2008; Stern, 2007). Kindermann et al. (2008) estimated that global deforestation could be reduced by 50% at a price of 10-21 USD per metric ton of CO<sub>2</sub>. However, several studies from Southeast Asia have shown that C payments fail in comparison to the lucrative palm-oil market (Butler et al. 2009; Fisher, Edwards, Giam, & Wilcove, 2011; Persson & Azar, 2010; Venter et al. 2009). Thus, there is a need to re-assess the cost for a metric ton of CO<sub>2</sub> in order to ensure that C credit payments provide a similar economic return as oil palm.

In this study, I measured ecosystem C pools along a chrono sequence of oil palm plantations in southern Sabah, Malaysia which provides a unique opportunity to quantify C sequestration during an entire oil palm rotation period. Moreover, given that I made measurements of individual C pools, I was also able to investigate changes in above- and belowground C pools to get a more mechanistic understanding of C sequestration in oil palm plantations. Specifically, this study seeks to 1) quantify total C sequestration (ton C yr<sup>-1</sup>) during an entire oil palm rotation period and 2) assess the relative importance of above-and belowground C pools and how these C pools change during a rotation period. I also determine the economic revenue for an entire rotation period of oil palm, and by combining this information with information about the difference in C sequestration between natural tropical forests and oil palm plantations I was able to calculate a more realistic C credit payment that is needed to stop the conversion of tropical forests into oil palm plantations.

# Material and method

## Study area

This study was conducted in Sabah, Malaysia Borneo where oil palm is planted on 1.5 million hectares, which corresponds to 90% of the available agricultural land in Sabah (Potter, 2015). In this area, average monthly temperature and precipitation (based on data collected between 1982-2012) ranges from 22-31°C and 80-350 mm respectively (Climate-Data, 2018). The study area is dominated by oil palm plantations and a smaller extent by different tree plantations. The soil is mainly mineral soil and ranges from low to medium fertility and are mainly categorized as Kumansi or Kapilit soils (for more details, see appendix 3).

I selected 12 plots (40 x 40) within a chrono sequence of oil palm plantations owned by Sabah Softwood Berhad (SBB), which owns and operates 2500 hectares of oil palm plantations in the area around Luasong, Sabah, Borneo (Figure 1). Sabah Softwood Berhad has oil palm plantations ranging from first generation up to third generation, with a rotation period of *ca.* 22 years. Plots were selected to represent an entire rotation period first generation, ranging from plot that was recently established (3 weeks since planting) to a 22 year old plantation. The following criteria was also used when selecting plots: (1) they were first generation of oil palm (i.e., prior to conversion to oil palm these plantations were forests), (2) the plots were placed on similar soil properties, slope and aspect, (3) located > 100 m from main roads, and (4) represented different ages since planting. In total, 12 plots were selected ranging in ages from ones converted in 1996 to a recently planted plantation in the summer of 2018.

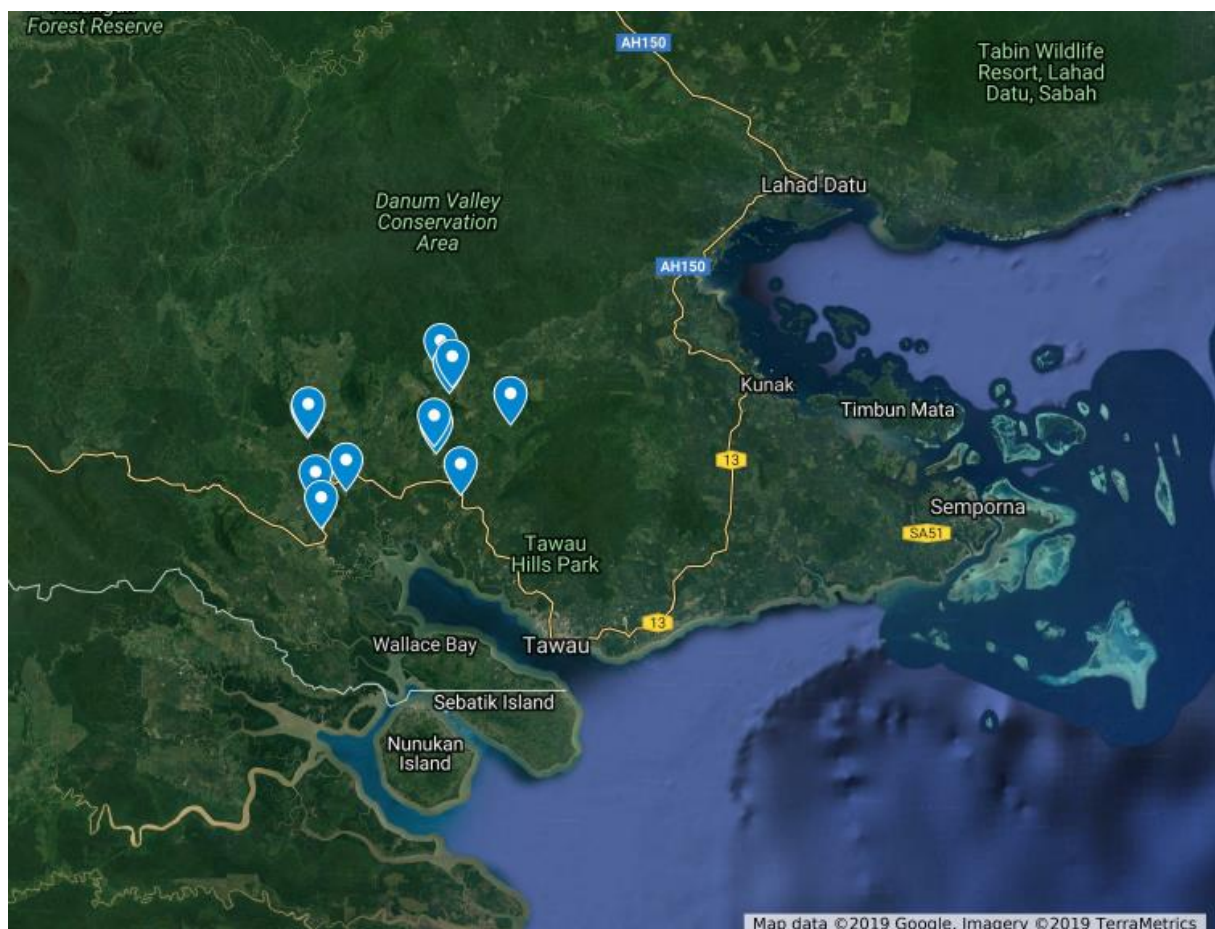


Figure 1. Map describing the locations for each of the 12 sample plots in palm oil plantations across Sabah, Borneo.

## Measurements of carbon pools

Plots were delineated using a laser rangefinder (Nikon Forestry Pro Laser Rangefinder) and the center and corners were marked with GPS (inreach explorer+) points for possible future reference. Each 40 x 40 m plot was subdivided into 16 smaller (10 x 10 m) sub-plots for above-and belowground measurements (Figure 2). Aboveground biomass and stumps were measured in the entire 40 x 40 m plots, whereas root biomass and soil C were measured in two of the 10 x 10 m sub-plots as well as one location adjacent to the 40\*40 m plot. Fine litter was collected within three of the sub-plots and oil palm fawns were measured in four subplots. Coarse woody debris (CWD) was measured along two 1 x 40 m transects located along the outside edge of each plot. Measurements of above-and belowground C pools were made in all 12 plots between September-October 2019.

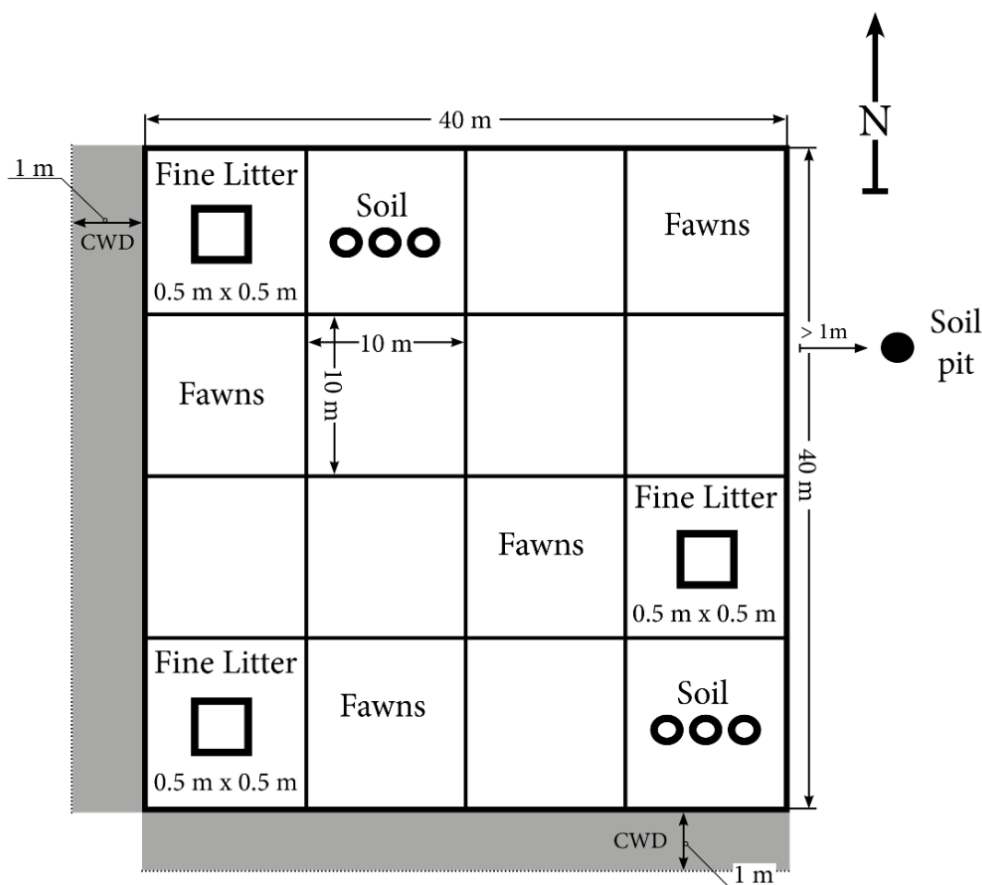


Figure 2. Schematics over one of the 12 40 x 40 m plots sampled across the study system, describing the default layout for the sampling in 10\*10-meter grids where fine litter is collected in the center of three sub-plots in a 0.5\*0.5m quadrats, soil is collected in the center of two sub-plots as well as one site adjacent to the 40\*40m plot. Senesced oil palm leaves were measured in four sub-plots. Coarse woody debris was collected in two 1 m wide and 40 m long transects (shaded area) that originated from the south west corner in each plot. A soil pit was also dug to a depth of 1 m minimum 1 m away from the sample plot where deeper soil samples were collected. Aboveground oil palms and stumps were measured in the entire 40 x 40 m plot.

