Carbon Impacts from Selective Logging of Forests in Berau District, East Kalimantan, Indonesia

Sandra Brown, Felipe Casarim, Sean Grimland and Tim Pearson

April 2011

ACKNOWLEDGEMENTS

We wish to acknowledge TNC Staff Bronson Griscom, and Benjamin Jarvis, TNC Berau staff Bambang Wahyudi, and Fakhrizal Nashr, and the for their hospitality and support to the field mission. Funding for this project was provided by “The Nature Conservancy”.

Cite report as

Brown, S., F. M. Casarim, S.K. Grimland and T. Pearson. 2011. Carbon Impacts from Selective Logging of Forests in Berau, East Kalimantan, Indonesia.

DISCLAIMER

This report is made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of Winrock International and do not necessarily reflect the views of USAID or the United States Government.

Contents

EXECUTIVE SUMMARY

Few studies have attempted to address the carbon emissions resulting from the degradation of tropical forests. Selective forest logging represents an important form of degradation of tropical forests, and may lead to future deforestation of the area by providing accessibility to these areas. This study focus on quantifying the carbon impacts from selective logging operations in four different forest concessions in the Berau district in East Kalimantan, Indonesia. The net impact of selective logging on the forest carbon stocks was estimated by:

- Measuring, on a gap-by-gap basis, the extracted biomass and carbon in the timber tree and the incidental carbon damage to surrounding trees;
- Estimating the carbon impact caused by the logging operations such as road and skidding trail construction, and land clearing for log decks; and
- Creating factors between total biomass damaged (extracted and collateral) per gap and the volume and carbon in the timber extracted.

The timber felling techniques employed by each concession (four concessions, referred to as E-H) have practically the same carbon impact on the forests whether on a per average gap, per m^3 timber extracted, or per t C extracted basis. The reduction in carbon stocks was approximately 3 t C/ t C extracted. The amount of deadwood left in the forest was also similar across all four concessions at (0.4 t C/ t C extracted). Differences in the carbon impact due to logging infrastructure, however, were evident among the concessions. The impact of haul roads ranged from 1,000 t C/km to roughly 1,300 t C/km, with this variability associated with the total C stocks in the forests rather than differences in road construction itself as widths were similar across concessions. Skid trails' impacts were very variable among concessions, ranging from 85 to 210 t C/km, and largely reflected the nature of the terrain logged (i.e. greatest impacts in hillier forests). Logging decks also showed significant carbon impact differences among concessions. In one of the concessions, the carbon impact per logging deck constructed was approximately 2.6 times greater than the average impact for the other three concessions (115 t C/deck as opposed to 40 t C/deck).

High resolution satellite imagery (60 cm) was obtained for one concession (E) in late 2010 to estimate the density of roads, skid trails and logging decks and to relate the density (m^2/ha of active concession area) to the timber extraction rate. The emission factors, expressed on a per cubic meter extracted basis, were: 1.44 t CO_2/m^3 for roads, 0.65 t CO_2/m^3 for skid trails and 0.07 t CO_2/m^3 for logging decks. The timber extracted from this concession in 2010 was very similar to that extracted in 2009, and similar to that for two other concessions (F and H). Thus we assumed we could use the data from the concession E to extrapolate the emissions across the active area of two other concessions in Berau (F and H). We adjusted the emission factors developed for the concession E by factors that reflect the different biomass carbon stocks of the forests and the widths of the skid trails for the other two concessions. Using the emissions factors per cubic meter and the timber extractions rates (m^3/ha), the total emissions ranged from 186 to 204 t CO_2/ha. These emissions represented 12-18% of the carbon stocks in trees of these forests. In other words, emissions from logging about 5.5 to 8 ha of forests (depending upon concession) with about 35 cubic meters of timber extracted would be equivalent to the emissions from clearing 1 ha of forest in the concession.

Several opportunities exist for improving forest harvesting practices that would reduce the carbon impact. We looked at several options for reducing emissions including improving the planning and design of roads, skid trails, and decks to reducing the amount of wood waste (avoidable waste) generated by the felled tree. As 50% or more of the felled tree is left behind in the forest, it would appear that there is an opportunity to extract the same volume of merchantable timber with a reduction in the number of trees felled and consequently the amount of skid trail construction. Such a practice could reduce the overall emissions by about 10%, not an insignificant amount.

It was found that medium resolution Landsat imagery was of limited use for estimating all emissions from logging infrastructure as only the road network can be identified. We conclude that to estimate all emissions from logging infrastructure with a high degree of certainty, the following is needed to combine with the field based data: (1) remote sensing imagery of resolution of about 50-60 c m, or less; (2) imagery of >90% cloud and shadow free (use of multiple images for same time frame could be used); and (3) subsampling of the active area for delineating skid trails by randomly selecting smaller logging block to include about 20% of the active logging area.

1.0 BACKGROUND

Much discussion occurs on the role forest ecosystems play in mitigating climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change indicates that land-use change and forestry, including deforestation and degradation, is responsible for nearly 20% of greenhouse gas emissions (IPCC, 2007), although this has recently been re-estimated to be more like 12% of GHG emissions (van der Werf et al. 2009) . There is concerted international interest in reducing emissions and incentivising the reduction of emissions from deforestation and forest degradation. Deforestation is clearly visible from satellite imagery, but forest degradation is harder to identify because it occurs through legal and illegal logging and opens up frontiers for agricultural expansion through the construction of roads and other infrastructure. Several studies exist that have focused on estimating the emissions from tropical deforestation but practically none exist that focus on degradation. This study focuses on forest degradation caused by conventional selective logging in forestry concessions in the district of Berau in East Kalimantan, Indonesia.

In this study we focus on the carbon impact of selective logging in four concessions under different management practices in Berau. To monitor logging impacts on carbon stocks, factors are needed to link reported data or readily monitored components with the total carbon impact. Many studies have examined logging and associated damage both in conventional and reduced impact scenarios; however, these studies have largely focused on the number of trees damaged (e.g. Uhl and Vieira 1989, Uhl et al. 1991, Verissimo et al. 1991, White 1994). The studies of Pinard and Putz (1996) and Feldpausch et al. (2005) detailed the carbon impact but not in the context of area and number of gaps, volume of timber extracted, and damage caused by construction of logging infrastructure (e.g. haul roads, skid trails, and logging decks). Winrock has developed methods and factors that link gap area or volume extracted with biomass damaged (Republic of Congo – Brown et al., 2005; Chihuahua, Mexico – Pearson et al., 2005; the Brazilian Amazon - Pearson et al., 2006; and East Kalimantan, Indonesia – Pearson et al., 2007). In this study we apply the methods developed in earlier work to the concessions in Berau.

2.0 SCOPE OF WORK

The goal of this study is to estimate the net impact of selective logging on the forest carbon stocks by:

1. Measuring, on a gap-by-gap basis, the extracted biomass and carbon in the timber tree and the incidental carbon damage to surrounding trees;
2. Estimating the carbon impact caused by the logging operations such as road and skid trail construction, and land clearing for log decks; and
3. Creating relationships between total biomass damaged (extracted and collateral) and the timber extracted and the area of canopy gap caused by logging.

