DETERMINATION OF EMISSION FACTOR FROM LOGGING OPERATIONS IN ULU JELAI FOREST RESERVE, PAHANG USING THE INTEGRATION OF UAV AND HIGH-RESOLUTION IMAGERIES

Siti-Nor-Maizah S[1, 2], Wan-Shafrina WMJ[1, *], Khairul-Nizam AM[1, 3], Aisyah-Marliza MK[1], Hamdan O[4]

[1]*Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia*
[2]*Universiti Teknologi Mara, Cawangan Perlis, Kampus Arau, 02600 Arau, Perlis, Malaysia*
[3]*Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia*
[4]*Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia*

**wanshafrina@ukm.edu.my*

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Logging activity is one of the lead drivers of carbon emission from tropical forest, and this increases greenhouse gases which cause global warming. In this study, we assessed the emission factors that contributed to total carbon emission from selective logging activities, including the overall impact that was associated with selective logging in several compartments of Ulu Jelai Forest Reserve (UJFR), Lipis, Pahang, Malaysia. Data from different remote sensing platforms such as digital aerial photographs generated from unmanned aerial vehicle and satellite images (Planetscope and Worldview) were used to extract forest attributes associated with the logging process. Based on the findings, the major sources of emission were found to be from the construction of logging infrastructure, followed by timber extraction and incidental damage. The estimated emission factor was 1.305 Mg C m^{-3} when the logging area was logged. The value of total carbon emission for the selected compartments when the selective logging was over was 7050.54 Mg C, with an average of 84.95 Mg C per ha^{-1}. This study explicates the relevant value of estimated carbon emission in the selectively logged tropical forest and we expect our approach to be utilised in determining the emission factor of other tropical forest units.

Keywords: Remote sensing, GPS, geospatial, carbon emission factor, logging infrastructure, timber extraction, incidental damage

INTRODUCTION

Forest degradation and deforestation cause substantial loss of carbon stock. Selective logging is the main activity that contributes to forest degradation aside from other forest clearing activities and forest fire phenomena (Pearson et al. 2017, PW Ellis et al. 2019). Monitoring forest degradation is essential in tropical forests to address the issues of forest carbon emission and climate change since tropical forests cover the biggest portion of the world's forests. Carbon dioxide emission in the atmosphere is derived from forest degradation and deforestation activities. It is estimated that 53% of the annual carbon dioxide emission from forest degradation is derived from timber harvesting and the rest is from harvesting wood fuel (30%) and forest fire (17%) (Pearson et al. 2017). Emission of carbon dioxide from forest degradation or forest loss into the atmosphere will encourage the rise of greenhouse gases and increase the temperature of the earth's surface (Saiful & Latiff 2019, Wan-Mohd-Jaafar et al. 2020a). Malaysia has encountered massive logging activity—legally and illegally—in recent years, causing concerns about the sustainability of the future forest. Uncontrollable and unmanageable selective logging can trigger large-scale forest damage even if a small portion of trees are being cut down or destroyed (Hamdan et al. 2016, Azian et al. 2019). Logging practice in Malaysia is conducted according to the Sustainable Forest Management (SFM), which was added to the Selective Management System (SMS) in 1978. Two logging techniques implemented under this SMS, namely, reduced impact logging (RIL) and low impact logging, focus on reducing major environmental issues due to logging activities (Azian et al. 2019).

Many studies focus on the emission of live trees and the carbon that is emitted from extracted timber. Assessment of carbon emission during the overall extraction processes is not evaluated, including the damages and residues that constantly occur and the impact from timber transport (Pearson et al. 2014, Ota et al. 2019). Through this study, we aim to highlight the issues of carbon emission from selectively logged forests. The study adopted the integration of geospatial technique and ground survey to assess carbon loss at selected logged forests. To assess carbon emission, we took into account harvested trees and all the associated incidental damages that occurred during logging. The manual process of assessing carbon emission in the tropical forest was based on ground measurement, allometric models and laboratory analysis. This process is tedious, labour intensive, costly, and time consuming for large areas, and very challenging for certain forest terrains and close canopies. Remote sensing is a reliable technique and data source for obtaining information on forest monitoring and environmental mapping (Saad et al. 2020, Wan-Mohd-Jaafar et al. 2020b). There are many technologies in geographic information system (GIS) and remote sensing which can facilitate in obtaining accurate forestry data; for example, the unmanned aerial vehicle (UAV), optical high-resolution satellite, airborne laser scanner devices such as LiDAR, and radar-based equipment. UAV is extremely popular these days in forestry analysis due to the advancement and improvement of its robotic systems and associated data analysis software (Saad et al. 2020, Mohan et al. 2021). The main goal of this study was to derive emission factors from selective logging and estimate the total carbon emission for certain logging compartments in Malaysia. Biometric data such as forest structure and logging coverage information was measured directly on the ground and from the UAV and remote sensing imageries. Data collected were used to calculate carbon stock from the overall logging process using the Winrock International carbon calculator which is based on allometric equations developed by Chave et al. (2005, 2014).