## Soil and fine root carbon

Inside the 40 x 40 m plot, two sub-plots were designated for soil samples, where three 0-10 cm and three 10-20 cm samples were collected in each sub-plot. Then in one location adjacent to the plot soil samples were also collected, three 0-10 cm and three 10-20 cm samples, in addition samples were collected at 25, 35, 45, 65, 75 and 95 cm depth. So, the samples taken outside the plot were taken down to 100 cm depth and were placed outside the plot to not disturb the soil inside the plot in case of future sampling in the same spot. Samples taken inside the plot were taken to only 0-20 cm depth. Soil samples were collected using a metal cylinder hammered vertically into the soil (7.2 cm diameter and 10 cm long). Shallow soil samples were collected at two intervals (0-10 and 10-20 cm depth) at all three locations (two inside the 40\*40m and one adjacent to the sample plot) with three replications per location, giving us a total of 9 samples for each of the two surface soil intervals (0-10 and 10-20 cm depth). For deeper soil samples, samples were collected in a soil pit (1 m deep) that was dug adjacent to the 40 x 40 m plot. Deeper soil samples were collected by hammering a shorter (7.2 cm diameter and 5 cm long) metal cylinder horizontally into the soil at: 25, 35, 45, 65, 75 and 95 cm depth and then aggregated into 20-50 cm (25, 35 & 45 cm samples) and 50-100 cm (65, 75 & 95 cm samples) intervals (Figure 3).

All stones and roots were removed from each soil sample. A sub-sample was then taken and dried to a constant weight (85°C) to determine bulk density as follows:

$$BD \left( \frac{g}{cm^3} \right) = \frac{\left( \frac{SubW_{dry}}{SubW_{fresh}} * FreshSampleW \right)}{Volume}$$

Where BD is bulk density, SubWdry is the sub-sample dry weight, SubWfresh is sub-sample fresh weight, FreshSampleW is the total fresh weight of the sample and Volume is the volume of the metal cylinder used. Bulk density was determined on three samples collected at 0-10 cm and 10-20 cm as well as on all the deeper soil samples.

The remaining surface soil samples (n = 6) were used to make a composite sample for chemical analyses together (n = 9 for both the 0-10 cm and 10-20 cm depth interval). A composite sample for chemical analyses was also made for the deeper depths by combining samples collected at 25, 35, 45 cm for the 20-50 cm depth interval and samples collected at 65, 75, and 95 cm for the 50-100 cm depth interval. Composite samples were homogenized for each depth interval and then a sub-sample was taken for analyses at the Sepilok Forest Research Centre. Total C was determined by dry combustion at 900°C using an Elementar Vario Max CN analyzer (Elementar Analysensysteme, Hanau, Germany). Soil texture was determined following the particle size distribution test by (Day, 1965). Soil pH was measured with a combination glass-calomel electrode in a 1:2.5 ratio of soil to pure (deionized) water. Nitrogen (N), phosphorus (P), aluminum (Al), and acidity were also determined for each sub-sample sent to the Sepilok Forest Research Centre.

Soil carbon was then calculated for each soil depth interval (0-10 cm, 10-20cm, 20-50 cm, and 50-100cm):

$$\text{Soil Carbon} = BD \left( \frac{g}{cm^3} \right) * \text{surface area} \left( 10^8 \text{ cm}^2 \right) * \text{depth interval} * \%C$$

For the deeper soil depths, the average of the bulk density from samples collected at 25, 35, and 45 cm was used as the bulked density (BD) when calculating soil C at 20-50 cm depth. Similarly, the average bulk density from samples collected at 65, 75, and 95 cm was used as the bulk density when calculating soil C at 50-100 cm depth. Soil C from the four depth intervals (0-10, 10-20, 20-50 and 50-100 cm) was then summed together to get the total amount of soil C in the upper 1 m of the soil profile. To be noted

Surface soil	0 - 10 cm x 3	} x 3
Surface soil	10 - 20 cm x 3	
Deep soil	20 - 50 cm x 3	
Deep soil	50 - 100 cm x 3	

Figure 3. Soil sample intervals used in this study and the number of samples collected for each depth interval. Surface soil layers 0-10 and 10-20 cm were collected at 3 location with 3 replications per location. Deep soils 20-50 were collected at 25, 35, and 45 cm, whereas soil samples for the deepest interval (50 – 100 cm) were collected at 65, 75, and 95 cm.

is that there are 3 soil samples missing: one 20-50 cm for both the 20-year-old and 5-year-old plantation and one 0-10 cm sample in the 7-year-old plantation.

Fine roots (< 2 mm) that were extracted from soil samples when determining BD were cleaned to remove soil debris and then dried to a constant weight (85°C) before being weighed. Fine roots were sent to the Sepilok Forest Research Centre for the determination of % C. However, results from these analyses was unrealistically low and likely the result of soil contamination on the roots. Therefore, we assume that the C content of fine roots was 42% as this value was found for tree roots in an adjacent area (Jensen 2019 unpublished). Fine root density (FRD) was determined as dry weight of fine roots multiple by the % C of fine roots divided by the volume of the metal cylinder. Fine root carbon was calculated for each depth as:

$$\text{Fine root carbon} = \text{FRD (g/cm}^3\text{)} * \text{surface area (10}^8\text{ cm}^2\text{)} * \text{depth interval} * \%C$$

Fine root C from the four depth intervals (0-10, 10-20, 20-50 and 50-100 cm) were summed to get the total amount of fine root C in the upper 1 m of the soil profile.

## Aboveground palm trees

In each 40 x 40 m plot, the height of individual oil palm tree was measured with a laser rangefinder (Nikon Forestry Pro Laser Rangefinder) according to the method defined by Thenkabail et al. (2004). There are two equations for determining aboveground biomass of oil palms using height; one is based on a limited height range of palm trees (Thenkabail et al. 2004) and another is based on a wide range of palms, not just oil palm (Goodman et al. 2013). I determined aboveground biomass of oil palms using both equations and the results were similar (Appendix 1) and I therefore chose to present results based on species specific height as described by Thenkabail et al. (2004):

$$\text{Dry mass (kg)} = 0,3747 * \text{palm stem height (cm)} + 3.6334$$

Oil palm was assumed to have a C content of 50% (Olson, Watts, & Allison, 1983) and aboveground oil palm C was calculated as:

$$\text{Aboveground oil palm carbon (kg C)} = \text{dry mass} * \%C$$

I did not have replication within the different aged plantation, and therefore to create a standard error for aboveground oil palms C for each oil palm age, I determined aboveground oil palm C based on the measurements of individual oil palms in the 40 x 40 m plot. In general, there were *ca.* 16 oil palms in each 40 x 40 m plots and thus the standard error for each plot was based on psuedo-calculations of aboveground oil palm C found in the plots. In other words, each individual oil palm in the plot was replicated as many times as there were oil palms, which created a standard error based on the number

of oil palms in the plot. Standard error for aboveground oil palm C is only presented in Table 2, to provide an estimate of the variation of oil palm C among the different plantations of varying ages.

In the younger plantations (plantations < 3 yrs.) it was not possible to calculate aboveground biomass using the height-based approach. Thus, to determine the aboveground C pool of young oil palms, length of each individual oil palm fawn connected to individual oil palm seedlings was counted and measured. To be noted is that the oil palm seedlings in the one year old plot has been replanted due to elephant damages. Therefore, the seedlings are a bit younger while the BGB should correspond well with being one year old. In a separate study, we measured the length, fresh weight and dry weight of 25 leaves from five 10-months old seedlings to create an allometric equation to convert length of fawns to biomass (Appendix 2):

$$\text{Dry mass fawn (kg)} = 0.06 * \text{length}_{cm} + 0.2$$

Dried sub-samples of young leaves were analyzed for total C content by dry combustion of the sub-sample at 900°C using an Elementar Vario Max CN analyzer (Elementar Analysensysteme, Hanau, Germany), Sepilok Forest Research Centre – Phytochemistry department in Sandakan). The amount of aboveground C in young oil palm seedlings was then calculated using the following equation:

$$\text{Oil palm carbon} = \left( \sum (\text{Dry mass fawn}) \right) * C\%$$

In three of the 40 x 40 m plots (specifically where oil palm had been planted in 1996, 1998 and 2009), there were tree stumps remaining from the conversion from forest into oil palm plantation. All tree stumps were identified as Borneo ironwood (*Eusideroxylon zwageri*) with a wood density ranging between 835-1,185 kg/m<sup>3</sup> (Wong, 1988). The height and diameter were measured for each tree stump. Additionally, the decay class was also recorded for each tree stump based on the classification described in Chao, Phillips, & Baker (2008). I used a C concentration of 46.5% based on the average C concentration from CWD (further explained in the CWD section), and calculated the amount of C associated with tree stumps as:

$$\text{Stumps carbon} = \left( \sum (\text{volume} * \text{Decay class}_2 * \text{density}) \right) * C\%$$

## Fawns

Oil palm fawns on the soil surface were measured separately because of their large amount compared to other fine litter. Additionally, oil palm fawns have an extreme heterogeneity distribution as pruned leaves are often collected into piles by workers. To determine the amount of C in senesced palm fawns, samples were taken from four randomly selected 10 x 10 m sub-plots in each 40 x 40 m plot (Figure 2). If the base of the fawn was within the sub-plot, then the length of the entire fawn was measured. On a sub-sample of fawns (n = 11) I measured their length and fresh weight in the field. I also took a sub-sample from these fawns and brought it back to the laboratory where they were dried to constant weight (85°C). I was then able to create an allometric equation to convert the length of fawns measured in the field into dry biomass (see appendix 4). A sub-sample was also analyzed for % C using dry combustion at 900°C with an Elementar Vario Max CN analyzer (Elementar Analysensysteme, Hanau, Germany). The amount of C in senesced palm fawns was estimated by multiplying the total dry biomass of senesced fawns in each sub-plot by the C concentration in senesced palm fawns:



$$Fawn\ carbon = \sum (1.04 * length_{cm} + 20.6) * C\%$$

Estimates of C in senesced palm fawns was calculated for each sub-plot and values reported are the mean  $\pm$  SE (n = 4).