The original plan was to include collection of aerial imagery over the concessions but this proved to take a lot longer than previous experience in collecting such imagery in East Kalimantan and during the delay the cost of plane rental went up significantly. Upon further investigation we decided to use commercial imagery that can be collected on request to meet desired standards. We used high resolution commercial imagery (WorldView-2 satellite at 0.6 m resolution) collected over concession areas that were logged in the October-November 2010 time frame to obtain data on roads, skid trails and gaps –these data are combined with the ground data presented in this report.

3.0 SELECTION OF CONCESSIONS

Four different natural forest logging concessions (IUPHHK-HA[1], referred to in this report as: "forest concession") were selected for this study based on a series of criteria (Figure 1). According to Griscom (2009, unpublished)[2] the four selected concessions were chosen because they represent a range of natural characteristics and are representative of the dominant logging practices in the Berau District.

There are two types of logging, in terms of extracted timber, allowed in forest concessions in Indonesia, limited production (HPT) or normal production (HPH). Limited production restricts the minimum DBH size of felled trees to 60 cm. In 2010 that size will decrease to 50 cm. Normal production allows for the felling of trees with a minimum DBH size of 50 cm, moving down to 40cm in 2010. Each concession is broken into cutting blocks, which are sub-units of the concession and are marked for production based on the year. Both types of logging, HPH or HPT, can occur within the same concession but not within the same cutting block.

A description of the four logging concessions sampled by Winrock staff are[3]:

- Referred to as concession F in this report, this concession was selected because it seemed to have conventional logging practices, although some attempts at erosion control were sometimes evident, such as: water bars and water diversion structures. The topography was the least rugged terrain compared with the other concessions and the forests appeared to be undistrubed. Forest production in this concession included a mixture of limited (HPT) and normal production (HPH).
- Referred to as concession E in this report, this concession showed some improvement towards reducing impacts of logging operations in comparison to F, however they are still far from carefully planned and implemented operations of timber harvesting. The terrain was more rugged than the first concession, and the forests appeared to have been previously logged.
- Referred to as concession G in this report, this concession appeared to be the only one actually using some of the "reduced logging impacts" (RIL) practices. It has been in operation for longer period of time and it been certified by FSC, although not officially yet (Griscom, 2009[1]). The main roads were well maintained and gravelled up to the current year's cutting block, unlike the other concessions. For 2009 operations, three cutting blocks had been finished and another four were scheduled to be completed still that year. All the logging for 2009 is under normal production limits (HPH).
- Referred to as concession H in this report, it was very rugged, with steep slopes, and the forest appeared to be undisturbed. The trees however seemed to be somewhat smaller than in all other three concessions (perhaps due soil and mountainous factors).This concession showed some attempts at erosion control (water bars and diversions found in closed areas) within the cutting areas. All logging in this concession was done under normal production limits (HPH). The rugged landscape, distance from the towns, and complicated logistics (i.e. precarious road access and necessity of crossing two rivers to arrive at the base camp) presented a real challenge to field sampling. Three cutting blocks had been finished when the field staff arrived. The blocks were finished in either late September or early October. One cutting block was finished in April 2009.

[1] According to James J. Halperin, a US Forest Service staff working at the Responsible Asia Forestry and Trade (RAFT).
[2] Griscom, B. 2009. Field scoping for Winrock Berau logging emissions study. Field scope work report. Unpublished. 4 pp.
[3] TNC has spent much time to develop relationships, built on mutual trust, with the four concessions that we studied that allowed us to sample within these concessions; as data and information is proprietary we do not refer to the concessions by name but instead use a letter code of E through H.

The area of each concession is large, covering up to 1000,000 ha, with about 1 to 2 thousand ha logged during 2009 (Table 1). (All tables in the report present the four concessions in the order given above.)

Table 1: The total area of forest concessions (ha) and area dedicated to logging in 2009 (ha).

Concession	Total Area (ha)	2009 Cutting Block Area (ha)
F	69,760	1,735
E	77,839	1,939
G	103,131	995
H	46,236	929

4.0 METHODOLOGY FOR ESTIMATING EMISSION FACTORS

4.1 General logging methodology

A model that illustrates the fate of live biomass and subsequent CO_2 emissions when a forest is selectively logged is shown in Figure 1[4]. The total annual emissions is a function of: (i) the area logged in a given year; (ii) the amount of timber extracted per unit area per year; (iii) the amount of dead wood produced in a given year from tops and stump of the harvested tree, mortality of the surrounding trees caused by the logging, and tree mortality from the skid trails, roads, and logging decks, and (iv) the biomass that went into long term storage as wood products. Some of these emissions would be offset by any regrowth that occurred in and around gaps created by the tree felling and infrastructure.

[4] This methodology only applies to emissions and not any removals due to regrowth of the logged forest

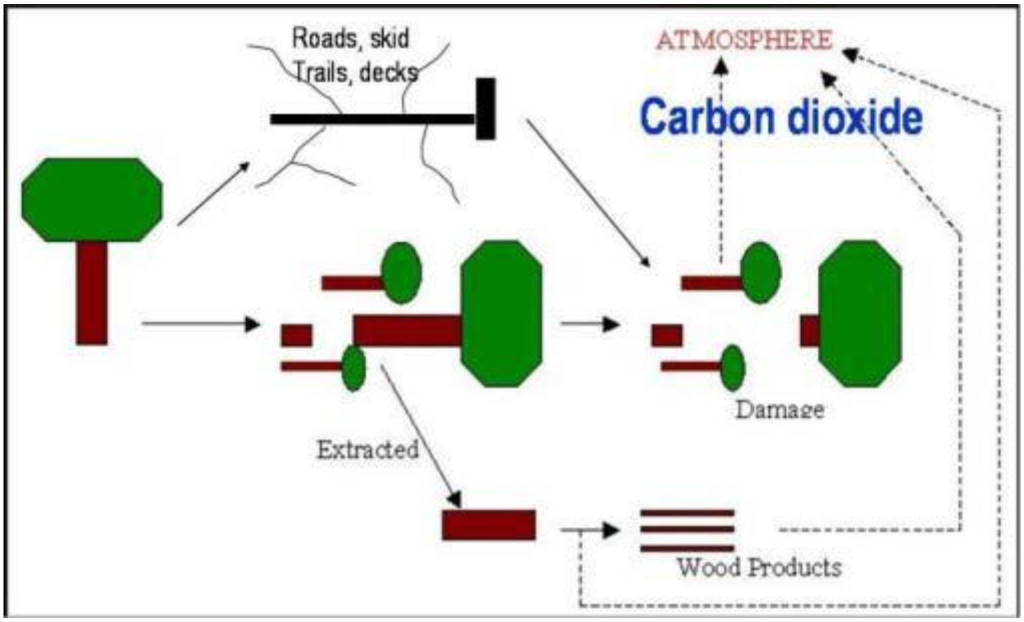


Figure 1: Movement of biomass carbon and subsequent CO_2 emissions from selective harvesting of tropical forests.