MATERIALS AND METHODS

Study area

The study area (3° 34′ N, 101° 52′ E–4° 32′ N, 101° 53′ E) is located in the Ulu Jelai Forest Reserve (UJFR), in the district of Lipis, Pahang, Malaysia. The reserve is approximately 83 ha (licensed area under the selected compartments) and is categorised as production forest with the second cycle of logging practice. UJFR experiences humid climate and annual precipitation ranging from 1500–2000 mm. Average temperature ranges from 24 to 34 °C. The terrain is quite hilly with elevations varying from 60 to 800 m above sea level. In this study, three compartments were identified and selected as study plots, namely, compartments 124, 159 and 160 (Figure 1).

Equipment and data

Equipment for ground data measurement and materials for geospatial data collection used in this study included diameter tape to measure tree diameter at breast height (DBH), stump and buttress, global positioning system (GPS) instrument to locate the coordinate of stump location, and measuring tape to measure the length of log, height of stump, branches, etc., logging infrastructure and logging damage.

Three sets of geospatial data were acquired in this study to obtain information that could not to be extracted from ground measurement due limitations and environmental conditions. Worldview-1 with 0.5 m resolution dated 11 May 2019 and Planetscope with 3 m resolution dated 18 May 2019 with four multispectral bands were used to map the logging compartments. Both data were acquired approximately six months after the operation. Digital aerial photographs were obtained from UAV. Both ground and UAV data were collected on the same dates from 19–23 August 2019. The UAV was flown over the study area on 19 August 2019 with DJI Phantom 3 device and controlled using Drone Deploy software. The UAV was launched from an open space area that was close to the sample plot, and the fly area covered the middle part of each logging compartment (compartments 124, 159 and 160) while the side and front lap coverage was 75 and 89% respectively. The flying altitude was adjusted to 100–170 m above ground level due to the terrain condition which had hills and valleys, and varying tree heights. Due to this condition, there is no accurate topographic data available but we do not expect this to interfere much with our study. For processing and analysis, Agisoft Metashape Professional 1.5 was used to process the UAV data, ENVI 5.2 was

