Improved logging in tropical rainforest for carbon sequestration

A case study in Borneo, Malaysia

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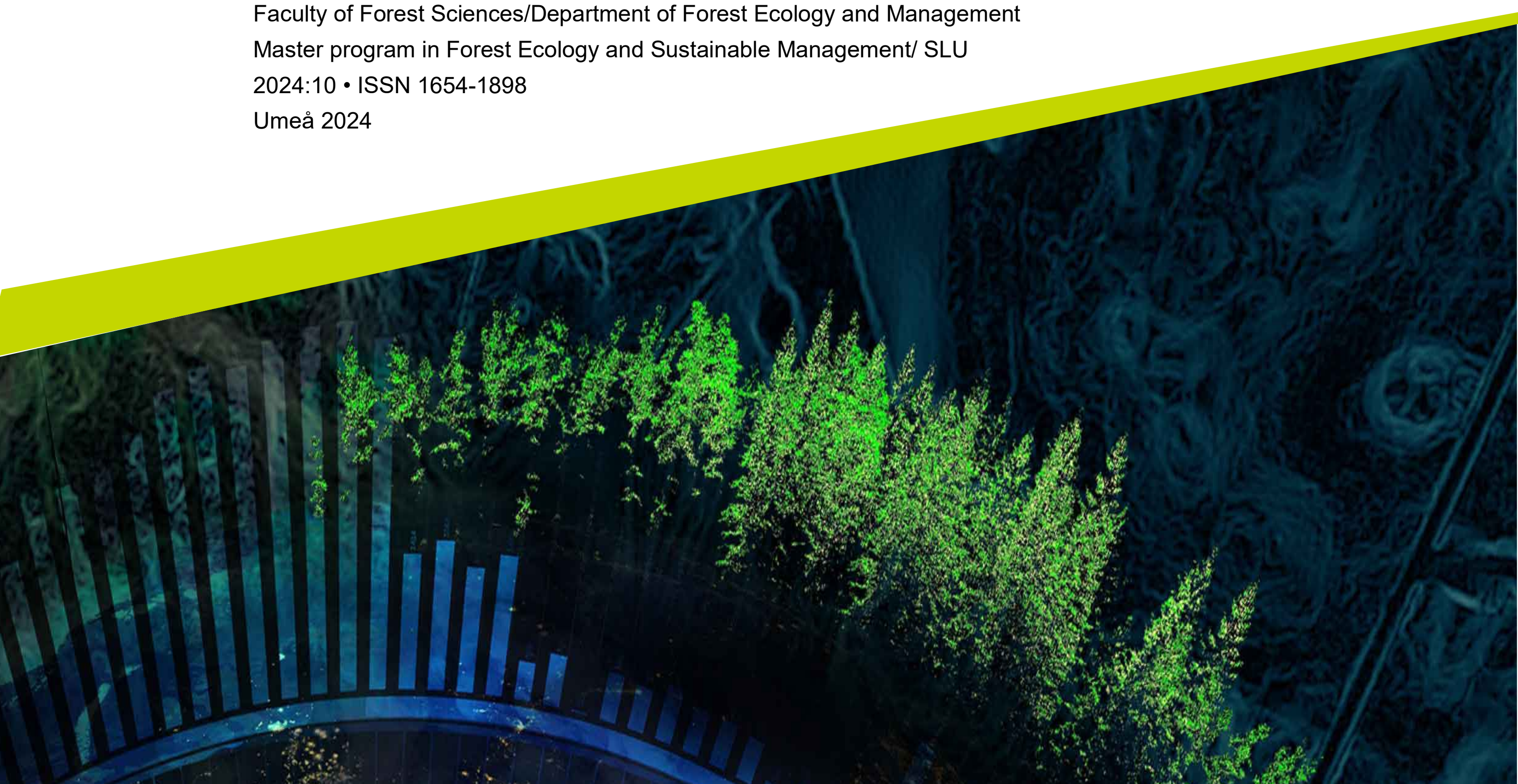
Independent Master´s Thesis project • 60 credits
Swedish University of Agricultural Sciences, SLU
Faculty of Forest Sciences/Department of Forest Ecology and Management
Master program in Forest Ecology and Sustainable Management/ SLU
2024:10 • ISSN 1654-1898
Umeå 2024



Improved logging in tropical rainforest for carb carbon sequestration: A case study in Borneo, Malaysia

Joseph Olugbenga Kayode

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Credits:	60 credits
Level:	A2E
Course Title:	Independent project in forest science at the Department of Forest Ecology Management
Course code:	EX0957
Programme/Education:	Master of Science in Forestry
Course coordinating dept:	Department of Forest Ecology and Management
Place of publication:	Umeå
Year of publication:	2024
Title of series:	Examensarbeten / SLU, Institutionen för skogens ekologi och skötsel
Part number:	2024:10
ISSN:	1654-1896

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Abstract

Improved methods for selective logging in tropical rainforests such as supervised logging which includes training of fellers in directional felling, climber cutting, and skid-trail planning could have the potential to mitigate carbon losses through reduced logging damages and improved tree growth. However, comparisons of carbon stocks and sequestration rates with conventional logging are scarce over realistic harvest intervals of 20-30 years, as well as their impact on the recovery of commercial species. In this study, I assessed aboveground carbon recovery and sequestration in a long-term forestry experiment in Sabah, Borneo, Malaysia comparing the effects of conventional logging (CL) and supervised logging (SL) in combination with climber cutting in a total of sixteen plots (each with a size of 1 ha). I considered aboveground carbon deficit and mean annual increment over 24 years after logging which are typical logging intervals in these forests. I also estimated the time to recovery of aboveground carbon based on the growth rates over the 24-year measurement period. The results revealed that the aboveground carbon deficit for conventional logging after 24 years approached zero only at harvest intensities below 50 m^3 ha-1. For instance, with conventional logging and climber cutting (CLC), the total AGC deficit at 100 m^3 ha^{-1} harvested volume was -25 Mg^3 ha^{-1}, doubling to approximately -50 Mg^3 ha^{-1} at 150 m^3 ha^{-1} harvested. In contrast, supervised logging reached deficits around zero up to harvesting volumes of 100 to 150 m^3 ha^{-1}.. Growth rates were increasing with harvesting volumes, and for dipterocarps in supervised logging with 150 m^3 harvested, growth rates were about 1.2 Mg ha^{-1} yr^{-1}, which was 0.3 Mg ha^{-1} yr^{-1} higher than conventional logging, but these trends were not significant. For total AGC growth rates the main result was an increased growth rate for conventionally logged plots without climber cutting, presumably due to rapid pioneer growth in these more disturbed plots. Estimated time to full recovery varied considerably between plots, partly due to challenges in estimating the recovery time required extrapolation over long periods. Estimated times to recovery should therefore be treated with caution, especially for the plots with low growth rates. However, for plots with climber cutting the recovery time was lower and the variation was less extreme and showed a significant difference in recovery time of 40 and 29 years for conventional and supervised logging respectively. Together, these findings suggest that supervised logging with climber cutting gives a more rapid recovery of carbon stocks which can allow for the full recovery of commercial and non-commercial trees at a harvesting interval of 25 years.

Keywords: harvest intensity, forest degradation, forest recovery, climber cutting, dipterocarps, Dipterocarpaceae skid-trails, Reduced ImpactLlogging (RIL), humid forests.