### Coarse woody debris

Coarse woody debris (CWD) was collected from two 1 x 40 m transects located along the periphery of each 40 x 40 m plot (see Figure 2). All CWD > 2 cm in diameter and at least 50% aboveground was collected and weighed in the field. A sub-sample was brought back to the laboratory and dried to constant weight (85°C). If the piece was too large to collect (i.e., a fallen tree trunk), the diameter and length that was within the 1 x 40 m transect was measured for determination for volume. We also recorded the decay class for larger CWD based on the classification system described in (Chao et al. 2008). Biomass of the larger CWD was then calculated by multiplying the volume by wood density (i.e., the mean wood density for tree species in Southeast Asia derived from the global wood density database (Zanne, A. E. et al. 2009)), and corrected for the different decay classes, since decay affects the wood density (Chao et al. 2008). Total CWD was calculated as the sum of all CWD > 2 cm plus the biomass of all large coarse woody debris in both transect. Carbon concentration was derived from a representative mixture of the different decay (Chao et al. 2008) classes collected in the field, for each individual plot. Carbon concentration was determined by dry combustion of the sub-sample at 900°C using an Elementar Vario Max CN analyzer (Elementar Analysensysteme, Hanau, Germany). This C concentration was also applied for the larger CWD where no field samples were collected. Values for the carbon contribution from CWD was calculated as follows and then scaled to a hectare;

$$CWD_{logs}\ carbon = \left( \sum (volume * Decay\ class_x * density) \right) * C\%$$

$$CWD\ carbon = \sum \left( \frac{Sample\ weight_{dry}}{sample\ weight_{fresh}} * W_{field} \right) * C\%$$

### Fine litter

In each 40 x 40 m plot, fine litter was collected from a 0.5 x 0.5 m square in the center of three 10 x 10 m sub-plots. Fine litter was defined as dead organic matter that could still be distinguished as either dead flowers, fruits, leaves, and/or branches that were < 2 cm in diameter. Highly decomposed palm fruits were included in the fine litter collection, while fresh oil palm fruits were excluded since they were regularly picked up by workers and rarely observed on the soil surface. All fine litter within the 0.5 x 0.5 m square was collected and dried (85°C) before being weighed. A sub-sample of each fine litter sample was analyzed for total C by dry combustion at 900°C using an Elementar Vario Max CN analyzer (Elementar Analysensysteme, Hanau, Germany), at the Sepilok Forest Research Centre. The amount of C in fine litter was determined by multiplying fine litter dry weight from each plot with the C concentration found for fine litter in the corresponding plot.

### Economic value of oil palm

We also calculated the economic value during the 22 year period of oil palm production. To do this, SSB provided us the weight of fresh fruit bunches (FFB) collected in each of the different aged oil palm plantations (i.e., 3, 5, 7, 9, 11, 14, 20, and 22 old plantations where I collected my samples). I calculated the average production of FBB from plantations ranging from 2 to 22 yrs old to determine the annual amount of FFB per hectare during the entire rotation period. Economic value was then estimated by

multiplying the weight of FFB by the average annual selling price of fresh fruit bunches in 2018 as determined by the Malaysian oil palm board (Malaysian palm oil board, 2018b):

$$\text{Economic value} = (\text{FFB production}_{\text{average}} * \text{productive years (20)} * \text{selling price}) - \text{management costs}$$

In addition to the revenue generated from oil palm, companies establishing oil palm plantations can also sell the timber during the conversion from secondary forests to oil palm plantation, which in turn provides an additional revenue of 9 860–12 750 USD (Fisher et al. 2011). This additionally revenue from the sale of timber is roughly equal to the establishment costs of a new plantation up until the first production of FFB (Wahid & Simeh, 2009). Therefore, neither the revenue generated from timber sale nor the initial established costs were included in the above equation for calculating the economic value of an oil palm plantation. However, the management costs of 553 USD ha<sup>-1</sup> yr<sup>-1</sup>, which includes costs associated with labor, fertilizers and harvesting (Ismail, Simeh, & Noor, 2003), were included in the calculations of economic value of oil palm plantations.

I also wanted to determine a more realistic C credit payment (USD/ ton of carbon) that would be equal to the economic revenue generated by oil palm production. To do this, I determined the difference in C sequestration between both primary and secondary tropical forests and oil palm plantations by using the following equation:

$$\Delta C_{\text{ecosystem}} = (C \text{ Pool}_{\text{TF}} - C \text{ Pool}_{\text{OP}}) + (C \text{ Sequestration}_{\text{TF}} - C \text{ sequestration}_{\text{OP}})$$

The first part of the equation represents the amount of C lost due to land conversion from tropical forest to a young oil palm plantation, whereas the second part of the equation represent the difference in C sequestration (kg C yr<sup>-1</sup>) between tropical forest and oil palm plantations during the entire rotation period of oil palm (i.e., 22 years). I divided the economic value of oil palm production during one rotation period by  $\Delta C_{\text{ecosystem}}$  to determine the C credit payment (USD /ton carbon) needed to conserve tropical forests at the same economical revenue as generated from oil palm. This type of calculation can be done for both secondary and primary forest. The amount of stored and sequestered C for secondary and primary forest is found by looking at other studies in tropical forests (Table 3). In addition, a study done exactly as this C study for oil palm plantations, but in a secondary forest belonging to the INIKEA project provides data for the C pools of equation (table 3) and is complemented by data from Berry et al. (2010) to cover the C sequestration. The INIKEA study is done with the same sampling method for the C pools in AGC and BGC as for this study on four control plots in untouched secondary forest.

## Statistical analyses

A one-way ANOVA was used to determine significant ( $P < 0.05$ ) differences among the 12 plots and soil conditions both on plot level as well as the different soil depths over time (Table 1). When a significant difference was found a post-hoc Tukey Honest Significant Differences was used to determine which means are significantly different from each other.

I used linear regression to test the relationship between oil palm leaf length and leaf dry mass and used this relationship to convert the length measurements into dry mass needed for deriving the leaf C pool. I also used linear regressions to determine if there is a relationship between total C in the plantation and time since planting as well as between individual C pools and time since planting. All linear regressions were done with 95% confidence interval. Data from each of the 40 x 40 m plot represents a different time since planting, except for the site with an age of 20, which is the average of the two sample plots. Individual values for all variables collected at each of the twelve sites are displayed in Table 2.

# Results

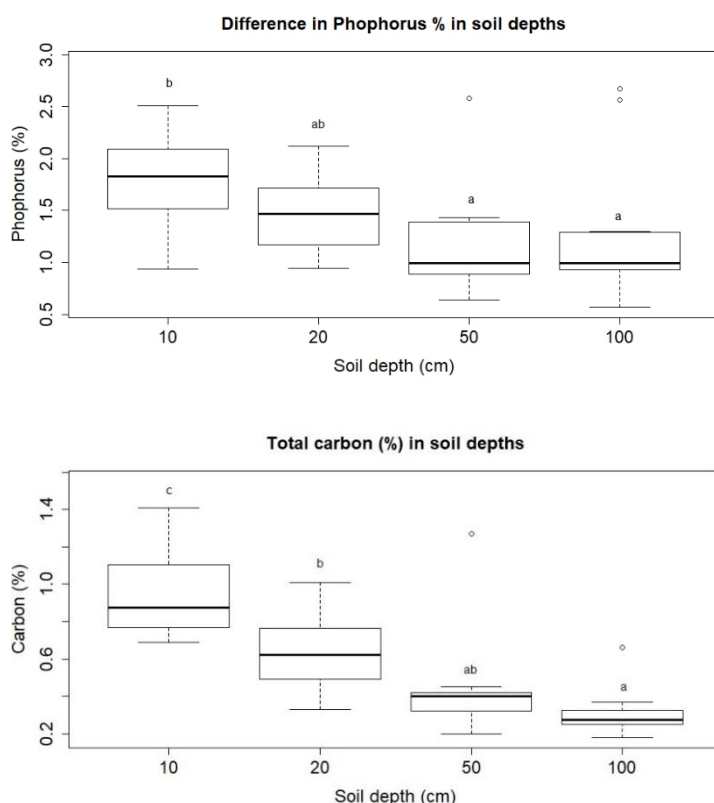
## Soil properties

In general, soil texture was not significantly different among the different plots, and consisted of 28% clay, 30% silt and 42% sand.

Table 1. The *p*-values and *F*-value from two-way ANOVA ( $\alpha = 0.05$ ) to see assess if there is any statistically significant difference in the soil properties between plots and soil depths. The statistically significant results are marked with \*.