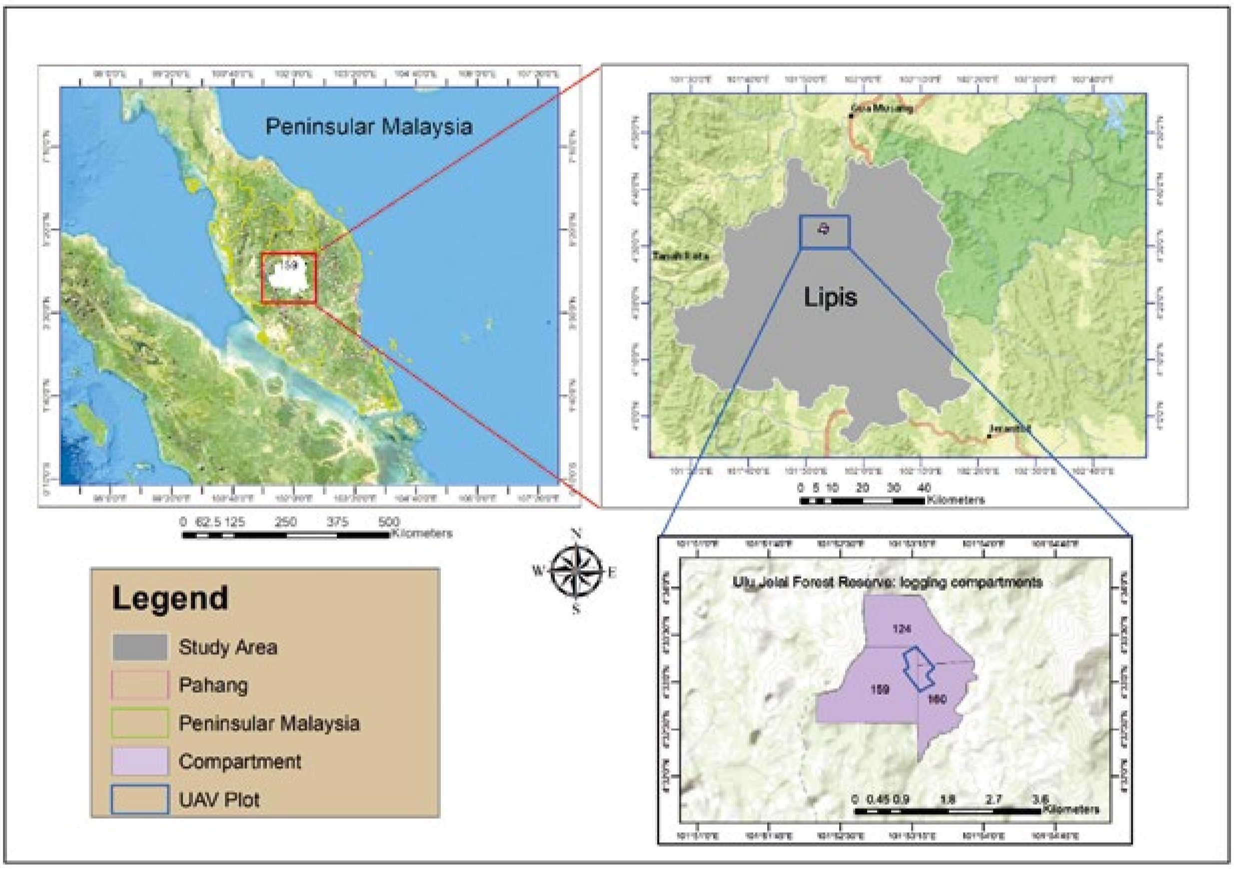

Figure 1 Study area in Ulu Jelai Forest Reserve, Lipis, Pahang; UAV = unmanned aerial vehicle

used to process satellite data and most of the GIS analyses and calculation of the areas for the carbon emission were performed using ArcGIS 10.4. Other ancillary data required was obtained from Pahang Forestry Department, Lipis District Forest Office, Forestry Department of Peninsular Malaysia, and Forest Research Institute Malaysia (FRIM).

Methodology

The general workflow of the study can be described into several stages: input data, pre-processing, data processing and feature extraction, validation, analysis, and output. The overall methodology of the study is illustrated in Figure 2. Parameters measured using remote sensing and GIS are tabulated in Table 1. The parameters measured from the field were stump diameter and height, incidental damage (diameter of associated fallen tree), wood density, tree species, canopy opening and log details (length of log, logging residues, and top cut diameter). Large coverage parameters such as road, skid trail and log yard were extracted using satellite and UAV.

Estimation of carbon emission from selective logging practice that was utilised in this study was based on Intergovernmental Panel on Climate Change (IPPC) gain–loss approach proposed by Pearson et al. (2014). This approach focuses on carbon loss due to extracted timber and forest damage resulting from the overall process of logging that takes place in the logging areas. The assessment of aboveground carbon for selective logging should be applied to every related structure that caused the degradation of forest, i.e. not only the extracted timber itself, but should include the residual damage such as branches, forest gap, log transportation, and affected non-logged trees.

The estimation of aboveground carbon was computed using Winrock International carbon calculator. The general process of ground measurement was successfully conducted based on the standard operation procedure suggested by Walker et al. (2012). The ground data collection involved the cooperation of three teams from the Institute of Climate Change, Universiti Kebangsaan Malaysia, FRIM, and Lipis District Forest Office. To estimate carbon