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Abbreviations

AGC	Aboveground Carbon
DBH	Diameter at breast Height
DiptAGC	Diptocarps Aboveground Carbon
ALL_TREE	All trees in the taxa
DIFF24YRS	Aboveground carbon Deficit 24 years after logging
RTIME	Recovery time
MAI	Mean annual increment
CC	Climber cutting
CL	Conventional logging
SL	Supervised logging
SLC	Supervised logging with climber cutting

1. Introduction

If management of tropical forests can be done in a sustainable way it may have the dual benefit of mitigating climate change via carbon sequestration and storage, as well as conservation of biodiversity of one of the most species-rich ecosystems (Turner and Corlett, 1996; Putz et al., 2020). Tropical forests store an estimated 558 Pg of terrestrial carbon which corresponds to about 45% of the world's terrestrial carbon (Abbas., 2020) and have an important role in the global carbon cycle (Drown et al. 2009; Baccini et al., 2017). Besides the significant roles the world's tropical forests play in climate regulation, they also support biodiversity and contribute to ecosystem services such as the production of high-valued wood, and water flow regulation (Hector, (2011)). Hence the development of sustainable logging methods for tropical forests could potentially provide biobased raw materials, conserve biodiversity, protect soil degradation, and support local livelihoods and economic revenue at the same time maintaining higher carbon stock than other prevalent land use options such as plantations for pulpwood and palm oil, while creating a sustainable carbon sink that is higher than in unmanaged old-growth forests.

Despite these many values, most tropical rainforests are selectively logged with poor forest harvest methods, resulting in damaged and over-harvested residual stands, which negatively affects their structure, productivity, and recovery (Bryab et al.,2013; Saad et al., 2020). This has been considered to be a large contribution to anthropogenic emissions of CO2 to the atmosphere (Bryab et al., 2013). In Malaysia for example, the logging technique used historically referred to as "conventional logging" (CL), has been shown to cause intense rainforest degradation (Pearson et al., 2014), and this is despite that Malaysian law imposes a diameter-cutting limit of 60cm dbh to ensure harvest intensities are sustainable. This logging is commonly unsupervised, meaning that tree fellers are untrained in felling techniques and climber cutting. Both tree felling and skidding of logs are done without planning and consideration of the residual stand. The resulting damages to the residual stand cause long recovery times of forest structure and biomass of commercial trees which in turn make the logging intervals of 25-30 years that are typically used too short to make the logging sustainable. The capacity of the forest to recover also depends on the magnitude of timber extracted and the magnitude of damage caused by the extraction (Sist and Ferreira 2007). Forest stands degraded from poor logging practices or too high harvest typically have a significantly lower capacity for carbon sink to a source of carbon to the atmosphere. Hence, the development of sustainable logging practices for tropical forests will need to account for carbon dynamics, the time to recovery (to assess sustainable logging intervals) as well as the level of extraction that can be done without seriously affecting either carbon dynamics or recovery time.

To improve the sustainability of tropical forest management several practices are considered promising including Reduced Impact Logging (RIL) and supervised logging (SL). Both practices use directional felling and climber cutting and planning of skid trails which have been shown to reduce forest damage and increase tree growth. For example, previous studies show that Reduced Impact Logging (RIL) reduces logging damage and improves seedlings development (Edward et al., 2013) and supervised logging can enhance the basal area development of the forest (Lussetti et al., 2016). Nevertheless, Reduced Impact Logging (RIL) methods are still rarely (or poorly) implemented because of their complexity guidelines resulting in high costs involved in planning, mapping, and often restricted allowable cutting volumes (Bedrij et al., 2022). To make improved logging techniques more attractive to use by real-world loggers, supervised logging has been suggested as more efficient as it simplifies some of the more expensive and time-consuming parts such as detailed mapping of trees and skid trails, and instead uses pre-aligned parallel skid trails at fixed distances together with supervised logging, involving directional felling and climber cutting (Cedergren et al., 2002 Forshed et al., 2006). It has been recognized as crucial for minimizing logging damage (Schnitzer et al., 2004). Other findings indicated that climber cutting did not significantly reduce logging damage (Cedergren et al., 2002).

With the aim to compare conventional logging of rainforests with more suitable forest management practices Sabah Foundation, a Malasysian forest management organization, together with the Swedish University of Agricultural Sciences (SLU) in 1992 established a forest management experiment in a mixed dipterocarp forest in Sabah, Malaysia (Cedergren et al., 2002; Forshed et al., 2006). In long-term evaluations, it was found that 18 years after logging, Supervised logging in combination with climber cutting produced more consistent basal area growth development of dipterocarps compared to conventional logging techniques (Lussetti et al., 2016). It is however unclear to what extent the development of basal area reflects carbon stocks that depend on changes in species composition and overall stand wood density. Furthermore, because loggers tend to come back about 20-30 years after the first harvest independently if the forest has recovered sufficiently or not, 18 years after logging is not sufficient to evaluate if the practices used are sustainable across realistic time periods. For both the more extensively used RIL methods and the supervised logging (SL) methods, there is still not enough information on the long-term recovery rates of above-ground carbon stocks.

Therefore, in this study, I aimed to evaluate the total and dipterocarp aboveground carbon (AGC) accumulation over 24 years post-logging across the four treatments of this experiment: conventional logging, and supervised logging with and without climber cutting. Additionally, I examined the magnitude of AGC deficit and recovery rate 24 years post-logging for conventional logging and supervised logging with climbing cutting). I estimated the time needed to reach zero carbon deficit (that is; full recovery) of AGC compared to pre-logging levels. I also assessed the effect of variations in harvesting intensities on these treatments, testing three hypotheses: (i) AGC deficit 24 years post-logging is reduced by supervised logging and climber cutting, with a larger effect at higher volumes of harvesting, (ii) Recovery time until zero AGC deficit is decreased by supervised logging and climber cutting, with a larger effect at higher volumes of harvesting, and (iii) Mean annual AGC growth rate over 24 years post-logging is increased by supervised logging and climber cutting, with a larger difference at higher volumes of harvesting.

2. Methods and Materials

2.1. Site Description

This research was conducted in the Gunung Rara Forest Reserve in the Malaysian state of Sabah, Borneo (approximately 4^0 33´N, 117^0 02´E) (Figure 1). The forest area is referred to as a virgin mixed dipterocarp forest, where trees biomass of the Dipterocarpaceae family account for at least 50% of the standing trees biomass. About 230 different tree species representing 60 families (trees>10cm DBH) have been identified in the experiment. The forest soils of the study area are Haplic Acrsols, which are acidic soils with clay-enriched horizons developed on sedimentary bedrock (Quesada, et al., 2011; Anda & Dahlgren, (2020). The area's average monthly temperature and precipitation range between 22-31^0 C and 80-350 mm respectively (Climate-Data, 2018). Altitude in the area ranges between 300 to 600 m above sea level.