The carbon footprint of a logging operation is estimated as the difference in carbon stocks between a forest that has been harvested and one that has not. To estimate the change in live biomass, one could measure the live biomass in a concession before a block was logged and then again after it was logged; the difference would give the change in the live biomass C—referred to in the IPCC guidelines as the stock change approach. However, the main problem with this approach is that two large C pools are being compared, and although the error on each pool could be small, the error on the difference, expressed as a percent, would be much larger. The method used in this study is the IPCC gain-loss approach that focuses on the losses from the logging gaps and related logging infrastructure and the gains from regrowth in and around the gaps and infrastructure. In this sense, it is more appropriate to measure the change in live and dead biomass pools due to logging impacts directly in the harvested areas. The carbon loss or change in live and dead biomass between the "before-logging" and "after-logging" scenarios is a result of the extraction of timber, the damage caused to residual trees from the logging activities, and the removals of trees due to construction of roads, skid trails and logging decks. This method assumes that all felled trees are extracted, where in reality trees could be felled and then not extracted for a variety of reasons (e.g. too damaged, hollow, mid-identified, could not re-locate to skid out). Where this practice is common and not monitored, the method described here will underestimate the total emissions associated with timber harvesting.

The emissions from selective logging is expressed in equation form as follows:

Emissions, t C/yr = [Vol x WD x CF x (1-LTP)] +[Vol x LDF] + [VOL x LIF]

Where:

Vol = volume of timber over bark extracted (m3)

WD = wood density (t/m3)

CF = carbon fraction

LTP = proportion of extracted wood in long term products still in use after 100 yr (dimensionless)

LDF = logging damage factor—dead biomass left behind in gap from felled tree and collateral damage (t C/m3)

LIF = logging infrastructure factor—dead biomass caused by construction of infrastructure (t C/m3)

The total emissions can be expressed on a t C per ha per yr basis if Vol is also expressed on a m3/ha basis. It is also possible to express Vol on a per unit area of gap basis as long as total area of gaps per ha of concessions is known. LDF and LIF can also be expressed on a t C per unit length or unit area basis, combined with knowledge on total length or total area of gaps or infrastructure.

The gain in carbon is accounted for as the growth in t C per ha per year for the area of logging gaps and buffer areas around the infrastructure. It is not clear how selective harvesting affects regrowth in recently logged areas. The removal of the large timber trees and the damage to residual trees may be enough to actually reduce the rate of carbon fixation of the stand per unit area after logging rather than stimulate it as is often assumed (the incremental biomass accumulation on very large diameter trees can be very high even if the radial growth is small). Based on measurements made in the Noel Kempff project area of Bolivia, we found that the rate of carbon fixation in gaps after logging did not differ from that in unlogged areas of the same forest—in other words, the trees around the edge of gaps and in the gaps did not accumulate more biomass carbon per unit area than trees in the unlogged areas of the forest. We also assumed that selective logging has no impact on soil carbon over a large concession because of the small area impacted (Johnson and Curtis 2001).

To quantify the biomass carbon damaged and dead due to development of logging infrastructure (roads, skids, and decks), additional pieces of information are needed: the total length of roads and skids and area of decks in a given logging block and the carbon stocks of the unlogged forest. We assume that the unlogged forest is "deforested" to build the roads and decks, and "degraded" in skidding the logs out (i.e. not all trees are removed—based on work by B. Griscom in other similar concessions they found that skid trails did not dame trees with DBH greater than 50 cm). Details of the steps used to estimate the carbon impact of the infrastructure development are given in the respective sections of the methods below.

Finally, not all the timber removed goes into long term wood products. Wood products have finite life times that vary depending on the product (Winjum et al.1998). To simplify the calculations so that wood product turnover rates do not need to be tracked over time, we assume that the amount going into permanent storage is the fraction remaining after 100 yr (commonly used in several IFM methodologies, including the protocols of voluntary markets such as ACR and VCS). The amount of wood that goes into long lived products after 100 yr depends on the amount of timber going into the different product pools. For conventional logging concessions, the amount of timber going into sawn wood is 30% and the remaining 70% goes into wood panels. Based on these proportions, the fraction of timber volume going into long term wood products is 4.4%. For FSC certified concession, the proportion going into sawn wood and wood panel is 40-60 %, and the fraction ending up in long term wood products is 5.1%.[5]

The original plan to estimate the length/area of roads, skids, and decks, was to include collection of aerial digital imagery at high resolution (about 10-50 cm) by flying transects over the concessions, with the length of transect based on the area of concession under active logging. The method was to use standard software (e.g. eCognition, Pearson et al. 2006) to measure the area of logging gaps and decks and the length of skid trails and roads in the imagery sample. These values would be expanded to derive estimates for the whole area under active logging in a given year. However, this did not materialize as mentioned above. Instead we did obtain some high resolution satellite imagery that we used to obtain logging infrastructure data for one concession only (see Annex 1) and we were able to use for two other concessions as discussed further below.

[5] From Bronson Griscom analysis based on data obtained from the concessions by Nawa Irianto of TNC.

We needed two other pieces of information—these are the amount of timber extracted per unit area per year and the total area logged per year obtained from the concessions. Total emissions are then estimated as the product of total change in carbon stocks, the timber extraction rate, and the total area logged.

4.2 Estimation of biomass of unlogged forest

Estimation of forest biomass stock for the unlogged forests in each concession was made by collecting field data in forest that was similar enough to represent forest conditions of each concession prior to logging. Circular nested-plots (Figure 2) were randomly placed in all four concessions to measure the trees upon which biomass estimates are based. A minimum of twenty (20) plots were established per concession (total of 82 across all four concessions). Data were collected using Winrock Standard Operating Procedures (Winrock International, 2009). Diameter at breast height (DBH) and tree species were recorded within the nested plots (Figure 3).

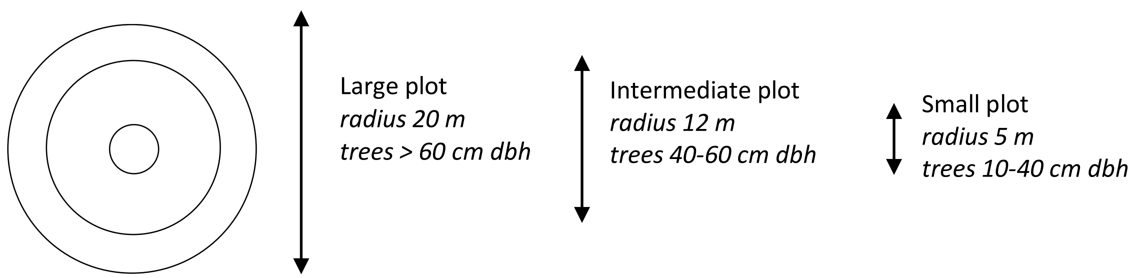


Figure 2: Schematic diagram representing a circular three nest plot.