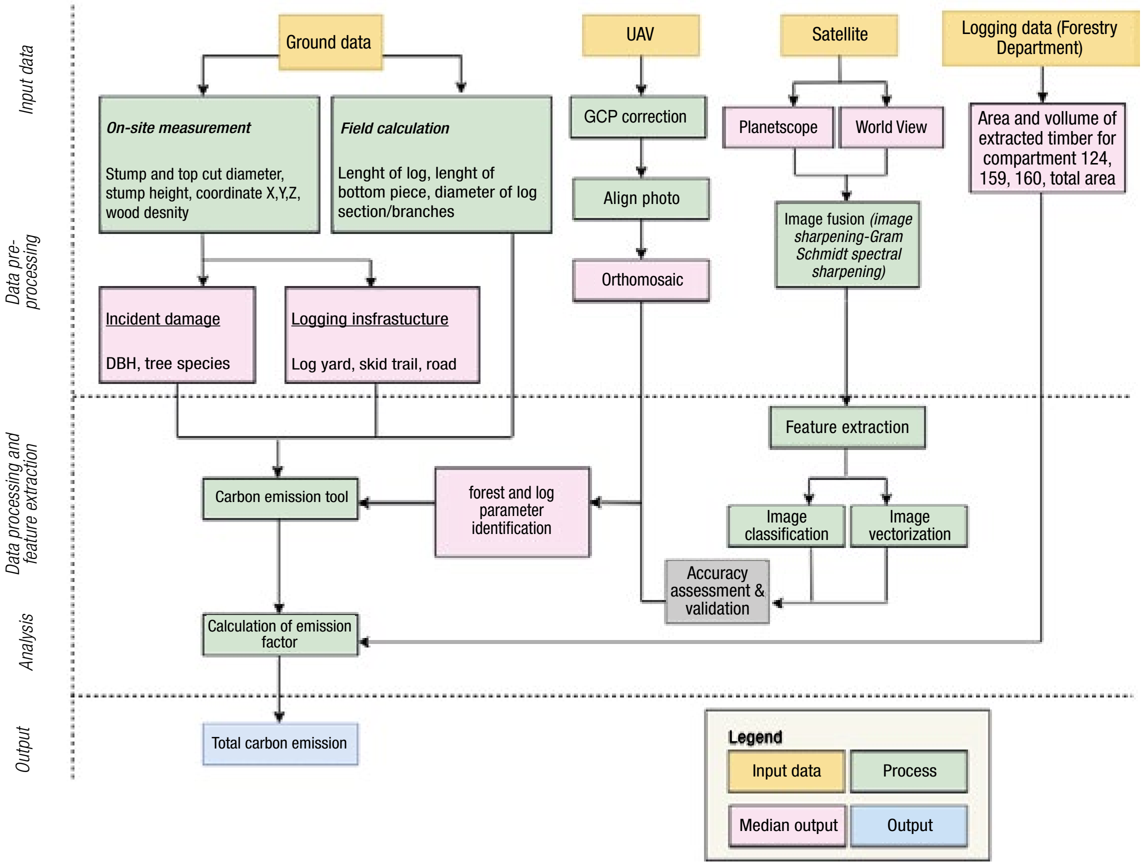

Figure 2 Methodological framework

Table 1 Parameters measured for determination of carbon emission factor and total emission

Field measurement	Remotely sensed data (UAV and satellite)
Stump height	Logging road length
Stump diameter	Logging road area
Incidental damage	Logging yards area
Canopy opening	Skid trail length
Logging residues and log section	Canopy gap
Top cut diameter	
Coordinate X, Y, Z	
Wood density	

loss after selective logging, data collection and measurements were concentrated on the remaining stumps at the site and the environmental damages that were caused by logging. A total of 21 stumps were left at the site after timber extraction. The amount of carbon was calculated for compartments 124, 159 and 160. The emission factor then was multiplied with the total actual volume of logged timber from all compartments to estimate total emission.

Stump selection in this study covered randomly the centre part of the each compartment based on the stump visibility, stump and tree condition, terrain condition, and accessibility to the area. These stumps were tagged by a logging contractor during the timber harvesting process before sampling and measurements were conducted. Stump height, length of the log, DBH, wood density (based on wood density database by Chave (2005, 2014)), length of every log section up to the first major branches of a felled tree, logging residues, incidental damage of other trees from felled timber trees and logging infrastructures were recorded in the field sheet.

The location of the stump was identified using a GPS instrument with ± 1 m accuracy. To avoid bias and wrong selection of stump and felled tree, an assessment was made on-site based on the left log section and branches available at the site. If there were no associated logs section or branches, the stump will not be measured. The selected incidental trees or felling damage were measured based on trees that had DBH ≥ 10 cm (EA Ellis et al. 2019).

UAV data processing and feature extraction using satellite data

It was necessary for us to collect UAV and satellite data since the study area was very large, and it was extremely difficult to collect details about road, skid trail, and gaps due to the terrain condition and site accessibility. Digital aerial photograph was produced by processing UAV data in Agisoft Metashape Professional 1.5 with 0.631 m ground sample distance (Figure 3).

Image fusion techniques were performed on satellite data using ENVI 5.2 and image data sharpening was applied to obtain one multispectral imagery with high spatial resolution for better image analysis and interpretation. Planetscope imagery of 3 m resolution dated 18 May 2019 with four bands was used as a low resolution and Worldview-1 0.5 m 11 May 2019 resolution single band was used as high-resolution imagery. The fusion method was applied to produce a single output of multispectral image with 0.5 m resolution. Image vectorisation was applied on fused satellite imagery to extract details about roads, skid trail, logging deck and forest gaps. Machine learning classification was performed on UAV to extract the same details (as satellite imagery) that covered the sampling area. The main road, skid trail, forested area, felled log and gaps, other objects, dead trees, no pixel value, and forested area were the eight region of interest classes created for the UJFR logging area using Envi 5.2. After defining the training data classes, machine learning classification was conducted using radial basis function kernels, and the output and accuracy reports were evaluated. For the radial basis function kernel, the penalty parameters were set to 100 and the parameters to 0.25. The training datasets chosen were then extracted into