2.2. Experimental setup

The experiment was designed as a randomized 2x2 factorial complete block design with four blocks, where the blocking factor was determined by the mean average slope in the plots, ranging from 4.1 to 24.7 degrees. Within each block, five gross plots measuring 5.76 hectares (240x240 meters) were established, with a net plot of 1 hectare (100x100 meters) positioned at the centre of each gross plot The net plots were further subdivided into one hundred 10x10 meter subplots, marked on the ground for easy identification. Each subplot was used to record and calculate the maximum slope and average slope for the total 1-hectare plot, respectively. A total of sixteen treatment plots were established across the four blocks, with each block containing each of the four treatments: SL, SLC, CL, and CLC (see Figure 2). The establishment of these plots coincided with initial measurements of diameter at breast height (DBH) of all trees with a diameter of ≥ 10cm, conducted between March and June 1992. Each tree was assigned a specific metal ID-tag buried in the soil at the trunk for identification. Climber cutting treatments were randomly assigned to established plots within the blocks. Climber cutting, using a machete, was conducted one year before the logging operation to remove all woody climbers with a diameter of ≥ 2cm. Subsequently, tree harvesting, limited to those with a DBH of ≥ 60cm, occurred from June to August 1993, resulting in the harvest of 133 trees (average 8.3 trees ha^{-1}), with hollow and fruit trees left unharvested. Biennial measurements of all trees in the plots were taken between September and November from 1993 to 2017. Variables recorded included ID number, species, coordinate distance using a 3600 Compass, and DBH using a diameter tape.

Measurements were taken at 1.3 meters above the ground whenever possible, or at 0.3 meters above the highest buttress if applicable. Metal detectors were used to relocate specific ID-tags for consistent tracking.

Figure 1. *Map of the location of the logging experiment in Sabah, Borneo, Malaysia (Lussetti et al, 2017).*

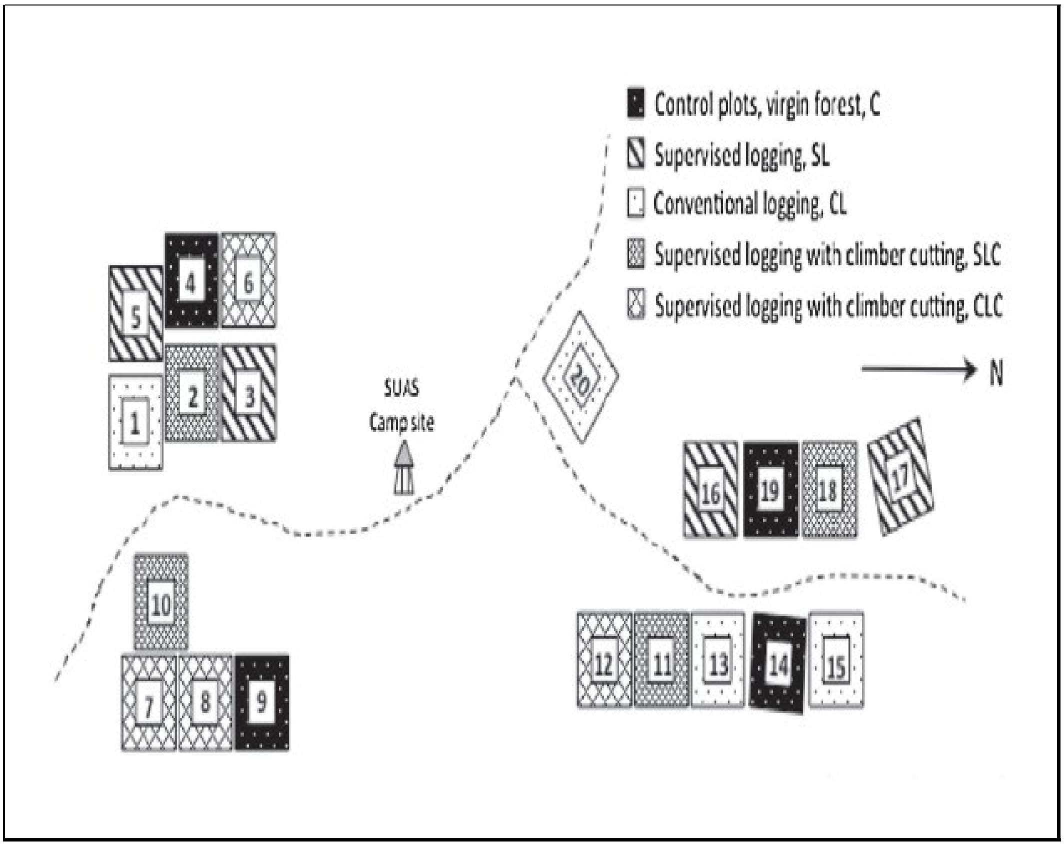

Figure 2. Plots layout of the experimental area of the logging experiment in Sabah, Borneo, Malaysia (Lussetti et al., 2017).

The aboveground carbon (AGC) levels before logging in 1992 were recorded for all trees in the experimental plots. For the treatments CL, CLC, SL, and SLC, the AGC values were 178, 197, 162, and 171 Mg ha^{-1}, respectively. Corresponding AGC values for the dipterocarps before the treatments (CL, CLC, SL, and SLC) were 110, 112, 88, and 98 Mg ha^{-1}. The remaining AGC levels in 1993 after treatments and the growth development until 2017 for each plot are detailed in appendices i and ii.

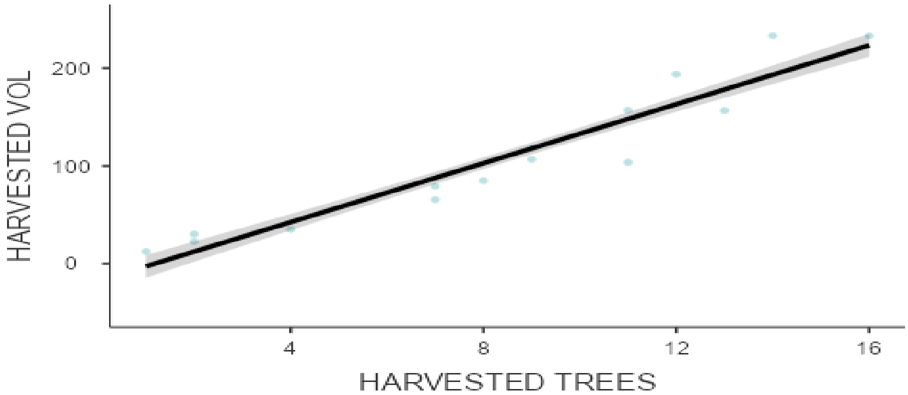

Figure 3. The relationship between harvested trees and harvested volume following selective logging in 1993 in the rainforest of Sabah, Borneo. The y-axis is the harvested volume (m^3 ha^{-1})

2.3. Logging Techniques

The two main logging techniques in the experimental plots were conventional logging (CL) and supervised logging (SL). The CL followed conventional practices in Sabah where tree felling and extraction were carried out without any specific guidelines or instructions to the fellers or crawler tractor operators. The tree fellers had no formal training in felling techniques. In supervised logging (SL), the trees were felled by the contractors who had formal training and guidelines during the logging operation. Skid-trails were systematically aligned at a fixed distance (about 60 m) from one another based upon assumptions that tractors had a winching distance of about 25 m depending on log length, and were allowed to reverse up to 5 m into the plot and thus could winch out all logged trees between the two skid-trails (Cedergen, et al., 2022). Before felling, the skid-trails were opened up to avoid damage to potential crop trees (PCT). Trees closely located to existing skid trails were felled into the adjacent skid-trail of an angle 45^0 to reduce damage to the deficit trees. Furthermore, tractor operators were not allowed to open up new tracks and logs were allowed to be skidded out from the area both up- and downhill within the plots (Cedergen, et al., 2022). Furthermore, SL included the use of directional felling. Trees were felled with great care and precision to a suitable felling hinge to ensure minimal damage to neighboring trees.