### Anova soil characteristics

		Clay	Silt	Sand	Phosphorus	Carbon %	Nitrogen %	pH	Acidity	Aluminum
Plot	P	0.487	0.096	0.161	0.093	0.242	0.683	0.208	0.087	0.055
	F	0.492	2.880	2.033	2.941	0.673	0.169	1.627	0.483	3.846
	d.f.	46	46	46	46	46	46	46	44	46
Depth	P	0.0691	0.872	0.208	0.016*	>0.001*	0.397	0.622	0.696	0.564
	F	2.534	0.234	2.033	3.837	19.93	1.011	1.011	0.483	0.689
	d.f.	44	44	46	44	44	44	44	44	44



Overall, there was no significant difference in soil nitrogen, pH, Acidity, aluminum, phosphorus or total C among sites (Table 1). However, there were significant differences among depth for both phosphorus and C concentrations, with higher concentration found near the soil surface (Table 1, Figure 4).

When combining all depths, there was no significant difference in BD among the different sites, with an overall average of 1.4 g/cm<sup>3</sup> (Appendix 2). The average BD for the different depths was 1.26, 1.31, 1.52 and 1.54 g/cm<sup>3</sup> for 0-10, 10-20, 20-50 and 50-100 cm depths intervals respectively.

Figure 4. Differences in soil carbon (top) and phosphorous (bottom) among four different soil depths 0-10 cm (10), 10-20 (20), 20-50 (50) and 50-100 (100), for soils collected across 12 palm oil plantations in Sabah, Borneo ( $n = 12$ ). The boxes represent the quartiles Q1 and Q3, the error bars represent, the standard error of the standard deviation and the black line in each box represents median, the dots are outliers in the data. Within each panel, boxes topped by the same letter are not significantly different from each other (Tukey Honest Significant Differences, at  $p = 0.05$ ). ANOVA results are given in Table 1.

## Total carbon sequestration

Due to an unrealistically high C value in soil for the 1-year old plot it has been removed from all following results, but year 1 values are still included for all results excluding soil C. Since there were two plots in 20 year old plantation, we use the average of these two plots in the subsequent graphs. When including all C pools (aboveground oil palm, stumps, CWD, fine litter, soil and fine roots) there was a significant ( $P < 0.001$ ) positive relationship between total C and time since conversion. The slope of this regression provides an estimate of the total amount of C being sequestered during an entire oil palm rotation period, which was  $2770 \text{ kg C ha}^{-1} \text{ year}^{-1}$  or nearly  $70 \text{ ton C ha}^{-1}$  during the rotation period. The intercept of this regression line represents the amount of total C remaining after the conversion from forest to oil palm, which was *ca.* 62 tons of  $\text{C ha}^{-1}$ .

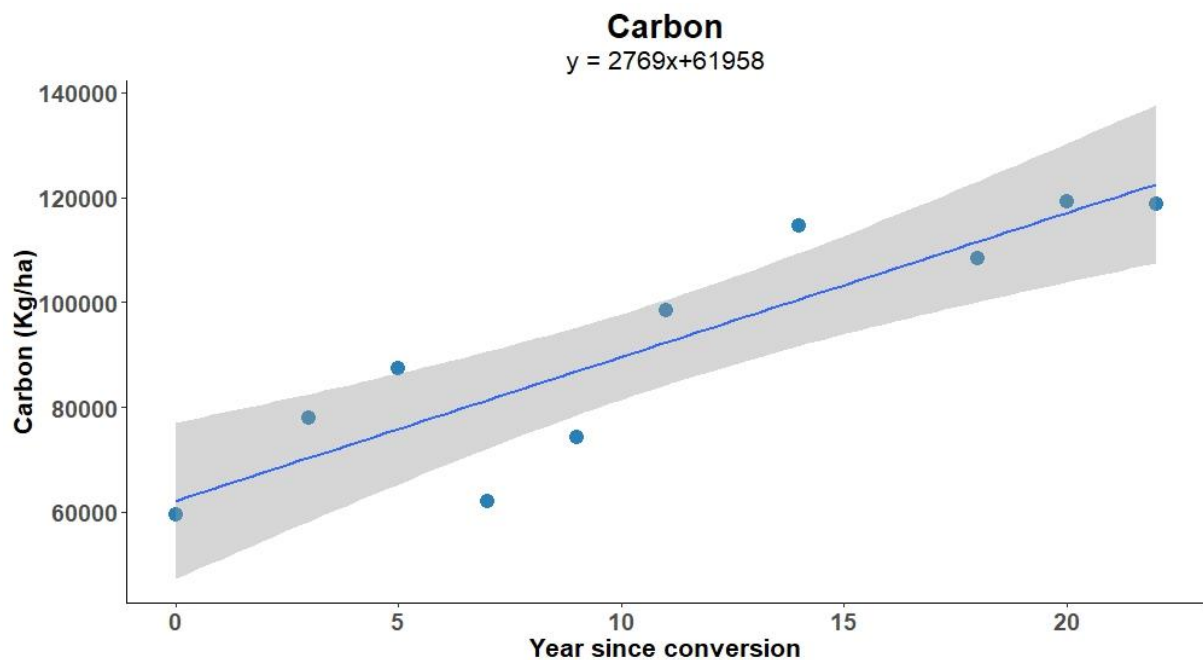


Figure 5. The overall sequestration of carbon during one rotation of oil palm plantation is shown by the inclination of the graph above. The  $R^2$  value is 0.792 and the  $P > 0.001$ . The 95% confidence interval is shown in the shaded grey area based on the regression model. Year one is removed due to unrealistic soil carbon value and the two measured plots in year 20 are represented as a mean.

## Individual carbon pools

With regards to individual C pools the relative contribution of different C pools to the total amount of C in an oil palm plantation varied with time since conversion. In general, the amount of C in aboveground oil palm was an important contributor to total C (26%), this was especially the case in plantation that were  $> 12$  years old where aboveground oil palm represents roughly 40 % of the total carbon. In contrast, soil C represents the biggest soil C pool in younger plantations representing roughly 80% of the total C in plantation that are less than 12 years old. Despite variation among other C pools in the different aged oil palm plantation, these C pools had a minor contribution to total C (Table 2).

Table 2. The mean ( $\pm$ SE) amount of carbon (kg C ha<sup>-1</sup>) in above- and belowground carbon pools in 12 sample plots representing an entire rotation period. The SE for soil and root C is calculated from the standard error from the different depth categories. \*Due to the complicated sampling of CWD, SE-values were unreliable and therefore excluded from the table. \*\* Due to unrealistic values of soil C in the one year old plantation it has been removed. Both 20 year old plantations are shown to show the variation among age classes which has not been accounted for in this study.

Years since conversion												
Above ground carbon (Kg/ha)	0.2	1	3	5	7	9	11	14	18	20	20	22
Oil palm	234 $\pm$ 37	150 $\pm$ 48	7080 $\pm$ 1405	8159 $\pm$ 1711	13148 $\pm$ 2559	17198 $\pm$ 3110	25161 $\pm$ 5565	34130 $\pm$ 5916	47431 $\pm$ 4993	51975 $\pm$ 3811	57944 $\pm$ 6366	45347 $\pm$ 3827
AGC % of total C	0.4	15.3	9.1	9.3	21.2	23.2	25.5	29.8	43.7	48.9	43.9	38.2
Below ground carbon												
Stumps	0	0	0	0	0	517 $\pm$ 37	0	0	0	0	156 $\pm$ 11	6756 $\pm$ 478
CWD*	453	42	744	8088	1902	48	5690	3494	0	2297	0	444
Fawns	0	0	16 $\pm$ 4,7	43 $\pm$ 8,7	35 $\pm$ 7,2	67 $\pm$ 5,2	26 $\pm$ 4,0	29 $\pm$ 3,1	16 $\pm$ 7,0	44 $\pm$ 2,2	38 $\pm$ 2,6	9 $\pm$ 2,9
Fine litter	912 $\pm$ 883	787 $\pm$ 488	390 $\pm$ 188	469 $\pm$ 212	611 $\pm$ 337	95 $\pm$ 3	251 $\pm$ 182	728 $\pm$ 468	1281 $\pm$ 799	669 $\pm$ 551	189 $\pm$ 107	431 $\pm$ 279
Soil	57766 $\pm$ 1685	0**	69577 $\pm$ 1932	70724 $\pm$ 1940	46363 $\pm$ 3631	56299 $\pm$ 1508	67343 $\pm$ 2253	76281 $\pm$ 3193	59710 $\pm$ 829	53513 $\pm$ 1270	71423 $\pm$ 3668	66665 $\pm$ 2513
Roots	14 $\pm$ 2	5 $\pm$ 1	6 $\pm$ 1	4 $\pm$ 1	28 $\pm$ 3	11 $\pm$ 1	10 $\pm$ 2	16 $\pm$ 4	29 $\pm$ 5	19 $\pm$ 3	18 $\pm$ 5	32 $\pm$ 5
Sum BGC	59146	834	70734	79329	48939	56966	73319	80549	61036	54245	74100	73413
BGC % of total C	99.6	84.7	90.9	90.6	78.7	76.6	74.4	70.2	56.2	51.0	56.1	61.8
<b>Total C in the plantation</b>	<b>59380</b>	<b>984</b>	<b>77814</b>	<b>87488</b>	<b>62087</b>	<b>74164</b>	<b>98480</b>	<b>114678</b>	<b>108467</b>	<b>106221</b>	<b>132043</b>	<b>118761</b>

## Oil palm

Carbon stored in aboveground oil palms (AGC) changed the most over time, ranging from 0.4% to 49% of the total C pool in young plantations to older plantations, respectively ( $R^2 = 0.968$ ,  $P < 0.001$ ,  $\alpha = 0.05$ ). The slope of this regression provides an estimate of  $2850 \text{ kg C ha}^{-1} \text{ yr}^{-1}$  in aboveground oil palm C, which is higher than the  $2770 \text{ kg C ha}^{-1} \text{ year}^{-1}$  found for the whole plantation.