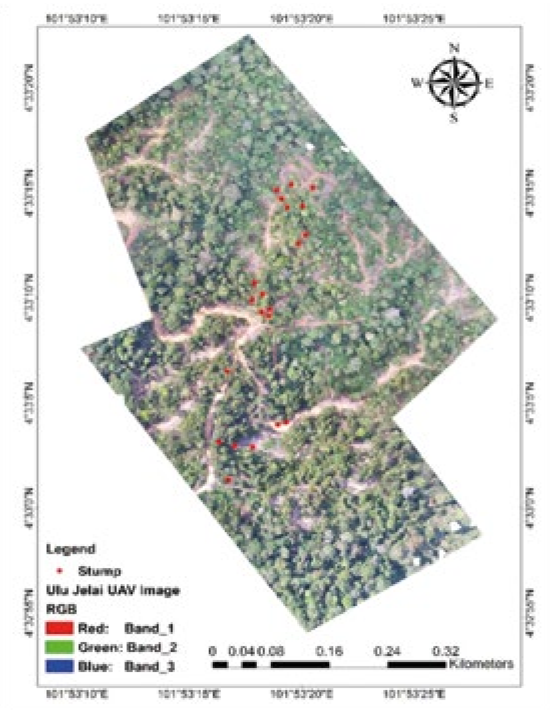

Figure 3 Orthophoto of study area and stumps distribution

five classes, each of which had the exact region of interest generated during the initial phase.

Estimation of total carbon emission

All ground data and data obtained from both UAV and satellite data was fed into a carbon calculator tool. The process of calculation for biomass and carbon estimation on the ground was based on allometric equations developed and adopted by Chave et al (2005) and we used the formulated carbon estimation calculator, which was suitable for tropical moist forest trees (equation 1). Total carbon emission (TCE) was derived from the sum of three main emission sources (equation 2), and the total emission factor (TEF) was measured using equation 3 (Pearson et al. 2014, Azian et al. 2019, Butarbutar et al. 2019).

$$AGB = WD \times \exp\left(-0.667 + 1.784 \times \log(DBH) + 0.207 \times (\log(DBH))^2 - 0.0281 \times (\log(DBH))^3\right) \quad (1)$$

where, AGB = aboveground biomass, WD = wood density and DBH = diameter at breast height.

$$TCE = (ELE + LDE + LIE) \quad (2)$$

where, ELE (Mg C) = total emission from extracted timber, LDE (Mg C) = total emission from incidental damage due to timber extracted, and LIE (Mg C) = total emission emitted during the construction of logging infrastructures.

$$TEF = (ELE + LDF + LIF) \quad (3)$$

where, ELE = emission from extracted timber, LDF = damage in biomass resulting from logging process (incidental damage), and LIF = emission resulting from infrastructures at the logging area, namely, road, skid trail and logging deck. Basic principles of determining carbon emission from selective logging impact according to Winrock International assessment were based on the following standard operation procedures: (1) estimation of carbon damage from extracted timber and (2) estimation of carbon damage from log extraction. Hence, emission factors between the volume of timber taken and the change in carbon pools can be created using this approach. These emission factors were used to predict the change in carbon pools depending on the volume of timber extracted and the length of infrastructure built during the logging process. Where necessary, adaptations were made for specific forest regions, land cover, and vegetation type in the sampling location (Walker et al. 2012).

RESULTS AND DISCUSSION

Feature extraction of forest attributes

Forest parameters extracted from satellite and aerial-based systems were the additional data needed for calculation of biomass and total carbon emission. The geospatial approach used in this study was a feature extraction procedure that involved classification processes, support vector machine (SVM) to produce a selective logging map and image vectorisation process. The overall accuracy of the SVM result in this research was more than 80% of overall accuracy and kappa value was 0.74. This value is significant with threshold below 1. Haul road, skid trail information, forest gap, and logging deck information were also extracted feature extraction. Figure 4 shows the logging compartment map of the study area based on the remote sensing system.

Table 2 shows the list of forest attributes from feature extraction process. Four attributes were identified, namely, skid trail, road, forest opening or canopy gap, and logging deck and their total length and area were measured.

Total carbon emission

The total carbon emission estimated in this study was focused on the overall selective logging impact in the permitted compartments. Carbon emission from the selective logging activity at UJFR is simplified in Tables 3 and 4. In this study, two logging decks were detected for the three compartments. Emission from the skid trail was 14.07 Mg km^{-1} C and from the road, 57.41 Mg km^{-1} C (Table 3). Each logging deck emitted 15.97 Mg C. Other emissions recorded were extracted emission from extracted log (0.29 Mg C m^{-3}), total logging damage factor (0.97 Mg C m^{-3}), and logging infrastructure factor (0.05 Mg C m^{-3}). The total emission factor was 1.305 Mg C m^{-3}.