2.4 Climber treatment

The two modes of logging techniques were combined with or without pre-commercial climber cutting (CC or NCC) in each block. Climber cutting was performed one year before the logging operation and involved cutting all woody climbers 2 cm or larger in diameter except for climbers belonging to the genus Ficus.

2.5 Harvesting intensities after 1993 logging.

The number of trees harvested per plot ranged from 1 to 16 and mean number of trees harvested was similar across the treatments. The number of harvested trees per plot strongly correlated with the harvested volume (Figure 3). The difference between the aboveground carbon stock before harvest and 24 years after harvest represents the aboveground carbon deficit for the study.

2.6. Assessment of Aboveground Carbon Dynamics and Recovery Time

The aboveground biomass stocks (AGB, kg) of each tree were estimated using an allometric model developed by Chave et al. (2014). Subsequently, for each measurement year, AGB for the trees in a plot was summed and recalculated to aboveground carbon (AGC, Mg ha^{-1}). The yearly AGC values for all trees and for dipterocarps were plotted over time for each harvested tree per plot (appendix I and ii, respectively). The results were used to plot growth rate curves in Excel to estimate growth after logging for the different techniques (CL, CLC, SL, and SLC) (Appendixes i and ii). A lagtime was identified, defined as the first year of AGC values being higher than the preceding year in a row. A regression was calculated from values starting from lagtime until the regression line intersected the initial value in 1992. Furthermore, the recovery time (year) was extrapolated to when the regression line crossed the initial residual stand level before logging in 1992. The AGC growth rate in dipterocarps and for all tree species was estimated from the slope of the regression lines (Apendixes I & ii).

2.7. Statistical Analysis

To test for the effect of difference logging treatments (mean AGC stock, AGC sequestration rate, and AGC recovery time), I used general linear models of the jamovi statistical package (GAMLj) which has R program package version 4.0 (2021). To account for the response of variables to logging intensities (harvested volume), I fitted each model with the total volumes extracted from logging in 1992 as a covariate. Since the goal of the modelling was to test the significance of treatment effects on the response variables (AGC deficit, AGC annual increment and AGC recovery time), for each of the response variable, I removed the least significant variables sequentially from the full model, unless the interaction showed significant effect with the covariate. The backward selection for removal started with removing the independent variables with the highest p-vales, until only variables with larger p-values than 0.05 remained. The effect (Pearson Chi-square Statistic in the loglikelihood ratio tests) and its corresponding p-value for each significant explanatory variable was reported along with the overall explained variance (adjusted r2) for each response variable (Table 1 and 2). I excluded plot

20 (CL treatment, in appendix i) from the statistical analysis because I concluded that it must have been disturbed (i.e. not being virgin forest) before the logging treatments 1993, while receiving a minor logging intensity and then continued growing far above the pre-logging stock in 1993.

3. Results

3.1 Aboveground carbon deficit 24 years after logging

In line with the first hypothesis, I found that the AGC deficit 24 years after logging for both dipterocarps and all species together was reduced by supervised logging and that the difference between the treatmennts was larger at higher harvested intensity (Figure 4; Table 1). This shows that the effect of the treatment on the aboveground carbon deficit of all trees 24 years after logging was dependent on logging intensity as shown by a significant interaction between the treatment and harvested volume ($P= 0.044$; Table 1). I also found a main effect of climber cutting ($P=0.037$) indicating more positive AGC deficit values without climber cutting for all species, while no effects of climber cutting were seen for dipterocarps (Table 1)

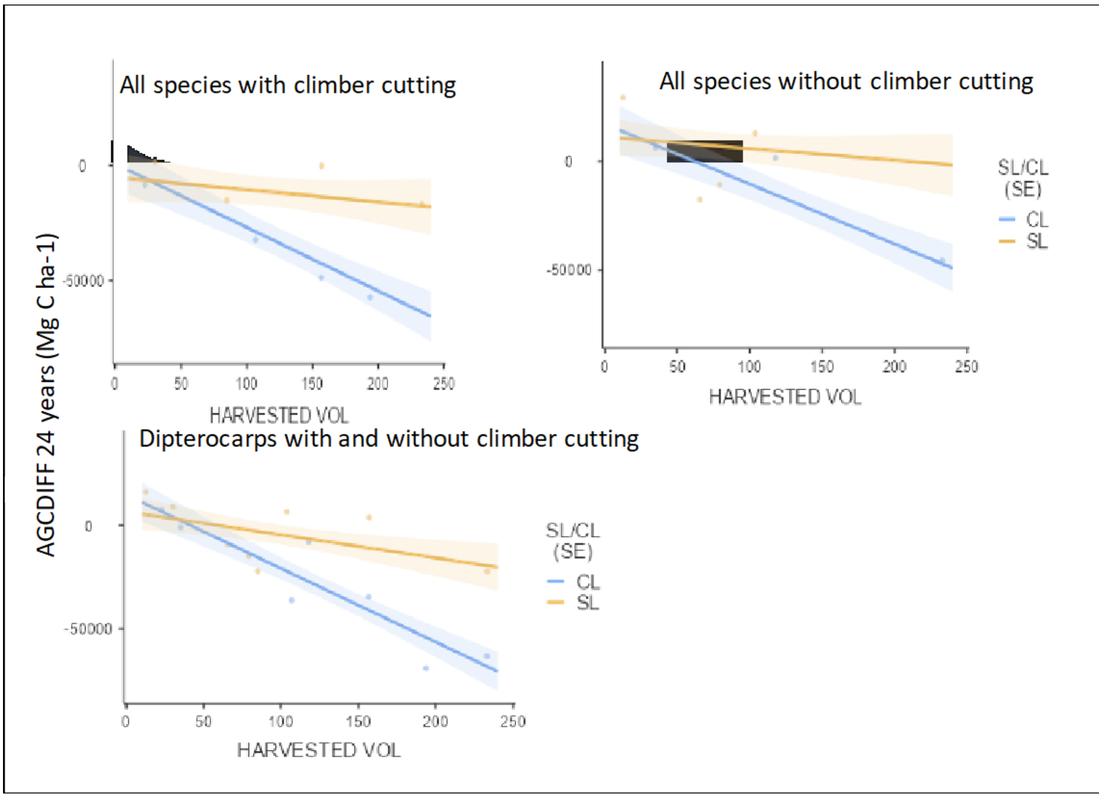

Figure 4. *Linear model results of significant treatment effects on aboveground carbon deficit 24 years after logging in a mixed dipterocarp rainforest of Sabah, Borneo (n=15). Treatments were conventional logging (CL) and supervised logging (SL) and climber cutting. Harvested volume and its interactions with treatments were included as covariate. The aboveground carbon storage of all tree taxa and dipterocarps species 24 years after logging was reduced as the harvested volume (in m3 ha-1) increased. The blue and orange colors show the observed (dots) and predicted (lines with 95% confidential intervals) carbon deficit*.

3.2 *Mean annual increment in aboveground carbon (AGC) 24 years after logging*

The mean annual increment 24 years after logging was increased with an average of 2.21 and 1.43 Mg ha^{-1} yr^{-1} for all tree taxa and for dipterocarps species respectively. There was a significant interaction of logging treatments and climber cutting (P-value=0.006), as well as a significant effect of harvest intensity (P=0.041) for trees of all taxa (Table 1). For dipterocarps species, there was no significant effect of harvest intensity (Table 2; Figure 5), but the trend was an approximately 0.3 Mg ha^{-1} yr^{-1} higher than MAI for supervised logging.