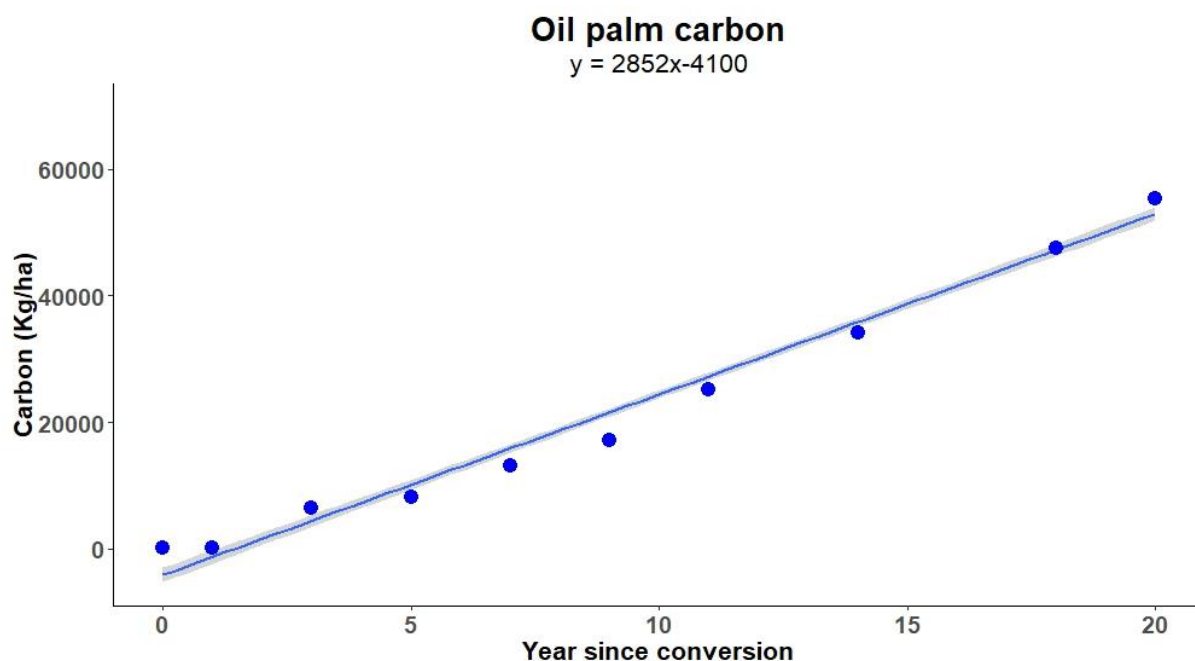


Figure 6. Linear relationship between time since planting and aboveground oil palm C (AGC) during an entire rotation period. The slope of this line provides an estimate of C sequestration in aboveground oil palm, which is highly significant ( $R^2 = 0.968$ ,  $P < 0.001$ ,  $\alpha = 0.05$ ,  $d.f. = 8$ ).

## Soil

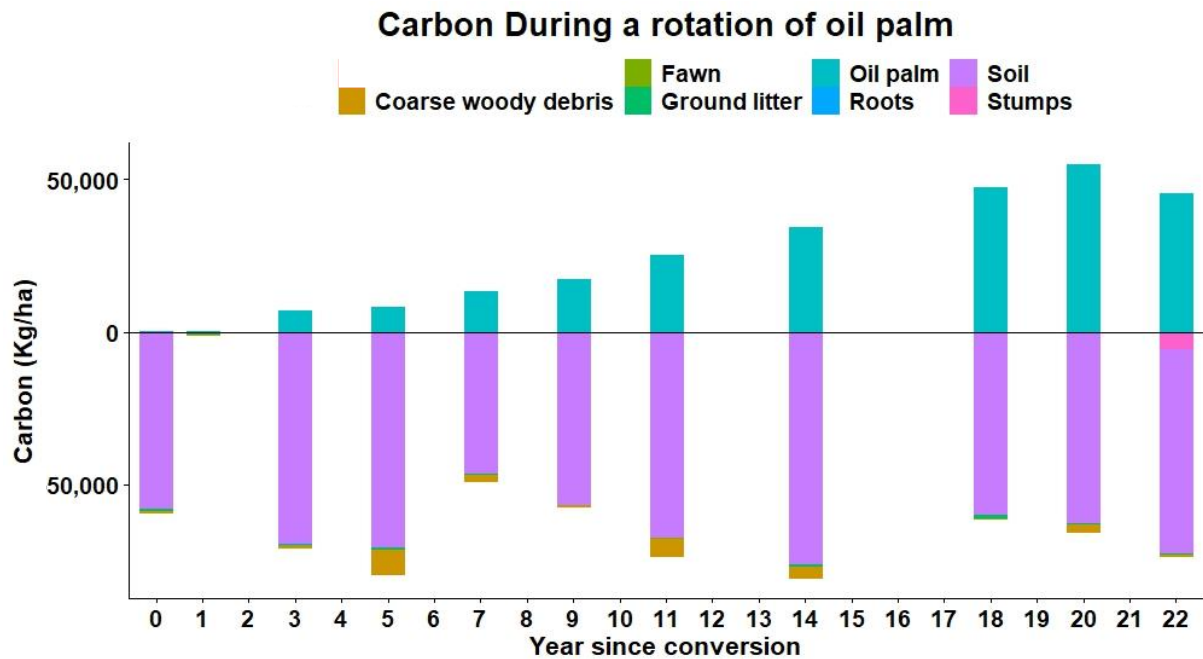


Figure 7. The distribution of oil palm carbon (C) shown per C pool with BGC displayed as below the zero line and oil palm being the only AGC displayed above the zero line. Year one soil C is removed due to strangely high values. Year 20 is an average of the two plots measured in that year.

In general, soil C represented 70% of the total C in oil palm plantations (Figure 7). However, in contrast to what was observed for aboveground oil palm, there was no statistically significant relationship between soil C and time since planting ( $R^2 = 0.0147$ , P-value = 0.723, d.f.=9). However, there was a significant negative relationship between soil C and time since planting for soil C at 10-20 cm soil depth ( $R^2 = 0.195$ , P-value=0.010). In contrast, there was a significant positive relationship between soil C and time since planting for soil C at 50-100 cm depth interval ( $R^2 = 0.203$ , P-value=0.008) (Figure 8).

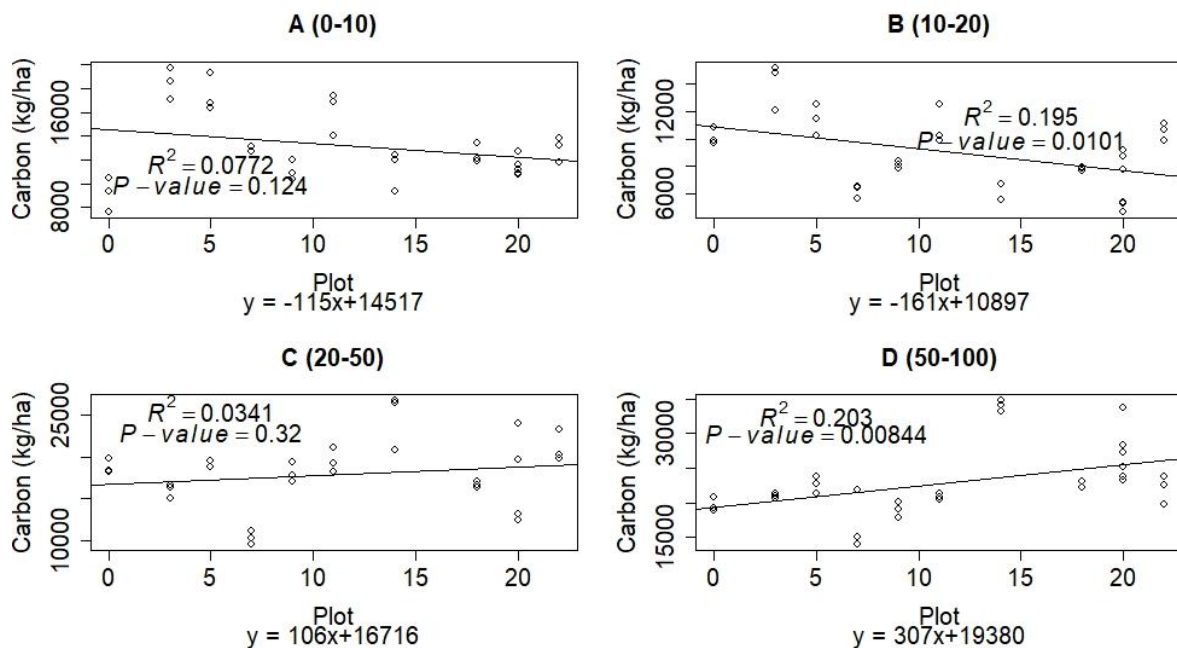


Figure 8. Linear regression between time since conversion and soil carbon kg C ha<sup>-1</sup> in the different soil depths: 0-10 cm (A), 10- 20 cm (B), 20-50 cm (C), 50 – 100 cm.

## Roots

In general, there was a significant positive relationship between fine root C and time since planting ( $P$ -value  $>0.001$ ,  $R^2$  0.631). This statistically significant positive relationship between fine root C and time since planting was found for all depth intervals, except the 20-50 cm depth interval (Figure 9). Despite these positive relationships, the contribution of fine root C to total C is relatively small, where in the 22 year old plantation fine root C contributes only 0.03% to the total C.