Figure 5 explains the overall emission from three main sources of carbon emission: (1) from extracted log/timber or felled log (80.64 Mg C per plot), (2) from logging damages which include

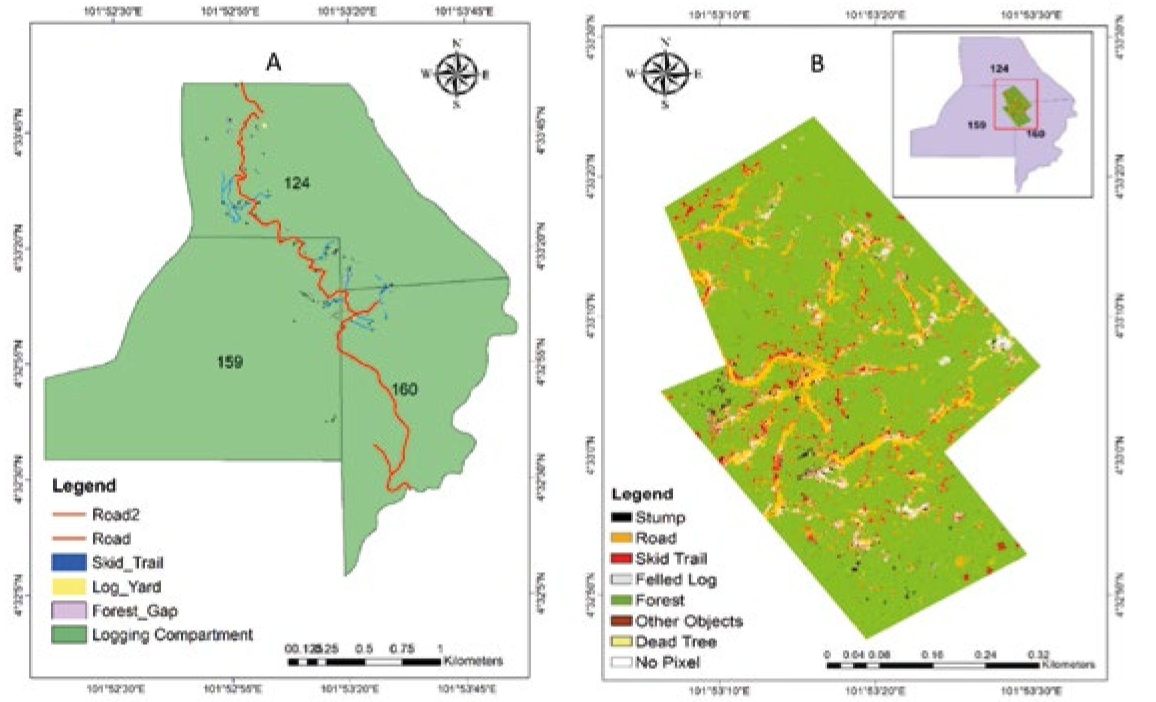

Figure 4 Logging compartment infrastructure map (a) and UAV plot (b)

Table 2 Forest attributes that were measured in the study

Attribute	Total length (m)	Total area (ha)
Road	6780.666	2.415
Skid trail	4760.968	0.699
Log yard	0	0.206
Canopy gap	0	0.144

Table 3 Summary of extracted timber volume and carbon emission for various sources and logging components

Source of emission	Mean	SE
Extracted timber volume (m^3 gap^{-1})	5.60	2.71
Total felled tree carbon (Mg C gap^{-1})	4.59	2.07
Extracted log emission (Mg C m^{-3})	0.29	0.00
Carbon extracted in log (Mg C gap^{-1})	1.42	0.69
Total carbon damage (Mg C gap^{-1}) = (top $_+$ stump $_+$ incidentals)	5.00	2.58
Total carbon damage per volume extracted – logging damage factor (Mg C m^{-3})	0.97	0.43
Total carbon emissions per area of canopy opening (Mg C m^{-2})	0.17	0.22
Carbon emission from skid trail (Mg km^{-1})	14.07	0.20
Carbon emission per logging deck (Mg C per logging deck)	15.97	24.72
Carbon emission per length of road (Mg C km^{-1})	57.41	0.00

SE = standard error

Table 4 Summary of total logged volume, total area, and total carbon emission from logging compartments

	Value
Total logged volume (m^3)	5402.71
Total logging area (ha)	83.00
Total volume ha^{-1} ($m^3 ha^{-1}$)	65.09
Total emission factor (Mg C m^{-3})	1.305
Total carbon emission (Mg C)	7050.54
Total carbon emission ha^{-1} (Mg C ha^{-1})	84.95