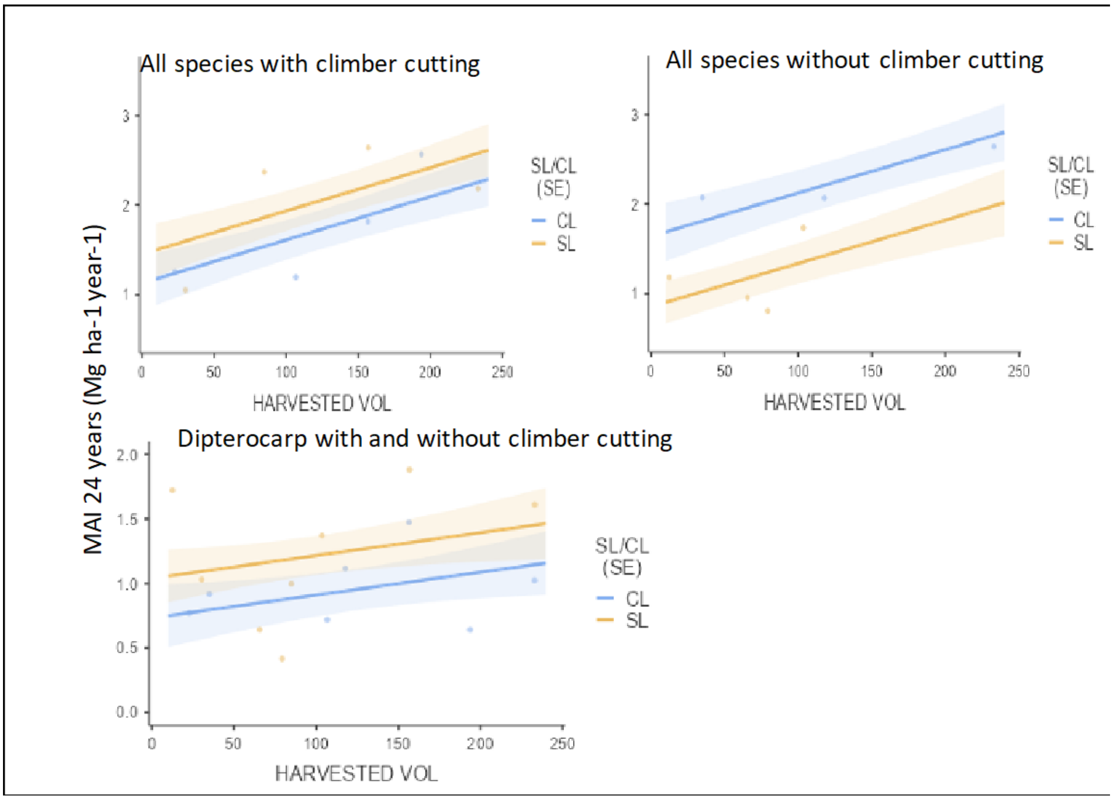

Figure 5. Linear model results of significant treatment effects on the mean annual increment (MAI 24 years after logging in a mixed dipterocarp rainforest of Sabah, Borneo (n=15). Treatments were conventional logging (CL), and supervised logging (SL) and climber cutting. The mean annual increment 24 years after logging was increasing as the harvested volume (in m^3 ha^{-1}) increased. The blue and orange colors show the observed (dots) and predicted (lines with significance at 95% confidential intervals) annual increment.

3.3 *Recovery time until zero deficit in aboveground carbon (AGC) 24 years*

The recovery time of AGC deficit for all species was significantly higher at higher harvest intensities but was also influenced by a significant interaction between climber cutting and logging treatment (P=0.028). The recovery time for dipterocarps species was dominated by high variation in recovery time with high values especially for conventional logging and without climber cutting. However, there were no significant differences in treatments for the dipterocarps (Figure 6; Table 2). The impacts of logging treatments supported the second hypothesis where at high harvest intensity, the recovery time decreased by supervised logging with climber cutting.

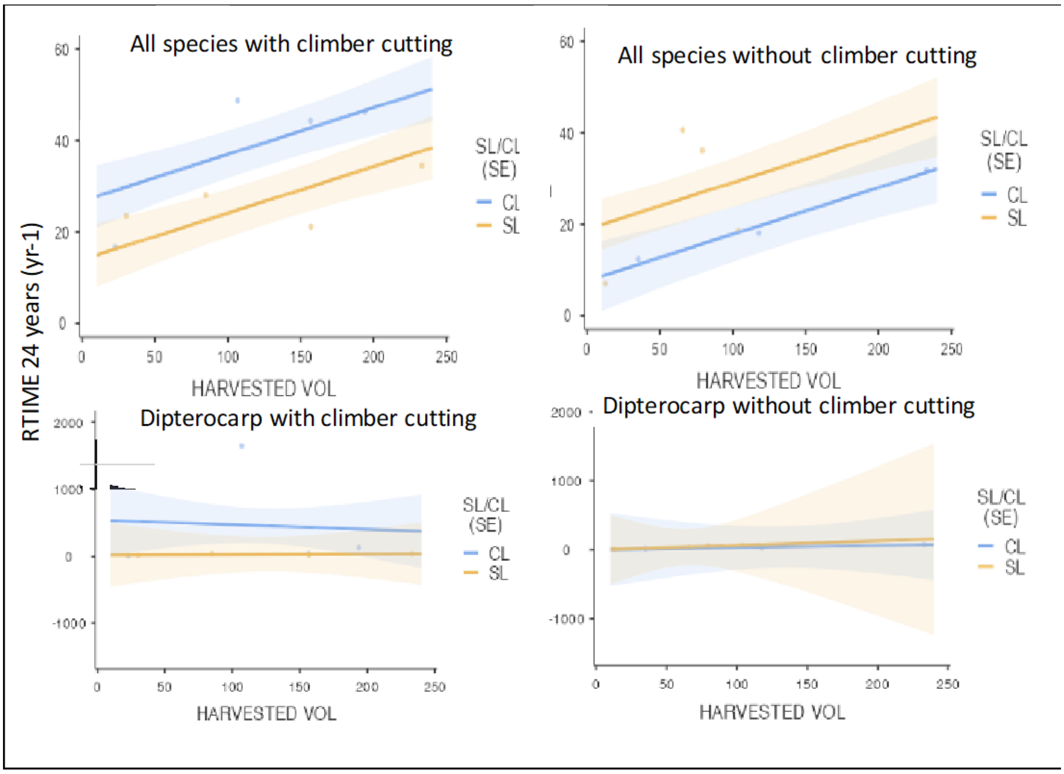

Figure 6. Linear model results of significant treatment effects on the rate of recovery 24 years after logging in a mixed dipterocarp rainforest of Sabah, Borneo (n=15). Treatments were conventional logging (CL), and supervised logging (SL) and climber cutting. Harvested volume and its interactions with treatments were included as covariate. The aboveground carbon storage of all tree taxa and dipterocarps species 24 years after logging was reduced as the harvested volume (in m^3 ha^{-1}) increased. The blue and orange colours show the observed (dots) and predicted (lines with significance at 95% confidential intervals) recovery time.