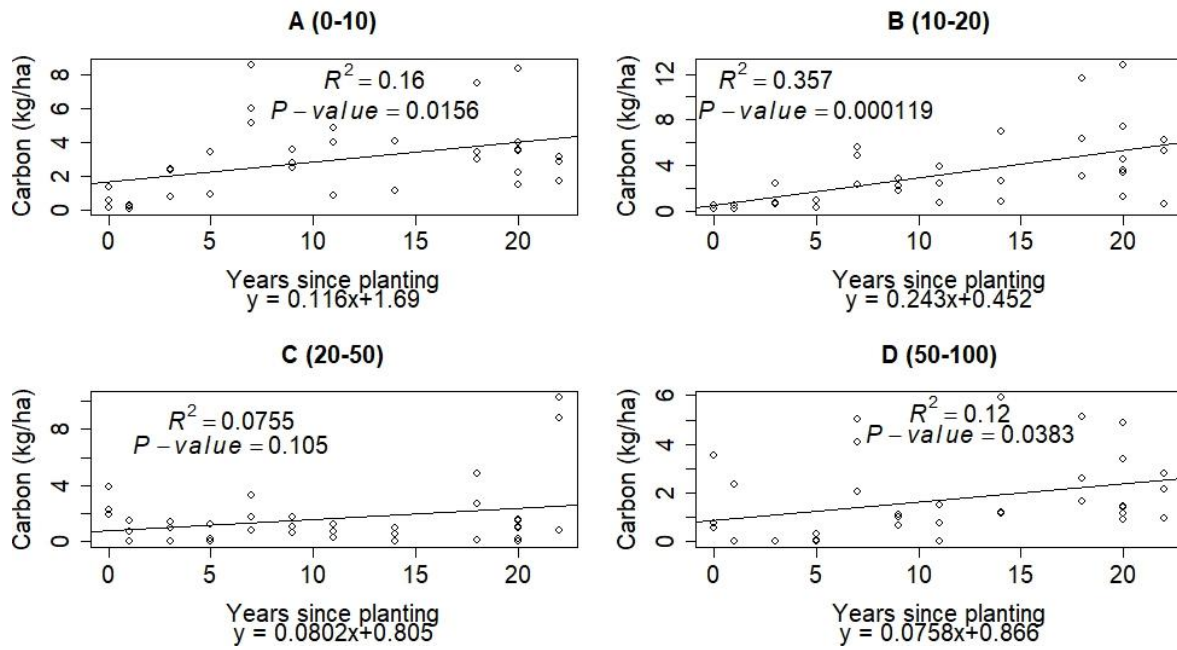


Figure 9. Linear regression between time since planting and fine root carbon at different depth intervals: 0 – 10 cm (A), 10 – 20 cm (B), 20 – 50 cm (C), 50 – 100 cm (D).

## CWD & Stumps

CWD was completely absent in two plots (18 and 20 year old) (Table 2). Stumps were only found in 3 of the 12 plots (9, 20 and 22 year old plantations). Carbon in stumps contributed very little to total C (table 2). Specifically, stumps in the 22-year-old plantation made up *ca.* 6% to total C, whereas in the other two sites (20 and 9 year old) it made up less than 1% of the total C. The contribution of CWD to total C was slightly higher, ranging between 0 and 10%. There was no significant relationship between C in CWD and time since planting ( $R^2=0.004$ ,  $P$ -value=0.771).

## Senesced fawns and fine litter

There was no significant relationship between time since planting and carbon in senesced fawns ( $R^2=0.020$ ,  $P$ -value=0.383). The contribution of senesced fawns to total C was very minor (0-0.09%).

For fine litter there was a significant positive relationship between time since planting and C ( $R^2=0.014$ ,  $P$ -value  $>0.001$ ). However, similar to CWD the contribution of fine litter to total C was minor, ranging between 0.13-1.53% of total C.



## Carbon pricing

For establishing a relation between the measured oil palm plantation and the previous forest stand the following table of literature has been used for defining the pre-existing carbon before conversion into oil palm plantations.

*Table 3 Above- and belowground carbon pools as well as estimates of C sequestration in natural tropical forests and oil palm plantations. The \* indicates that the BGC was estimated by a model, \*\* Indicates both AGC and BGC was included in the sequestration.*

<b>Sources for carbon in forests</b>	<b>Location of study</b>	<b>C sequestration Ton ha<sup>-1</sup> yr<sup>-1</sup></b>	<b>AGC Ton ha<sup>-1</sup></b>	<b>BGC Ton ha<sup>-1</sup></b>
(Berry et al. 2010)	Sabah	0.28-1.4		
(Hector et al. 2011)	Sabah		136-234	
(Dirocco, 2012)	Malaysia		149	27*
(Jensen, 2019)	Sabah		96	120
(Noordwijk, Ningsih, & Rahayu, 2015)	Sabah			54
(Guillaume, Muhammad, & Yakov, 2015)	Indonesia			54-62
<b>Sources for carbon in oil palm plantations</b>		<b>C sequestration Ton ha<sup>-1</sup> yr<sup>-1</sup></b>	<b>AGC Ton ha<sup>-1</sup></b>	<b>BGC Ton ha<sup>-1</sup></b>
(Nunes, Ewers, Turner, & Coomes, 2017)	Sabah		18	
(Lamade & Bouillet, 2005)	Countries with oil palm	13**		
(Thenkabail et al. 2004)	West Africa	3		
(Noordwijk et al. 2015)	Sabah			50
(Kongsager et al. 2013)	Ghana		45	
(Rahman et al. 2018)	Borneo			40-70
(Sanquetta et al. 2015)	Brazil		40	

The economic value of oil palm plantations is solely based on profit, and I have excluded industrial expenses and associated with refining FFB as this would be a very complex calculation and this information is difficult to find. Production of fresh fruit bunches (FFB) was provided from SSB, although data for the 18-year-old plantation is missing. The average production of FFB during the 20 productive years was 21 ton<sup>-1</sup> ha<sup>-1</sup> year<sup>-1</sup> (figure 10).

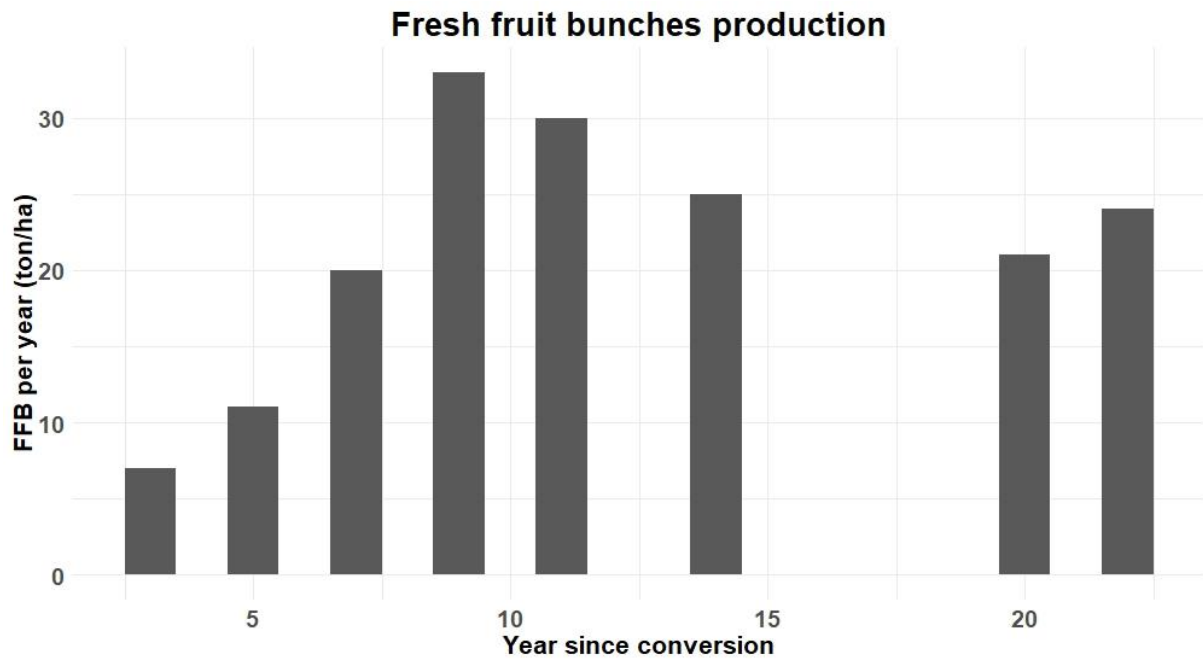


Figure 10 The fresh fruit bunches (FFB) production in the different oil palm plantations, 18 years is still missing and 20 years is an average of the two plots in that age.

Using the average selling price of 113 USD ton<sup>-1</sup> FFB<sup>-1</sup> (Malaysian palm oil board, 2018b), together with the management cost 553 USD ha<sup>-1</sup> (Ismail et al. 2003) during the 20 years which was not covered by the timber sales of conversion (Wahid & Simeh, 2009), I estimated an economic value of 37 168 USD ha<sup>-1</sup> during the entire 22 year rotation period or 1 689 USD ha<sup>-1</sup> year<sup>-1</sup>.

When changing the land use from forest to oil palm the rate of C sequestration as well as the C pools changes considerably (Table 3). On the one hand, C sequestration capacity increases up to 4 times compared to estimations by Berry et al. (2010) when converting forest into oil palm plantations. On the other hand, there is initially a considerable loss of AGC of 136 to 234 ton C ha<sup>-1</sup>. So, after 20-22 years, oil palm plantations only contain 22-38% of the total C (AGC) compared to forest. If looking at both above and below ground C these oil palm plantations that are 22-years old contain roughly 55% of the AGC and BGC of tropical forests.

This calculation is looking only at C in the trees of the forests and oil palm C in the oil palm plantations. Based on these numbers, making C credits USD C ton<sup>-1</sup> competitive with the economical profit of oil palm plantations would cost 197-351 USD/ton C for logged forest. So, since secondary forest stores less C per hectare than primary forest, every ton of C will be more expensive to conserve in secondary logged forest than in the primary rainforest.

When I compared all the C collected in oil palm plantation to the study done in INIKEA secondary forest the results were different, 216 ton C instead of 136 ton C is lost in secondary forest. In INIKEA the average C storage for control plots in secondary forest was found to be 216 M C ha<sup>-1</sup> (Jensen, 2019). Since there was no time scale for the four plots measured in INIKEA and therefore no C sequestration derived, this value was used together with the C sequestration value for secondary forest from Berry 2010. Using the same equation as the example above with these other values indicates the price for C would have to be 333 USD ton<sup>-1</sup> C for secondary forest to be financially equal to a generation of oil palm plantation.