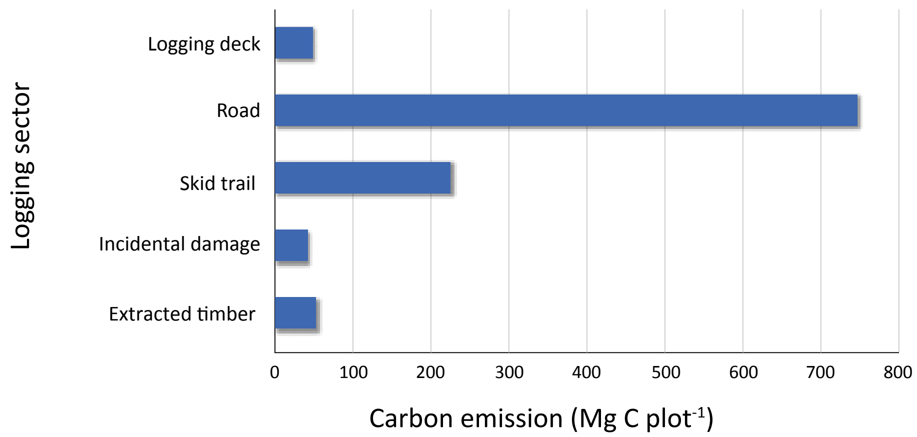

Figure 5 Total carbon emission from different logging sector

incidental damage (42.38 Mg C per plot); and (3) from logging infrastructure (skid trail = 225.07 Mg km^{-3} C, road = 746.85 Mg km^{-3} C and logging deck = 47.91 Mg C per logging deck). From the assessment, the biggest percentage contributor was from logging infrastructures (89.24%) followed by timber extracted (7.06%) and logging damage (3.71%).

Regression analysis was used to investigate the factors that influence the amount of carbon dioxide released into the atmosphere. Total carbon emission showed moderately high correlation with wood density from the incidental tree (Figure 6B). Based on the predictive analysis presented in Figures 6C and D, AGB for incidental damage was highly correlated with total incident emission and logging damage factor which ranged from 0.4 to 2.1 Mg C m^{-3}. This is because incidental damage also contributes to carbon emission when trees are logged.

Total emission factor at the permitted logging area was estimated as 1.305 Mg C m^{-3}, which was the factor of carbon emission when the logging compartment was opened for logging activities. Based on the total volume of overall timber harvested, with 83 ha of logging area, it was estimated that 7050.54 Mg C was emitted. From the result, the estimated emission per hectare was found to be 84.95 Mg C. The estimated result of overall emission from logging infrastructure was slightly lower due to the total length of skid trail and road which was shorter than other compartments in the same forest area since the measurement was compared with the feature extraction from remote sensing analysis. Coverage of logging area might also be disturbed at the time of observation which was six months after logging. After selective logging, tropical forests experience massive forest and vegetation growth due to climate, forest density, weather conditions, and soil type. We did not have the data for carbon emission before and after logging, therefore, no comparison was done. However, the carbon calculator developed by Winrock International is