Table 1. Summary results of the generalized linear model analysis showing responses of the effect of two logging techniques conventional logging and supervised logging (CL and SL) with a combination of climber cutting or no climber cutting (CC or NCC) for all tree taxa in the tropical rainforest of Sabah, Borneo, Malaysia, Covariate= Harvested volume, DEFICITAGCF24YRS= defficit AGC 24 years after 1993 harvest (Mg ha^{-1}), RTIME= time of recovery (years), MAI= mean annual increment in AGC stock,(Mg ha^{-1} year^{-1}) NI= variable not included in the model, the Value in the bracket= indicates the P-value, and the Bold value indicates significant results (P= 0.050 or less)

RESPONSE VARIABLE	SL/CL	CC/NCC	SL/CL *CL/NCC	COVAR	SL/CL *COVAR	CC/ *COVAR	R^2	Residual /df
DEFICIT AGC24YR	0.171 0.6799)	**4.342 (0.037)**	NI	**9.138 (0.003)**	**4.058 (0.044)**	**NI**	0.753	**10**
MAI	0.984 (0.321	0.316 (0.574)	**7.410 (0.006)**	**4.193 (0.041)**	**NI**	**NI**	0.595	**10**
RTIME	0.024 (0.887)	1.696 (0.193)	**6.346 (0.028)**	**6.346 (0.012)**	**NI**	**NI**	0.560	**10**

Table 2. Summary results of the generalized linear model analysis showing responses of the effect of two logging techniques conventional logging and supervised logging (CL and SL) with a combination of climber cutting or no climber cutting (CC or NCC) for dipterocarps species in the tropical rainforest of Sabah, Borneo, Covariate= Harvested volume, DEFICITAGCF24YRS= deficit AGC 24 years after 1993 harvest (Mg h^{-1}), RTIME= time of recovery (years^{-1}), MAI= mean annual increment in AGC stock, NI= variable not included in the model, the Value in the bracket= indicates the P-value, and the Bold value indicates significant results (P= 0.050 or less) .

RESPONSE VARIABLE	**SL/CL**	**CC/NCC**	**SL/CL *CL/NCC**	**COVAR**	**SL/CL *COVAR**	**CC/ *COVAR**	**R^2**	**Residual /df**
DEFICIT AGC24YR	0.396 (0.529)	NI	NI	**22.099 (<.001)**	**6.023 (0.014)**	NI	0.792	11
MAI	1.840 (0.175)	NI	NI	1.220 (0.268)	NI	NI	0.108	12
RTIME	0.230 (0.631)	0.268 (0.604)	0.227 (0.634)	1.220 (0.268)	0.001 (0.972)	0.25 (0.875)	0.221	11

4. Discussion

The aim of this study was to investigate the long-term influence of supervised logging techniques on carbon dynamics in mixed dipterocarps rainforests in Sabah Borneo, suggested as more sustainable methods for selective logging in tropical rainforests. To accomplish this, I studied the carbon sequestration potential up to 24 years after logging, comparing the effects of supervised logging involving fellers trained in directional felling, to conventional logging techniques. I hypothesized that logging treatments would interact with harvest intensities so that supervised logging with climber cutting would have higher forest stocks, faster recovery time, and higher annual growth only at high harvest intensities. The overall results showed that supervised logging with or without climber cutting enhanced quick recovery, as well as maintained the aboveground carbon growth of the commercial timber of dipterocarps compared to conventional logging while enabling a forest ecosystem to return to its previous state, especially at high harvest intensity. Specifically, 24 years after supervised logging even at harvest intensities of 100-150 m^3 ha^{-1}, aboveground carbon storage had recovered to pre-logging levels. In contrast, conventional logging only achieved recovery at harvest intensities below 50 m^3 ha^{-1}. These results were consistent both for the total aboveground tree biomass and for the ecologically and commercially valuable dipterocarps species. Therefore, considering that logging needs to be sustainable both economically and from a climate perspective without compromising the availability of these for future generations, the results underscore the importance of both the recovery of the commercial trees and total aboveground carbon stock recovery for the sustainable management of forest ecosystems.

A key result from my study was that the benefit of supervised logging on carbon dynamics was most pronounced during high harvest intensities. Notably, at high harvest intensities levels, particularly above 8 trees per hectare {median of 10 trees per ha (118 m^3 ha^{-1}); Figure 6}, conventional logging were leading to over 50% damage to the remaining aboveground carbon stock (Lussetti, et al., 2017). In contrast, supervised logging mitigated such damages facilitating faster recovery, and fully recovered total and dipterocarp stocks within a relatively short period (20-30 years), even at harvesting levels as high as 8-12 trees per hectare demonstrating clear advantages over conventional logging. In dipterocarp-dominated rainforests, harvesting of commercial trees above the allowable cutting diameter of 60 cm are generally higher than in African and Neo-tropical forests, which contribute to the high profitability of the logging operations in SE Asian rainforests. However, harvesting at such high rates using conventional logging methods has led to the destruction of the remaining stand and a low recovery rate (Lussetti et al., 2016; Khaih et al., 2020). In studies conducted following selective logging in tropical rainforests of Southeast Asia, the magnitude of timber extracted or logging is consequently high, which slows down the growth and thus has an impact on the rate of recovery (Cox et al., 2016; Butarbutar et al., 2019; Philipson et al., 2023). My results suggest that SL could be a good alternative to CL by allowing a higher level of extraction (i.e. 8-12 trees ha^{-1}) during logging with less impact on the carbon sequestration potential of these forests. The 24-year period as in my study, I consider the typical rotation cycle for re-logging in tropical forests, falls within the range of 20 to 25 years. This timeframe aligns with the economic considerations of landowners who often aim to balance the need for timber extraction with the time required for forest regeneration and the financial returns from logging operations (Bogle 2012).

The variation across treatment in carbon deficit after 24 years could partly be explained by the corresponding variation in the annual increment over the same period. For example, the mean annual increment of the aboveground carbon for dipterocarps was found to increase consistently with harvest intensity and following supervised logging average of 1.18 Mg ha-1yr-1 compared to conventional logging 0.90 Mg ha-1 yr-1 (Figure 5). However, these effects were not significant in the regression model. That this was not significant despite the carbon deficit being significant could possibly be because the carbon deficit is a combination of both the amount of the stand remaining and the growth rate of this stand over time. It is expected that the aboveground carbon growth rate could vary with the magnitude of harvested volume and species composition, depending on the response of the economically dominant dipterocarps species. This corresponds well with the findings of Hector et al. (2011) and Kirby and Potvin (2007), they showed that mixed dominant dipterocarps forests are mostly with diverse dominant large-size tree species that are in turn vary depending on the diameter at breast height (DBH), and plant growth habit which contribute significantly to carbon storage. At the same time, the mean annual growth for trees of all taxa increased more with climber cutting compared to without climber cutting at high harvest volumes (Figure 4). In addition, the total aboveground carbon growth rate had a significant interaction between treatment and climber cutting where non-climber cutting seemed to induce a higher growth rate for conventional logging and a lower growth rate for supervised logging. This could potentially be due to the extra disturbance from uncut lianas promoting the growth of pioneer species in conventional logging but not in supervised logging. However, some studies have shown that climber cutting did not affect damages connected to harvest operations (Parren and Bongers, 2002; Schitzer et al., 2015), while others acknowledged the significance of liana cutting to enhance both growth development and carbon sequestration (Finlayson et al., 2022; Putz et al., 2022). One explanation for the positive influence of climber cutting could be its functionality in reducing damage to the remaining trees (Forshed et al., 2006). Other studies have shown or/argued that climber cutting increases aboveground carbon as a result of canopy openness, which allows sunlight penetration and likely enriches carbon sequestration for the long term in residual trees and regeneration of pioneer trees (Arets, 2005; Kirby and Potvin, 2006). The treatments revealed no significant influence on the aboveground carbon growth rate for dipterocarps, and the lack of significant influence of logging treatment on dipterocarp carbon growth could reflect the long-term nature of forest recovery processes. While immediate impacts of the logging treatments may be observed in carbon deficit measurements, the full effects on tree growth and carbon accumulation in dipterocarps may manifest over longer timeframes, necessitating continued monitoring and assessment beyond the 24-year period studied.