# Discussion

This study is unique in that it is the only study that I am aware of that has quantified both above- and belowground C pools during an entire rotation period of oil palm. Compared to the total amount of C stored in a nearby tropical forest (i.e., the INIKEA sow-a-seed project), the conversion of tropical rain forest to oil palm plantation resulted in the loss of ca 160 ton of C ha<sup>-1</sup> when looking at both AGC and BGC. During the 22-year rotation period, nearly three tons of C ya<sup>-1</sup> is being sequestered each year, with majority of this C sequestration associated with aboveground oil palms. When combining this information with the economic revenue associated with oil palm, it becomes obvious that the current price for C (27 USD per ton CO<sub>2</sub>) does not provide the necessary financial incentive to limit the widespread expansion of oil palm plantations on C rich forest land.

The results show that majority of the C lost during land conversion from tropical forest to oil palm was from aboveground C pools. For example, estimated aboveground C pools in tropical primary and secondary forest ranged between 136-234 ton C per hectare and this amount would be lost in conversion to oil palm. There is also an additional loss in soil C. When comparing soil C in a nearby secondary forest to the amount of soil C in the youngest plantation in this study, there was a 22% reduction in soil C which corresponds to roughly 17 tons of C per hectare. This amount is similar to other studies that have reported a 20% reduction in soil C when converting tropical forest into agriculture (Murty, Kirschbaum, Mcmurtrie, & McGilvray, 2002). Thus, the total loss of ecosystem C as a result of land conversion to oil palm plantation ranges between 153 and 251 ton of C per hectare, which is a substantial amount of C.

We found that the rate of C sequestration in oil palm plantation in northern Borneo was *ca.* 3 tons of C ha<sup>-1</sup> yr<sup>-1</sup> which is considerably higher than estimated C sequestration rates for natural forest and forests regenerating after logging at nearby sites (0.3 and 1.4 tons C per ha<sup>-1</sup> yr<sup>-1</sup>; respectively; Berry et al. (2010)). Moreover, my calculation of C sequestration in oil palm excluded FFB, which can represent a substantial C pool (Figure 10) that is often overlooked. In a study that included FFB, it was estimated that oil palm plantations can sequester 13.5 ton C ha<sup>-1</sup> yr<sup>-1</sup> (Lamade & Bouillet 2005). Thus, oil palm plantations can sequester four times more C per hectare compared to tropical forests thereby suggesting that oil palm has the potential to mitigate against rising atmospheric CO<sub>2</sub> concentrations (Berry et al. 2010). However, oil palm plantations are usually burnt at the end of the rotations, converting the sequestered C back to CO<sub>2</sub>. Further, despite the higher C sequestration rates of oil palm, it is important to point out that at the end of the rotation period the amount of aboveground C stored in oil palm plantation is still 55% of natural tropical forests. For the oil palm to sequester the 160-ton C ha<sup>-1</sup> lost in the conversion would take around 3 generations (2.6 rotations or 57 years). However, identifying the time for recovering lost C in conversion with the current data set is very hard, a study following the effects of C from plantation to different products is needed to make such an estimation. However, these estimations are of great importance for the discussion concerning sustainability of crude palm oil, biofuel made from oil palm and all other products connected to oil palm.

Aboveground oil palm C and soil C are the two largest C pools in oil palm plantations (Table 2), whereas CWD, senesced fawns, fine litter, and fine roots make up only a minor part (<10%) of the total C. In the younger plantation (<12 years), soil C represent nearly all the C in these plots (< 80%), whereas in the older (>12 years) plantations, aboveground oil palm contributes to ca. 40-50% of the total C. These changes in where C is being stored is largely the result of a significant increase in aboveground oil palm biomass with time since planting; the aboveground C sequestration rate in aboveground oil palm is 2.9 ton C ha<sup>-1</sup> yr<sup>-1</sup> (Figure 6). In contrast, we found no overall change in soil C during the rotation period. These findings further contrasts previous studies which have reported that conversion to oil palm

plantations can result in net gain of soil C (Flynn et al. 2012; Hassan, Jaramillo, & Griffin, 2011; Sauerborn, 2008; Verhoeven & Setter, 2010). However, empirical data of soil C through an entire rotation period are extremely rare, and the only other study that we are aware of that has assessed soil C during an entire rotation period reported no change (Khasanah, van Noordwijk, Ningsih, & Rahayu, 2015), which is consistent with my findings. These results further highlight that aboveground oil palm biomass is largely responsible for high rates of C sequestration in oil palm plantations.

One way to reduce the amount of tropical forests being converted into oil palm plantations is to provide payment of C credits for intact tropical forest. It has previously been suggested that offsetting the opportunity costs of forest conversion (i.e., payment of C credits) is economical in many tropical countries (Stern 2007; Kindermann et al. 2010). For example, it has been estimated that 50% of the world's deforestation could be stopped for as little as 5 USD per ton of CO<sub>2</sub> (Stern, 2007). However, several studies have shown that the current C payment is much too low compared to the lucrative amount of money that is generated through the production of palm-oil (Butler et al. 2009; Fisher et al. 2011; Persson & Azar, 2010; Venter et al. 2009). In this study I was able to provide a more realistic C credit payment needed to financially compensate for a conversion of tropical forest into oil palm plantations. Based on the production of FFB during an entire rotation period and the selling price of FFB, I determined an economic revenue of 37,168 USD ha<sup>-1</sup> during the entire rotation period or 1,697 USD ha<sup>-1</sup> yr<sup>-1</sup>. I also determine that the difference in C sequestration between oil palm and secondary forest during a rotation period (22 yrs) was 1,4-2,5 ton C ha<sup>-1</sup>. Dividing the economic revenue by the difference in C sequestration I get a C credit payment of 197-351 USD per ton of C, or 54-96 USD per ton of CO<sub>2</sub>. This amount is considerably more than the current price for C (27 USD per ton of CO<sub>2</sub>), and highlights the need for other non-carbon-related payments for ecosystems to help mitigate the conversion of tropical forest into oil palm plantations.

## Conclusion

In conclusion, I used a unique data set of above-and belowground C pools collected along a chronosequence of oil palm plantations representing an entire rotation period to determine the C sequestration rate of oil palms in northern Borneo. Despite a substantial loss of C during conversion, oil palm plantations sequester ca. 3 ton of C ha<sup>-1</sup> yr<sup>-1</sup> which is 4 times the greater than many forest ecosystems. Aboveground oil palm was largely responsible for the high rate of C sequestration in oil palm plantation, whereas there was no obvious change in soil C during the rotation period. Dividing the economic revenue of oil palm by the difference in C sequestration between tropical forest and oil palm plantations, I calculated a C credit payment of 54-96 USD per ton of CO<sub>2</sub>, which is considerably less than the current ETS price for C. Thus, if we want to limit the conversion of tropical forest to oil palm plantations the current C credit payment is not enough and additional payments for other ecosystem services (i.e. biodiversity and water quality) are needed.

# References

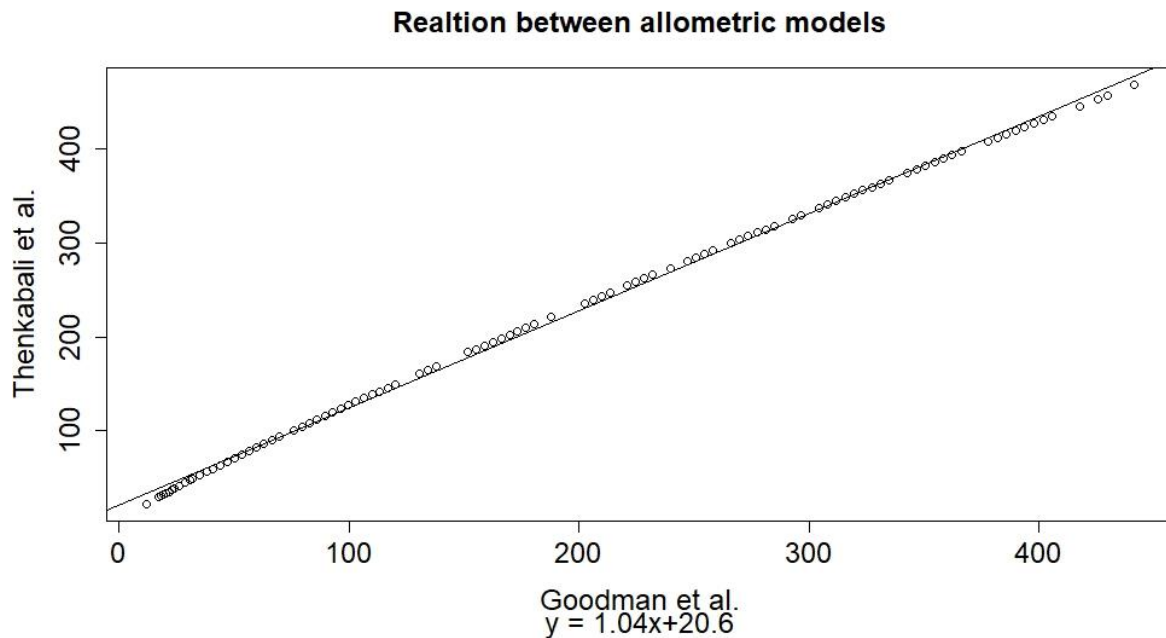
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## Appendix 1

For converting oil palm which is three years or older the function from Thenkabail et al. (2004) was used. However, since it is based on young palms up to age of five years, results was compared to a model from Goodman et al. (2013) which refers to a closely related palm species. In the end they were only slightly different even in the higher ages (7.9 kg/dry mass) as can be seen in the figure \* below, so it was decided to use the function from Thenkabali et al. (2004).