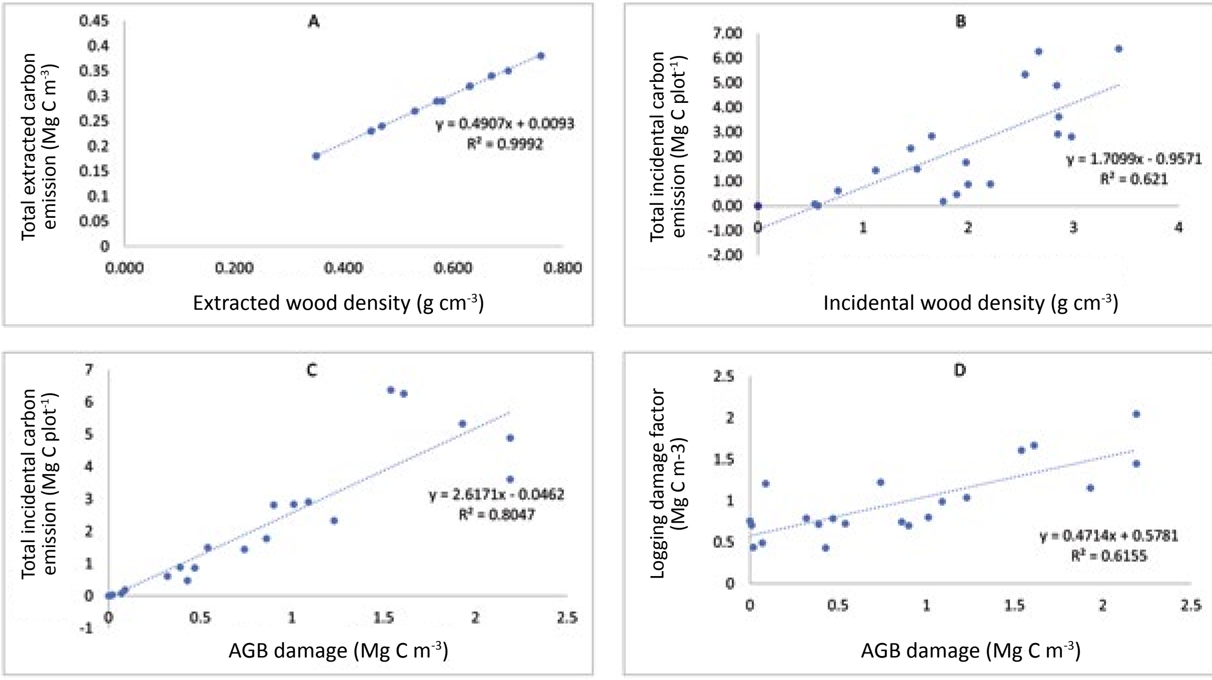

Figure 6 Predictive correlation between: (A) extracted wood density and total extracted carbon emission, (B) incidental wood density and total incidental carbon emission, (C) aboveground biomass (AGB) of incidental damage and total incidental carbon emission and (D) AGB of incidental damage and logging damage factor

widely and extensively used and has proven to be relevant in assessing carbon emission and impact from selective logging (Walker et al. 2012, Azian et al. 2019).

The total carbon emission for logging compartments 124, 159 and 160 might be different from other logging locations due to existing conditions of the logging area, terrain, tree species, and the number of trees permitted to be logged. Results of emission from both the skid trail and road are slightly lower than the values reported by Azian et al. (2019). This was due to the later time of data collection (i.e. six months vs two weeks after logging), which affected the regrowth of trees and bushes. As a result, some of the logging infrastructures could not be measured directly on the ground or from space. For the rest of the emission, our results showed almost similar values to Azian et al. (2019). From the overall findings, emission contributed by logging infrastructures was generally higher than emission from extracted timber since building logging infrastructures will require many trees to be felled. Selective logging reduces major damages resulting from unwanted fallen trees and leaves remaining trees for the next carbon pool. Average carbon emission for each hectare of logging compartment in this study is consistent with data from the previous studies conducted in the same forest (Noraishah et al. 2015, Mashor et al. 2017). However, there are still slight differences since the approaches chosen are different, so is the total compartment area and volume of timber extracted. Managing the best technique (i.e. RIL) in selective logging practice improves the effect of carbon emission from forest areas. A study on similar forest type and condition, namely in Kalimantan, Indonesia shows an improved reduction in carbon emission after selective logging, i.e. from 8.2 to 11.3% reduction (Griscom et al. 2019). Most of the reduction can be achieved using RIL by minimising haul road, skid trail and open gap which reduces logging waste. Although there were limitations in this study and data collected were minimal, we were able to estimate the carbon emission based on extracted information left on the ground data. The selection of samples was the main challenge since the logging area has been abandoned for a long period. Many remaining stumps, logs, and tree crowns were already damaged due to weather reaction, composition processes, and regrowth of trees and bushes. The emission factor generated from the study is significant to estimate the overall logging impact for logging compartments based on the volume of actual timber extracted. This factor can be used to estimate the total carbon emission from a different location with similar forest conditions especially those within the same tropical region. To improve the results, it is suggested to increase the number of sample plots or stumps, along with wider coverage of the logging compartment. A comparative study of before and after logging may be useful and more accurate to measure the changes of carbon stock in forests and carbon emission from the damage due to harvesting activity. Therefore, a pattern of carbon changes can be effectively assessed.

The total carbon emission assessment from selective logging in the Malaysian tropical forest is important to demonstrate the carbon impact from logging activities. Only a minimal number of studies have been implemented to date to monitor carbon assessment from selective logging in Malaysia, even though Malaysia is practising selective logging under SFM in most of the compartments licensed under Malaysia authority.

CONCLUSIONS

This study underscores the importance of assessing selective logging impact using ground data measurement and geospatial technology. Our results provide the total carbon emission from three sources of emission which were affected by selectively logging practices, namely, (1) extracted timber, (2) logging damage including residue and damage from other associated timber trees, and (3) logging infrastructure, due to the construction of skid trail, logging road and logging deck. RIL technique can reduce massive damage to the forest and residual stands and leave the forest with healthier and richer forest stands which can store more carbon and help to regulate the ecosystem. This study provides reliable and relevant interpretations based on the area of study and the number of samples collected. By assessing the emission factor of carbon when a compartment was opened for logging, overall carbon loss due to logging can be estimated by analysing the total volume of timber extracted from the forest. We expect our result to serve as a benchmark to analyse the improvement of adopting SFM in the timber harvesting sector in Malaysia. Furthermore, the findings of the study can be used to assess the effectiveness of the logging practices elsewhere.

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