In line with the results from carbon deficit analyses, I also found that time to recovery was generally lower for SL than for CL, particularly for the commercially valuable dipterocarps. Some SL plots had recovered dipterocarp biomass already at 24 years, the extrapolation assumed that all plots should be recovered by 25 years, whereas a lot of variation in recovery times for CL plots was observed (that is; extrapolation of recovery time up to 130 years). Again, recovery time was strongly influenced by the amount of timber extraction during logging and the variation in logging obviously initiated a lot of variation in recovery time. Hence, the model result of the analysis showed a lot of variation in time to recovery, and with some extreme recovery times for dipterocarps in certain plots with high extraction and low growth rates. This uneven variation across treatments and harvesting intensities validates assumptions of equal variances in the linear regression models. The variation was more pronounced in the recovery rate of dipterocarps species (Appendix i and ii), particularly for the treatments without climber cutting (NCC). For harvesting volume which had been influential for the other variable (AGC deficit), there were no apparent effects for dipterocarps, but only for all species, perhaps due to the extreme variations at higher harvesting intensities. However, the model suggests that for dipterocarps recovery times are consistently faster, and with less variation, for plots with combined climber cutting and supervised logging, at the same time other treatments (CL with or without climber cutting) cause longer recovery times and variation. The estimated recovery times for dipterocarps of 25 years for supervised logging with climber cutting are consistent with the carbon deficit values at 24 years and do not require large extrapolations in time. These values can be compared to 130 years of recovery time for conventional logging with climber cutting. There are few reliable estimates of recovery time of logged dipterocarp forests, especially for improved logging methods. However, the results of total biomass growth rates in secondary forests with conventional logging generally imply recovery rates in the range of 40-100 years or more (Mackey et al., 2020; Gräfe et al., 2020 & Geng et al., 2021), which are consistent with my estimates based on conventional logging. In a previous study of directional felling with reduced impact logging (RIL) and conventional logging techniques (Butarbutar et al., 2019), the logging treatments (including thinning, enrichment planting, liberation etc) revealed no significant influence on the aboveground carbon stock recovery after harvest, but there were significant differences between the species composition in the treatment plots which depended on logging intensities per plot. Furthermore, without RIL with liana cutting, as a result of the crowns of the trees connecting to neighbourhood trees, there is a tendency of destroying the residual stand when harvested trees are pulling along or hitting other trees as they fall. Previous related studies emphasized the need for healthier residual stands which have a better-influenced regeneration of dipterocarps (Putz et al., 2001; Mashor et al., 2017; Butarbutar et al., 2019). In my study, despite the magnitude of dipterocarps commercial trees harvested, supervised logging consistently recovered faster than the conventional logging systems. This probably implies that in using SL, fewer trees were damaged during the harvest, and this could influence healthy residual trees and consequently more aboveground carbon deficit.

In a study conducted in East Kalimantan, Indonesia using selective logging techniques provided valuable insights into the aboveground carbon growth rate which ranged between 1.65 and 4.61 $tCha^{-1}$ $year^{-1}$ (Butarbutar et al., 2019), demonstrating the potential for significant variation in carbon accumulation following selective logging. Another similar research conducted in the tropical rainforest of Sabah over 30 years reported annual growth rates of total aboveground carbon ranging from 1.06 to 4.58 tC ha-1 year-1 (Hector et al., 2011), which is comparable to or slightly higher than the rates observed in my study in Sabah (1.4-2.86 tC ha^{-1} $year^{-1}$). The influence of logging techniques on aboveground carbon growth rates in these experimental sites depends on the magnitude of aboveground carbon losses by harvests. Understanding the trade-offs between carbon loss during logging and subsequent carbon recovery is crucial for forest managers and policymakers seeking to develop prudent management plans that promote the long-term sustainability of tropical forests and therefore have the following implications for future forest practices and development such as; consistent moderation of aboveground carbon effects by supervised logging even after 24 years post-logging, and this highlights the importance of adopting supervised logging techniques to minimize carbon losses and promote ecosystem resilience over the long-term.

While avoiding damages with systems such as supervised loggigng is preferable, considering the economic value and ecological significance of dipterocarps, replanting dipterocarps during afforestation and restoration programs emerges as a potentially valuable strategy for forest ecosystems. Reintroduction or enrichment of dipterocarps can enhance biodiversity, promote carbon sequestration, support the sustainable management of valuable timber resources and offer several significant of environmental and economic benefits (Budiharta et al., 2014; Ang et al., 2016; Phan 2020).

Conclusion

Despite the history of unsustainable conventional logging, it seems that with improved logging methods, damages during logging operations can be reduced and it is possible to achieve logging where carbon stocks of commercial as well as total tree species recover within 24 years. The much larger harvesting volumes that are possible with supervised logging are promising for an economically viable system, but further studies should evaluate the financial outcomes and compare them with other forest management options. This study provides reliable carbon sink management information on improved forest harvest potential as a result of improved logging operations. If improved logging techniques like supervised loggigng are considered, there is huge potential for the Malaysian Borneo rainforest to play in mitigating climate change by maintaining high carbon stocks at the same time as providing biobased raw materials that can potentially substitute fossil based materials. This study provides a piece of reliable information on the techniques that can give more resilient forests for aboveground carbon stock, growth and species composition. These could help in quantifying and predicting different management strategies on forest structure and dynamics to promote an increase in long-term sustainable high timber quality forest stands in dipterocarp dominated Asian Rainforests.