Data and analyses at the plot level are extrapolated to the area of a full hectare to produce carbon stock estimates. Extrapolation by use of scaling factors occurs by calculating the proportion of a hectare (10,000 m^2) that is occupied by a given plot (Equation 1). These scaling factors were adjusted for slope as discussed below (Section 4.2.1).

$$(1)\ \ Scaling\ Factor = \frac{10000\ \mathrm{m}^2}{\text{Area of Nest }(\mathrm{m}^2)}$$

4.2.1 Selection of allometric equation for biomass estimation

Above-Ground Biomass

For determining above-ground biomass (AG) four allometric equations for tropical forests were tested (Yamakura et al., 1986; Brown, 1997 – updated; Chave et al., 2005; and Basuki et al., 2009) and the best fit for the collected data was selected. The equations are as follows:

(2) $AGB = \mathrm{EXP}[-2.2197 + (2.5958 * (\mathrm{LN}(\mathrm{DBH}))]$ Yamakura et al

(3) $AGB = \mathrm{EXP}[-2.289 + 2.649 * \ Ln(DBH) - 0.021 * (Ln(DBH))^2]$ Brown

(4) $AGB = \rho * EXP[-1.499 + \left(2.148 * \mathrm{LN(DBH)}\right) + (0.207 * \left(\mathrm{LN(DBH)}\right)^2) - (0.0281 * (\mathrm{LN(DBH)})^3)]$ Chave et al.

(5) $AGB = \mathrm{EXP}[-1.201 + (2.196 * (\mathrm{LN(DBH)})]$ Basuki et al

Where;

AGB = aboveground biomass in kg/tree

DBH = diameter at breast height in cm

ρ = wood density g/cm^3

EXP = “e” to the power of

Equations 3 and 4 were developed for all tropical forests whereas the equations 2 and 5 were specifically developed for lowland *Dipterocarp* forests in Indonesia. The Basuki et al. (2009) equation consistently underestimates AGB values compared to the estimates from Brown and Chave et al. equations and compared to the equation by Yamakura et al., also based on dipterocarp forests (Figure 3). We do not know why the Basuki et al. equation gave such different results especially as it was developed from destructive harvesting in East Kalimantan region, but as the authors were unwilling to share their original field tree data with us we have no way of investigating further. The Yamakura et al equation produced the highest biomass estimates, and for the large biomass concessions (F and G), the estimated biomass was almost twice that of Basuki et al. The Brown and Chave et al. equations performed about the same. However, we decided that the Chave et al. is the most appropriate to use in this study because it is a more recently developed equation, uses a larger dataset (about1,500 individuals and a r^2 of 0.99), contains a high number of large diameter trees (68 trees > 70 cm diameter of which 8 are > 120cm, and largest is 156 m DBH), and it takes into consideration wood density in addition to DBH.

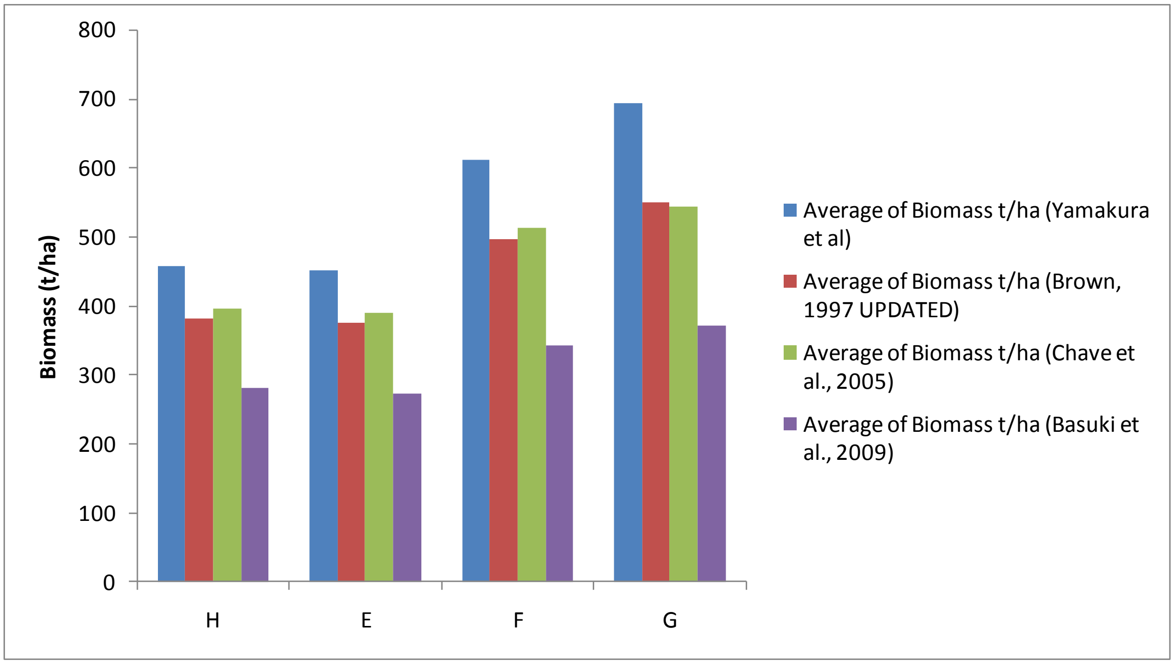


Figure 3: Average biomass (t ha-1) estimated using four allometric equations (Eq. 2-5) across all visited forestry concessions.

To use the Chave et al. equation, we needed the density of each measured tree. We noted the species of the tree in the field data record, and then using Reyes et al. (1992) we assigned a wood density to each tree. Where a species-specific density value was not available, we applied a genus level value if available, and failing that we used the regional average for SE Asia (0.57 t/m^3).

Several trees that were measured in the plots exceeded the maximum size of the trees that the Chave et al. equation was built upon. To test the validity of the equation for these large trees, we approximated their biomass by first estimating the volume of the bole (from DBH and length), estimated its mass using the wood density for the species or genus, and added an estimate for the branches and leaves to arrive at an estimate of the aboveground biomass. We then compared this approximation to the estimate obtained by applying the allometric equation. From this validation we concluded that no adjustment of the estimate resulting from the use of the Chave et al. equation due to DBH size was needed.

Below-Ground Biomass

Below-ground (BGB) biomass at the stand level was estimated using the root to shoot (R:S) ratios given in Mokany et al. (2006). This relationship allows for estimating a forest's below-ground biomass based on the above-ground biomass on a per hectare basis. The ratios used were established for tropical forests as follows:

- if AGB < 62.5 t C ha^{-1}, BGB (t C ha^{-1}) = 0.205*AGB; or
- if AG > 62.5 t C ha^{-1}, BGB (t C ha^{-1}) = 0.235*AGB

For BGB estimation at tree level, we use the liner equation reported in Mokany et al. as given in Equation 6. Although the original data base was based on stand level data, the fact that the equation is linear makes it applicable to the tree scale too.

(6) $BGB = 0.26 * AGB,\ r^2 = 0.78$

Total Biomass

After defining the most appropriate method and allometric equation for estimating above-ground and below-ground biomass, these values needed to be corrected due to the slope of the terrain. Because all carbon measurements are reported on a horizontal-projection basis, establishment of plots on sloping lands must use a correction factor to take into account slope. This is especially true for the forest concessions in Berau, where the landscape is quite hilly. This correction factor calculates the correct projected distance (Equation 7) accounting for the fact that when distances measured along a slope are projected to the horizontal plane, they will be smaller. Therefore, slope was measure on each plot (when slope >10%) and biomass estimations were calculated by applying the correction factors.