*A comparison of two different allometric equations for deriving dry mass from height where both models derives similar carbon contents based on the given heights.  $R^2$ : 0.9991 and  $p= 2.2e^{-16}$*

The used function from the Goodman et al. (2013) article is;

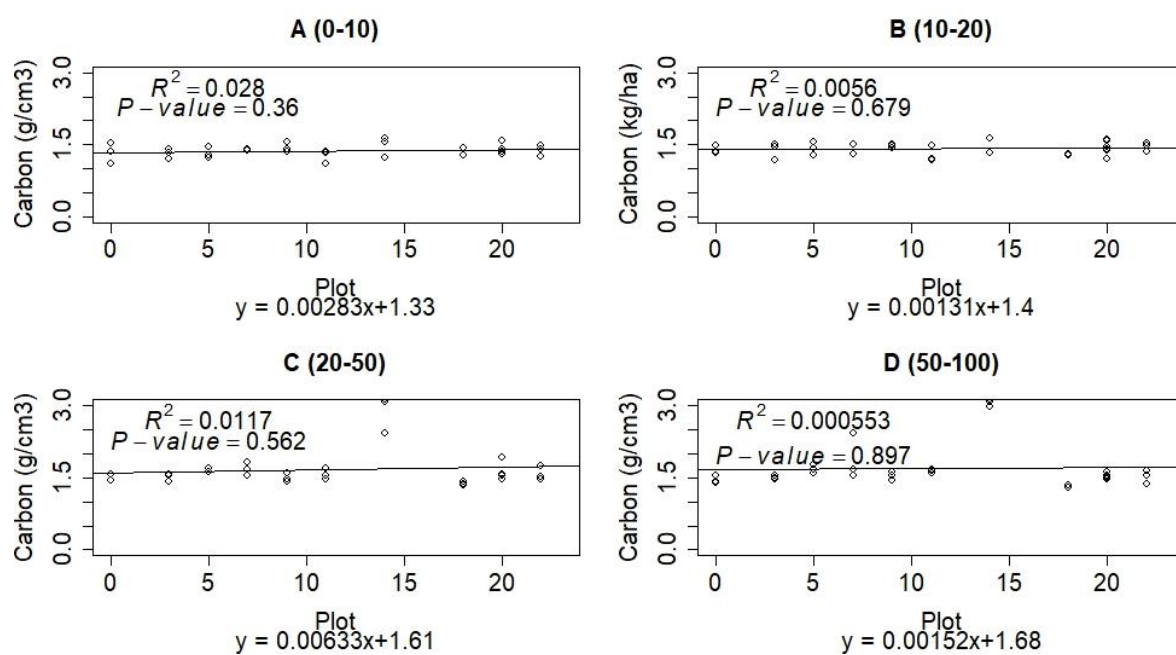
$$\text{Above ground biomass (kg dry mass per tree)} = \text{Exp}(3.2579 + 1.1249 * \ln(H_{\text{stem}} + 1))$$

The algorithm used from Thenkabali et al. (2004) for converting oil palm height to dry mass is;

$$\text{Dry weight (kg dry mass per tree)} = 0,3747 * \text{palm stem height (cm)} + 3.6334$$



## Appendix 2



Soil bulk density (BD; g/cm<sup>3</sup>) at different soil depths (0-10, 10-20, 20-50 and 50-100 cm). No statistically significance between time since conversion and BD at any of the depths.

## Appendix 3

Soil family	Kapilit
Location	Kalabakan valley (grid ref. LH 278842)
Surroundings	Moderate hills; amplitude 120 m (400 ft)
Site	Lower slope
Slope	39°
Elevation	90 m (300 ft)
Site drainage	Normal
Parent material	Sandstone
Vegetation	Dipterocarp forest
Soil drainage	Well drained

Horizon	Depth cm (in)		Description
A	0-5	(0-2)	Dark yellowish brown (10YR 3/4); humic sandy loam; moderate very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; abundant roots; clear wavy boundary
E1	5-28	(2-11)	Yellowish brown (10YR 5/6); sandy loam; weak very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; few angular sandstone fragments; thin broken cutans; many roots; gradual wavy boundary
E2	20-38	(11-15)	Yellowish brown (10YR 5/6); sandy loam; weak very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; many sandstone fragments; thin broken cutans; common roots; diffuse wavy boundary
Bt	38-88	(15-35)	Yellowish brown (10YR 5/6); sandy clay loam; moderate very fine to fine subangular blocky structure; wet, slightly sticky and slightly plastic; many sandstone fragments; thick patchy cutans; common roots
R	88+	(35+)	Sandstone

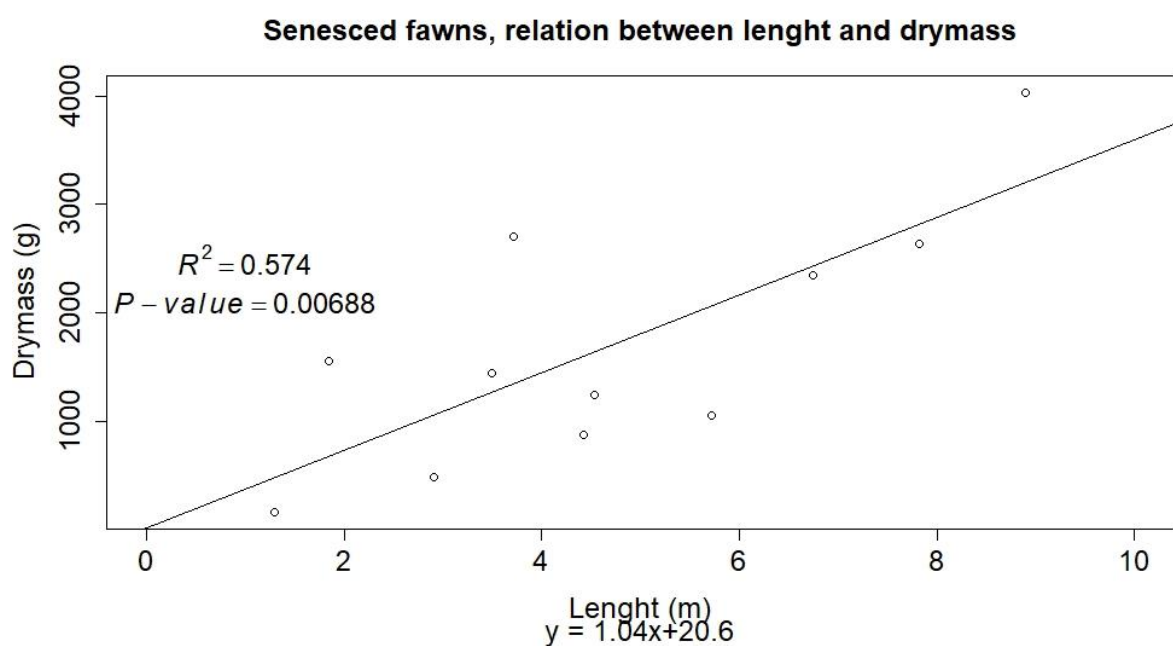
Dept cm	Particle size distribution %			Org. C%	Total N%	Avail. P ppm	pH H <sub>2</sub> O	Exch. cations meq%				CEC Meq %	Base satn. %	Total		
	Sand	Silt	Clay					Ca	Mg	K	Na			P ppm	K %	Mg %
0-5	72	20	8	4.8	0.31	19	4.5	1.5	0.9	0.4	0.1	7.7	38	182	0.35	0.17
5-28	65	20	15	0.5	0.09	3	4.7	0.1	0.3	0.3	0.1	7.3	11	110	0.46	0.21
28-38	67	18	15	0.4	0.06	2	5.1	-	0.5	0.3	0.1	7.7	12	100	0.54	0.26
38-88	67	15	18	0.2	0.05	1	5.2	-	0.4	0.3	0.1	8.1	10	144	0.76	0.27

Soil family	Kapilit
Location	Kalabakan valley (grid ref. LH 278842)
Surroundings	Moderate hills; amplitude 120 m (400 ft)
Site	Lower slope
Slope	39°
Elevation	90 m (300 ft)
Site drainage	Normal
Parent material	Sandstone
Vegetation	Dipterocarp forest
Soil drainage	Well drained

Horizon	Depth cm (in)		Description
A	0-5	(0-2)	Dark yellowish brown (10YR 7/4); humic sandy loam; moderate very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; abundant roots; clear wavy boundary
E1	5-28	(2-11)	Yellowish brown (10YR 5/6); sandy loam; weak very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; few angular sandstone fragments; thin broken cutans; many roots; gradual wavy boundary
E2	20-38	(11-15)	Yellowish brown (10YR 5/6); sandy loam; weak very fine to fine subangular blocky structure; wet, non-sticky and non-plastic; many sandstone fragments; thin broken cutans; common roots; diffuse wavy boundary
Bt	38-88	(15-35)	Yellowish brown (10YR 5/6); sandy clay loam; moderate very fine to fine subangular blocky structure; wet, slightly sticky and slightly plastic; many sandstone fragments; thick patchy cutans; common roots
R	88+	(35+)	Sandstone

Depth cm	Particle size distribution %			Org. C%	Total N%	Avail. P ppm	pH H <sub>2</sub> O	Exch. cations meq%				CEC Meq %	Base satn. %	Total		
	Sand	Silt	Clay					Ca	Mg	K	Na			P ppm	K %	Mg %
0-5	72	20	8	4.8	0.31	19	4.5	1.5	0.9	0.4	0.1	7.7	38	182	0.35	0.17
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28-38	67	18	15	0.4	0.06	2	5.1	-	0.5	0.3	0.1	7.7	12	100	0.54	0.26
38-88	67	15	18	0.2	0.05	1	5.2	-	0.4	0.3	0.1	8.1	10	144	0.76	0.27

## Appendix 4



*The linear regression giving the relation between senesced oil palm leaf length and dry mass. This was used for fining the carbon contribution of senesced oil palm leaf in oil palm plantations*

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- 2018:8      Författare: Rasmus Behrenfeldt  
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