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Popular science summary

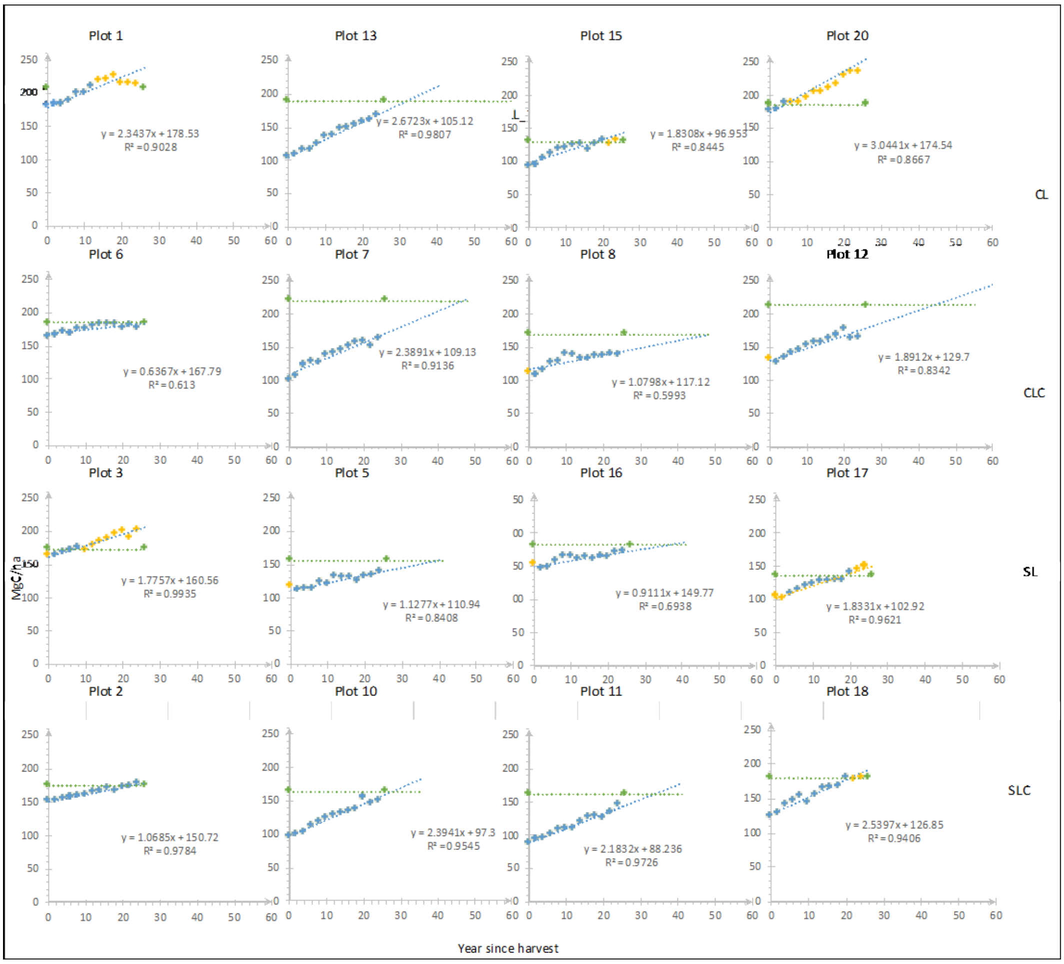
There is huge potential for Malaysian Borneo to play a crucial role in mitigating climate change if improved logging techniques that could potentially create a sustainable carbonsink with higher carbon stock than degraded forest or plantation. Therefore, this study revealed the improved logging techniques of supervised logging (directional felling and pre-aligned skid trails), and climber cutting in above ground carbon sequestration and carbon storage in relation to a published data from fast growing timber plantation and old-growth and secondary rainforests.

Acknowledgements

I would like to express my sincere gratitude to everyone who has supported me throughout the journey of completing my master’s thesis. First and foremost, I am deeply thankful to my supervisor, Ulrik Ilstedt, and the assistant supervisors, Daniel Lussetti and Petter Axelsson, for their invaluable guidance, insightful feedback, and continuous encouragement. Their expertise and patience were crucial to the development and completion of this research. I also extend my heartfelt thanks to the faculty and staff of the Forest Ecology and Sustainable Management at the Swedish University of Agricultural Sciences, Umeå for providing a stimulating and supportive environment. Special thanks to my colleagues and friends for their camaraderie, constructive discussions, and moral support during challenging times. Finally, I am incredibly grateful to my family for their unwavering love, patience, and encouragement. Their belief in me has been a constant source of motivation.

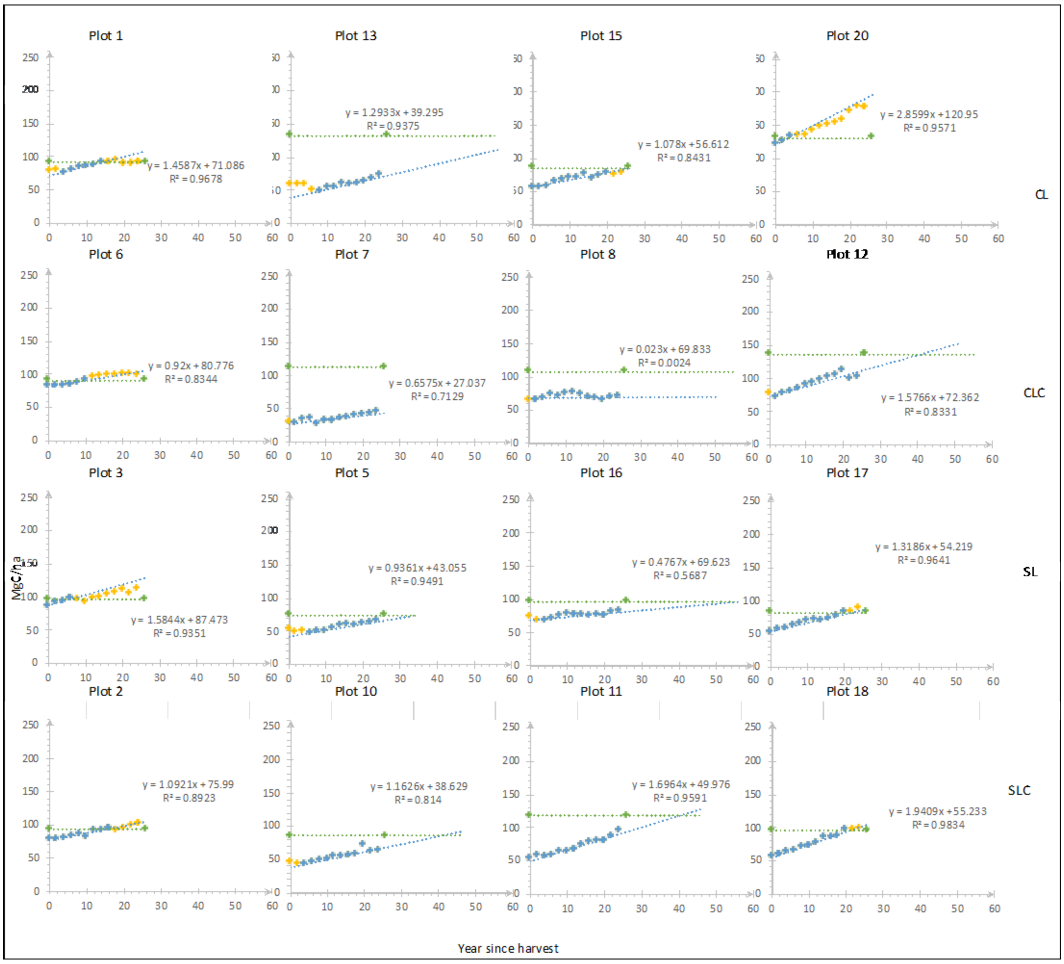
Thank you all for your support and belief in me

Appendix i



The above figure showing the AGC growth rate for all tree taxa, blue dot= rate of growth, yellow dot= extrapolating the linear regression from the lag time to when y = AGC in 1992, green dotted line= linear (value 1992), blue dotted line= linear (rate of growth)

Appendix ii



The above figure showing the AGC growth rate for all dipterocarps, blue dot= rate of growth, yellow dot= extrapolating the linear regression from the lag time to when y = AGC in 1992, green dotted line= linear (value 1992), blue dotted line= linear (rate of growth)

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