(7) $D = \cos(\alpha) * d$

Where:

D = Correct projected distance (m)

α = Slope angle (degrees)

d = Measured distance (m)

4.3 Timber extraction

As stated earlier, this study focuses in logging gaps for estimation of the carbon impacts of forest logging operations. The logging gaps of trees felled and extracted in 2009 were examined in Berau in October 2009. Most of the felling occurred between August and October 2009, however a few sites from one concession were cut in April 2009.

The volume of the extracted log was estimated using length of the log (measured in the field) and the cross-sectional areas at the two ends of the log (bottom and top cut; Figure 4). Biomass of the commercial log was calculated by multiplying the estimated volume by the wood density. Species specific wood density was used when known or the value of 0.57 t m^{-3} when unknown (see above). The carbon fraction of biomass was assumed to be 0.5 as commonly used.

The biomass of the tree crown and stump was estimated by subtracting the biomass of the extracted log from the total biomass of the felled tree based on the Chave et al. equation.

The area of the logging gaps was measured as the area with unimpeded direct vertical penetration of light. A best approximation was made of the shape of the gap, and the necessary dimensions recorded to estimate the area.

Figure 4: Stump of a felled timber tree.

4.3.1 Incidental-damage measurements

Incidental damage to trees was defined as those trees with a DBH $\geq$ 10 cm that were severely impacted by tree felling (Figure 5). Damaged trees were classified as either 1) snapped stem, 2) uprooted or 3) snapped stem sprouting. To estimate the amount of damaged vegetation in each plot, the Chave et al. biomass equation was applied to measurements of DBH of the damaged trees and a wood density value.

During the felling of a large timber tree it is possible that large branches could be broken off from neighbouring surviving trees. However, careful inspection in each plot showed that after two weeks in two different concessions, this did not occur in any of the plots. In this case the inspection for limbs was dropped to increase the time efficiency of the data collection.

The total damage left in the forests caused by logging was calculated as the sum of the biomass of the crown and stump (i.e. total aboveground biomass-biomass of the log extracted) plus the biomass of the roots of the felled tree and the aboveground biomass of snapped and uprooted trees.

Figure 5: Felled tree and incidental damage caused during the felling of the tree.

4.3.2 Estimation Factors

To estimate carbon impact from readily available indicators, factors were created linking: 1) extracted volume with extracted biomass and damaged biomass left as dead wood in the forest and 2) area of logging gaps and extracted volume, extracted biomass and damaged biomass left as dead wood in the forest.

4.3.3 Logging Infrastructure

Additional carbon impact resulted from the construction of logging decks, roads and skid trails for extracting timber from the forest exists. Logs are dragged out of the forest on skid trails (Figure 6) and piled on logging decks (Figure 7).

The impact of skid trails was estimated per unit of length with the assumption that all non-commercial trees (DBH < 50 cm) in the path of the skidder would be killed. Length of some skid trails was determined using the tracking feature of a hand-held GPS, and the width of skid trails was measured directly in the field. These measurements allowed for an estimate of the carbon impact per unit length of skid trail.

Figure 6: Skid trail.

To create the logging decks, it was assumed that forest operators would entirely clear a patch of forest not avoiding larger diameter trees. The mean area of logging decks was determined from measurements of 42 logging decks across the four concessions. Results were expressed in t C/ha of logging deck (area of deck x biomass carbon of forest).

Figure 7: Logging deck.

Lastly, roads also represent a major impact of logging operations in forests (Figure 8). Roads are used to transport the logs both within the concession and out of the concession. Main haul roads are usually built with disregard to the commercial species on the path of the road and therefore a complete clearing of a patch of forest was assumed in the calculations of the carbon impacts generated by this infrastructure. Given the size of roads, we assumed the impact of logging roads was calculated by correlating the area of roads with a measured carbon stock for unlogged forest per unit area in each concession. The mean width of road was recorded with 113 measurements. Results were then expressed as t C loss per unit length of haul road.

Figure 8: Haul road.

4.3.4 Extracted timber into wood products

To estimate the amount of biomass carbon that goes into long term wood products (proportion in storage after 100 yr), we multiplied the extracted biomass carbon (t C/m3 extracted) by the proportion in long lived product—estimated from data obtained from the concessions. The amount that goes into long term wood products depends on the final product type the wood is sued for. According to data obtained from the concessions, 30% goes into sawn wood and 70% into wood panels for concession E, F, and H, resulting in a value of 4.4% for the amount going into storage after 100yr. For certified concession G, 40% of the timber went into sawn wood and 60% into wood panels, resulting in a value of 5.1% for the amount going into storage after 100yr.

5.0 RESULTS

5.1 Biomass carbon of unlogged forests

A total of 983 trees in 82 plots were sampled across all concessions. On average there were 20 sampled plots per concession. The estimated average biomass across all concessions was 346 ± 26.5 t C ha^{-1} (mean ± 90% confidence interval; CI=8% of mean)(Table 2).

The carbon stock in these forests is high compared to other tropical forests. Forests in concession G area appear to have the highest C stocks, followed by F and H; and forests in concession E had the lowest stocks. Across all four concessions, the uncertainty around the mean is about ±8% at 90% confidence, but for each individual concession the 90% CI is about 11-16% of the mean. The relatively small CI and the relatively few plots demonstrate that the carbon stocks in these forests are not highly variable—the coefficients of variation were about 30-45%. Based on the variation across all concessions, about 50 plots would be needed to estimate the carbon stock for the forests in all four concessions (assuming one population of interest) to a 90% CI of ±10% of the mean.

Table 2: Number of sampled plots in each concession along with corresponding average carbon stock (in t C ha^{-1}) and the respective 90% confidence intervals.

Concession	Number of Plots	Average carbon stock (t C ha^{-1})	90% CI (% of Mean)
F	17	365.6	13.1
E	22	282.9	15.4
G	22	427.0	16.1
H	21	317.2	10.5
Grand Total	**82**	**346.0**	**7.7**

5.2 Carbon impact of extracted timber trees

On average 30.4 m^3 of timber was extracted per hectare across all four concessions[6]. In terms of individual concessions, timber extraction ranged from 13 m^3 ha^{-1} in G to 38 m^3 ha^{-1} in E (Table 3).

Table 3: Timber extracted (m3) and areas logged (ha) in 2009 along with extraction per area (m3 ha^{-1}) for 2009.

Concession	Extraction (m^3)	Area Logged (ha)	Extraction per area (m^3 ha^{-1})
F	56,244	1,531	36.7
E	60,624	1,594	38.0
G	7,102	544	13.0
H	7,010	207	33.8

A total of 357 forest gaps caused by logging of 380 trees during 2009 were analysed. More trees were felled than indicated by the number of gaps because some of the gaps were formed by multiple felled trees (17 plots contained 2 trees and 3 plots contained 3 trees per gap).

The total average DBH of felled trees across all forest concessions was 103 cm, and the mean length of extracted logs was 23.3 m, providing an average volume of 18 m^3 per gap (Table 4). Concession E extracted the most volume per gap, but the variation in extraction per gap is highly variable (90% CI of 15-24% of mean). On average 48% ± 3.3% (mean ± 90% confidence interval) of the total biomass of each tree was extracted, with the remaining 52% left to decompose in the forest. The total biomass left in the forest to decompose was the remaining 52.0% of each tree plus all collaterally damaged trees (snapped or uprooted) by the timber treefall.

[6] Information based on concessionaries' report of harvested area and generated volume of wood (in m^3). Data were reassessed with calculations made by TNC Berau staff Bambang Wahyudi, and sent to Winrock by TNC staff Benjamin Jarvis.

Table 4: Key mean timber extraction characteristics (with the 90% confidence interval as a percent of the mean in parenthesis) for all four concessions.

Concession	DBH (cm)	Commercial Log Length (m)	Volume Extracted (m^3 gap^{-1})	Extracted Timber (% of total Biomass)
F	103.5 (6.1)	23.3 (4.3)	15.7 (14.5)	48
E	105.4 (6.1)	24.0 (5.6)	21.0 (24.2)	48
G	102.8 (6.3)	23.3 (5.7)	18.8 (18.5)	51
H	99.5 (6.4)	22.5 (4.5)	15.3 (15.1)	46

The average area of canopy gap due to tree felling is largest in concession F (384 m^2) and smallest in concession G (190 m^2) (Table 5). The reason for the larger gaps in the F concession is likely due to poor felling practices as indicated by the about twice as much gap area per m^3 timber extracted.

Table 5: Mean canopy gap area (m^2) and canopy opening area per volume of extracted timber (m^2 m^{-3}).

Concession	# of Gaps	Mean Gap Area (m^2)	90% CI (% of Mean)	Gap Area per Volume of Extracted Timber (m^2 m^{-3})
F	98	383.6	18.9	22.6
E	91	211.9	13.6	10.1
G	83	190.8	11.6	10.2
H	85	194.8	14.0	12.7

The total carbon impact of felling a tree on a per average gap, per m^3 timber extracted, or per t C extracted basis is remarkably similar across all four concessions (Table 6). The 90% CI is less than 6% of the mean for the total dead biomass carbon left on site on a per cubic meter or t C basis but larger (about 12%) when expressed on a per gap basis. This higher variability on a per gap basis is due to the high variability in gap size.

The collateral damage represents about 16% of the total dead left in the forest on a per gap basis but 22% of the total on a per m3 or t C basis. About 46-51% of the carbon in the felled tree is removed in the logs. The total carbon impact (sum of dead biomass left in the forest and the extracted log) is about 13- 16-7 t C/gap, 0.8 t C/m^3, and 2.7-3.1 t C/t.

Table 6: Mean carbon damage factors associated with timber extraction (90% confidence interval expressed as percent of mean in parenthesis) for all four concessions expressed on a) per gap basis, b) per cubic meter removed in each gap basis, and c) per t C removed in each gap basis. The total dead left represents the amount of biomass carbon left in the gap after extracting the log (felled tree damage+ collateral damage-extracted log). The total impact including the extracted log is the sum of the total dead left and extracted log.

Concession	Extracted Log ($t\ C_L\ gap^{-1}$)	Felled Tree Damage ($t\ C_T\ gap^{-1}$)	Collateral Damage ($t\ C_C\ gap^{-1}$)	Total Dead Left ($t\ C\ gap^{-1}$)
a) Per gap basis				
F	4.8	13.0	1.3	9.5 (22.6)
E	6.0	14.6	1.4	10.1 (29.0)
G	5.4	12.4	1.5	8.5 (18.5)
H	4.3	10.7	1.9	8.3 (24.3)
Average	5.1 (9.9)	12.7 (12.3)	1.5 (9.3)	9.1 (12.3)
Concession	**Extracted Log ($t\ C_L\ m^{-3}$)**	**Felled Tree Damage ($t\ C_T\ m^{-3}$)**	**Collateral Damage ($t\ C_C\ m^{-3}$)**	**Total Dead Left ($t\ C\ m^{-3}$)**
b) Per cubic meter removed basis				
F	0.28	0.74	0.10	0.56 (12.1)
E	0.28	0.72	0.12	0.56 (12.9)
G	0.28	0.66	0.11	0.48 (10.4)
H	0.28	0.67	0.16	0.55 (9.5)
Average	0.28	0.70 (3.8)	0.12 (10.7)	0.54 (5.8)
Concession	**Extracted Log ($t\ C_L\ t\ C^{-1}$)**	**Felled Tree Damage ($t\ C_T\ t\ C^{-1}$)**	**Collateral Damage ($t\ C_C\ t\ C^{-1}$)**	**Total Dead Left ($t\ C\ t\ C^{-1}$)**
c) Per t C removed basis				
F	1.0	2.6	0.35	1.96
E	1.0	2.6	0.43	2.01
G	1.0	2.3	0.39	1.70
H	1.0	2.4	0.59	2.00
Average	1.0	2.5 (3.8)	0.44 (10.7)	1.92 (5.8)

5.3 Logging Infrastructure

Logging practices result in infrastructure establishment in the forest so felled timber can be sorted and removed. To estimate the carbon impact of the construction of such infrastructure, the appropriate forest carbon stock of each concession (i.e. taking into account specific assumptions discussed below) was coupled with the respective areas of skid trails, logging decks and haul roads as described in the methods section. We assumed a complete clearing of the forested area for building logging decks and haul roads; for skid trails we assumed that no tree with DBH greater than the minimum diameter allowed for cutting (50 cm) was felled in the construction of the trails.

5.3.1 Skid Trails

The average carbon impact based on measuring over 16 km in length and 13 ha in area of skid trails across all four concessions was approximately 169 ± 12 t C/ha or 111± 14 t C/km (Table 7). The concession H created the widest skid trails and the largest emission factors per km of skid, followed by G with F and E having the least emissions.

Table 7: Characteristics of skid trails and carbon emission factors for each concession.

Concession	Average Skid Trail Width (m)	Area of Skids/length (ha/km)	Skid Trail Emission Factor (t C km^{-1})	90% CI (% of Mean)
F	5.4	0.54	84.6	15.0
E	5.7	0.57	88.5	6.8
G	7.8	0.78	139.6	35.7
H	8.5	0.56	105.2	64.0
Average	6.64	0.66	110.5	14.1

5.3.2 Logging Decks

A total of 42 logging decks were measured across all the concessions, and the total mean area of a logging deck was about 1,650 m^2, accounting for an average carbon impact of 56 ± 13 t C $deck^{-1}$ (mean ± 90% confidence interval). It important to highlight though, that each concession manages the forest differently; therefore, the range of logging deck areas varied from 150 to 7,000 m^2. Logging decks configuration were also variable raging from geometric shaped clearings in the forest (large rectangular areas) to long and narrow strips along the roadside where logs where piled (Figure 9).

The carbon impact of logging decks per concession was highly variable due to the large range in size of decks (Table 8). For this structure, concession F has the largest area of decks and the largest carbon impact; the other three concessions are comparable to each other with respect to area and emissions per deck.

Table 8: Characteristics of logging decks and associated carbon impact (t C/deck).

Concession	# of Sampled decks	Average Deck Area (ha)	Mean Logging Deck Carbon Impact (t C $deck^{-1}$)	90% CI (% of Mean)
F	9	0.32	115.6	33.9
E	19	0.13	36.1	29.2
G	10	0.09	40.1	38.3
H	4	0.18	55.7	49.0
Average	42	0.16	56.0	23.3

Figure 9: Logs piled along the roadside exemplifying a different manner to store logs that came out of the forest.

5.3.3 Haul Roads

Widths of haul roads averaged 33 m, measured across the path of trafficable road (effectively used by trucks), based on 74 measurements about equally distributed across three of the concessions (no measurements were made in concession H). Little variation in road widths was observed among concessions (from 31.04 m in G to 35.86 m in E). In terms of carbon emissions, each kilometer of road constructed represented an overall 1,150 t C of biomass carbon going from the live to the dead biomass pool (Table 9), with the variation reflecting the difference in carbon stocks of the forests.

Table 9: Average road width (m) and estimated carbon emission factor from its construction (t C/km).

Concession	# of Road Widths Measured	Average Road Width (m)	Carbon Emission Factor from Road Construction (t C km^{-1})*	90% CI (% of Mean)
F	18	32.6	1,190	18.5
E	28	35.9	1,014	9.0
G	28	31.0	1,325	10.3
H	N.A.[†]	33.2	1,051	N.A.

[*]No road width measurements were taken in H and estimations were based on the mean values of road width from other 3 concessions and biomass stocks from concession H itself.

5.4 Carbon stored in wood products

Very little of the carbon in the timber harvested is stored in products with a >100 yr life (Table 10). The extracted carbon per m^3 of timber is basically the same for all concessions because this value depends on the wood density of the species harvested, which tends to be similar across all concessions. Concession G with its reported low extraction rate (13 m^3/ha) stores the least amount of carbon in long lived products.

Table 10: Estimated quantity of carbon stored in products with a life > 100 years for each of the concessions.

Concession	Extraction per Area (m^3 ha^{-1})	Extracted Carbon per Volume of Timber in Long-term Wood Products (t C m^{-3})	Carbon Stored in Long-term Wood Products (t C ha^{-1})
F	36.7	0.012	0.44
E	38.0	0.012	0.46
G	13.0	0.014	0.19
H	33.8	0.012	0.41

5.5 Comparison of all emission factors for the four concessions

There is practically no difference in the total damage per t C extracted in the logs across the four concessions—with an average of about 3 t C/t C removed (Table 11). The amount of dead wood left in the forest per t C extracted is also practically the same for all four concessions (about 1.9 t C/ t C extracted). These values are practically the same as those we obtained for two other concessions in East Kalimantan—1.7 t C/t C extracted (Pearson et al. 2007). These results clearly indicate that the different timber felling techniques employed by each concessionaire have the same impact per logging gap in the forest—in other words the average reduction in carbon stock per t C extracted is the same across all gaps. We have found from other similar studies across a range of tropical countries that the emission factor per t C extracted varies as a function of the log length, with the factor increasing as the long length decreases (Pearson et al. 2007)—the data for the four concession studied are in line with these other studies.

There are differences however in the logging infrastructure factors (Table 11). The carbon impact of haul roads per km is large (more than 1,000 t C), but differences among the concessions reflect the differences in the total C stock of the forests rather than any difference in road construction (i.e. width was similar across all). Large differences occur in the carbon impact per km of the skid trails—skid trails in concession H have the largest impact. This concession logs in the hilliest forests. These differences in the impact of the skid trails is more to do with the nature of the trails themselves rather than the C stock of the forests—our estimates of the C impact include only the carbon stock in trees smaller than 50 cm DBH, which ranges from 155-186 t C/ha. Concession F, the poorest managed concession, had the largest carbon impact by far from the logging decks (2-3 times larger than the other three concessions). Even though differences exist among the concessions on logging infrastructure damage factors, these are expressed only on a per unit length or area basis—it does not account for any differences in the actual length and area in a given concession. These will be discussed in the next section based on the analysis of the high resolution imagery for one of the concession—E.

5.6 Carbon removals from regrowth

After logging and the creation of gaps in the canopy, there is bound to be carbon sequestration in the remaining trees around the gap and in new trees the in-grow (ingrowth) in the gap. However, there is also a high likelihood that some of the remaining trees in the gap area will die due to delayed mortality from damage incurred during the tree felling. To obtain a full carbon balance in a concession, data of the rates of carbon accumulation and delayed mortality would be needed. Such data would be obtained from the measurement of long term permanent plots that to our knowledge do not exist in the concessions we studied.

The carbon accumulation that occurs only in the gaps is the quantity of interest, and not the carbon accumulation over the whole logged area. The carbon accumulation from regrowth in the gaps is the result of the direct human impact. It is often assumed that thinning the forest, as basically happens in the logging gap, will cause the remaining trees to increase their rate of growth. It is a typical silvicultural practice to thin stands to enhance the growth of the residual trees, but this practice is designed to increase the radial growth of the residual trees, not the rate of accumulation of biomass. In logged plots, it is the big trees that are removed from the plot, and although the radial increment of the remaining trees may increase, the biomass carbon increment of these plots of smaller trees will be lower than in plots where large trees are still present. Based on work in Bolivia[7], where 100 paired plots were established (one plot included a logging gap and the other nearby did not) and re-measured 4 years later, it was found that there was no difference in the rates of carbon accumulation between the two sets of plots—in other words there gap creation did not increase the rate of carbon accumulation.

To estimate the removals of carbon from regrowth in the gaps, we argue that it is only the area of gaps created that is the area of interest. The average gap area (in m2/m3 in Table 5) was multiplied by the timber extraction rate for each concession and expressed as ha of gap per ha of forest, expressed as a percent. The results are 8.3% for concession F, 3.6% for E, 3.4% for H and 1.7% for G. We have no data on rates of carbon accumulation after logging but it is likely in the range of 1.5-2.5 t C/ha. Using the percent of active logging area in gaps for each concession and an approximate rate of 2 t C/ha, results in a removal of CO_2 of 0.1-0.6 t CO_2 per ha per year. However it is likely that all previously logged areas are experiencing the same rate of carbon accumulation, thus the total removals would be the annual rate per ha times the number of years a given concession has been in operation in the area. For this discussion, we assume at least 10 yr, thus the annual removal is about 1-6 t CO_2/ha

[7] From data for the Noel Kempff Mercado Climate Action Project, unpublished data from Winrock.

(concession G to F). In sum, the annual rate of CO_2 removals is small compared to the emissions from the gap due to timber extraction.

The forests along the edges of roads and the decks could also have enhanced growth and thus enhanced carbon sequestration due to exposure to the more light from the large continuous road gap; the extent of this is unknown and beyond the scope of this project. However, it is a worthy research topic.

Table 11: Summary of key emission factors due to timber extraction for each of the four concessions.

Concession	Timber extraction (m^3 ha^{-1})	Total C Emissions per t C Extracted* (t C t C^{-1})	Total Carbon Emissions Due to Damage (t C_d ha^{-1})#	Carbon Impact of Haul Road (t C km^{-1})	Carbon Impact of Skid Trails (t C km^{-1})	Carbon Impact of Logging Decks (t C $deck^{-1}$)
F	37	3.0	30.7	1,190	84.6	115.6
E	38	3.0	32.1	1,014	88.5	36.1
G	13	2.7	9.8	1,325	139.6	40.1
H	34	3.0	28.5	1,051	210.7	55.7

*This includes the carbon in the felled tree and collateral damage

The estimates of total carbon due to timber extraction assume that all timber felled is extracted; any timber felled and not extracted would not be included here as such timber is not recorded by the concessions. Thus the estimated carbon emissions reported here are likely underestimated.

6.0 SPATIAL ANALYSIS OF LOGGING IMPACTS

To complete the assessment of emission factors, additional data are needed in relation to logging infrastructure such as skid trails, logging decks, and haul roads, and that these items be associated with timber extraction rates. The goal of this section of the report is to use the results from the spatial analysis of the high resolution imagery (in Annex 1) to extrapolate the emissions factors for the logging infrastructure based on field data to the total logged area in a given year. A second goal is to determine if the method used for this particular study could be developed into a monitoring methodology for emissions from timber harvesting in Berau.

6.1 Emission Factors

A summary of the emission factors for the infrastructure in concession E obtained from the image analysis and the field data is in Table 12. We used these data for extrapolating the field based infrastructure factors to the whole active logging area for two other concessions: F and H as they extracted similar amounts of timber per ha in 2009 (37 and 34 m^3/ha) as concession E in 2009 and 2010 (38 and 36 m^3/ha). We assumed that given the approximately similar amounts of timber extraction for the three concessions that the density of roads, skid trails and decks per ha of active logging area would also be similar to each other. Thus the total emissions from all sources includes concessions F, E. And H.

Table 12. Density (km/ha or m^2/ha) and emission factors (t C/m^3 and t CO_2/m^3) for logging infrastructure in the concession E based on imagery and field data.

	Density-length (m/ha of petaks)	Density-area (m^2/ha of petaks)	Emissions factor (t C/m^3)	Emission factor (t CO_2/m^3)
Roads	18.3	502	0.39	1.44
Skid trails	70.7	401	0.20	0.73
Logging decks	-	25	0.02	0.07

We adjusted the emission factors in Table 12 by factors that reflect the different biomass carbon stocks of the forests (Table 2) and the widths of the skid trails (Table 7). We used the width of the roads obtained from the imagery for all three of the concessions of 27.4 m rather than the widths measured during the 2009 field work (33-36 m) as the data from the imagery was based on a larger sample size and we felt they are more accurate and precise. The adjustments resulted in the emissions factors in units of t CO_2/m^3 extracted, shown in Table 13.

Table 13. Emission factors, t CO_2/m^3extracted, for roads, skid trails and decks for three concessions in Berau

Concession	Roads	Skid trails	Decks
F	1.83	0.59	0.09
E	1.44	0.73	0.07
H	1.72	0.88	0.08

Using the emission factors in Table 13 and the extraction rates in Table 11, results in an estimated emission of CO_2 in t/ha (Table 14). Emissions from roads clearly dominate the emissions from infrastructure, even though the density of skid trails, on a length basis, is very much higher than for roads (Table 12). However, the overall area-density of roads is about 20% higher than for skid trails. Emissions from decks are very small.

Table 14. Emissions from logging infrastructure t CO_2/ha for three concessions in Berau

Concession	Roads	Skid trails	Decks
F	67.0	21.8	3.3
E	51.8	22.8	2.5
H	58.1	29.6	2.8

Total emissions of carbon dioxide per ha for the three concessions is about 195 t/ha, or about 12-18% of the total stocks. In other words, emissions from logging about 5.5 to 8 ha of forests (depending upon concession) with about 35 cubic meters of timber extracted would be equivalent to the emissions from clearing 1 ha of forest in the concession.

Concession G, the one concession practically FSC certified, extract only about 13 m3/ha, resulting in an emissions from gaps and retirement of wood products of 35 t CO_2/ha—no information is available for the emissions from infrastructure.

Table 15. Total emissions, in t CO_2/ha, from gaps, retirement of long-term wood products, and logging infrastructure for three concessions in Berau. It is assumed that all dead wood and the proportion of wood products that are retired are emitted to the atmosphere in the year of harvesting.

Concession	Gaps*	Retirement of long-term wood products	Total infrastructure	Total emissions t CO_2/ha
C1	75.4	36.1	92.0	203.5
C2	74.0	35.3	77.1	186.4
C3	68.2	34.0	90.5	192.8

*The estimates of total emissions per ha here due to gaps assume that all timber felled is extracted; any timber felled and not extracted would not be included here as such timber is not recorded by the concessions. Thus the estimated carbon emissions reported here are likely underestimated

The uncertainty in the emission factors based on the field data (t C/m3 extracted, t C/t C extracted, and carbons stocks of forests) is low because the 90% CI for all the relevant factors used in arriving at the emission factors in Table 15 ha are within the range of the ±10% of the mean. The largest source of uncertainty is the reported timber extraction (total cubic meters extracted and area extracted from) as these data were obtained from the concessionaires and are of unknown quality and the quality likely varies by concession (it could be accurate but have no way of confirming this). Thus, all emissions factors that use the extraction rate in their calculation (e.g. emissions per ha) are of unknown uncertainty. As confidence in the reported extraction rates improves across concessions in Berau, then the confidence in the emission factors per ha will also improve. Given the difficulties in obtaining independent estimates of the felling and extraction rates using high resolution imagery (even satellite imagery to 50-60 cm resolution could not be used to unambiguously detect logging gaps) or any satisfactory ground based method used to date, more focus is needed on ways to ensure that extraction rates reported by concessionaires are accurate.

In terms of the imagery analysis, we are highly confident in the measurements for the area of roads and decks as they are clear in the imagery, but less so for the skid trails where they disappear under the canopy and/or lost in shadows, etc. (see Figures 12-14 in Annex 1 for example). However, confidence was gained because in the imagery for concession E the lengths of the skid trails measured inside each petak that were relatively similar to each other as were the extraction rates per petak reported by the concession.

6.2 Monitoring Methodology

To determine if the interpretation of remote sensing imagery could be used to develop a monitoring plan, we originally proposed to use a combination of free data such as Landsat along with very high resolution commercial satellite data, to identify an affordable and scalable mix of data sources and analytical methods to achieve credible monitoring of emissions reductions that could be achieved through the switch to improved logging practices. Thus the first step was to determine if such an approach could be used to develop a baseline methodology, and if so could it then be used for monitoring.

We obtained imagery from DigitalGlobe for two images from the WorldView-2 satellite. The images are 4 band multi-spectral, pan-sharpened to 0.6 meter resolution. The images were acquired by the satellite on November 9 and November 12, 2010 and covered 2,499 hectares. We then attempted to obtain Landsat imagery for the overlapping area and similar dates. As we describe in Annex 1 (see Annex 1 Figure 1), we were unable to acquire any quality imagery from this source for the area and time period, after searching the archives and contacting colleagues in the field (e.g. Dr. Matt Hansen who extensively uses such data). For the one reasonably clear image (Annex 1 Figure 2), the bands of missing data and clouds/shadows make this image of limited use. And, all that one can really "see" in the image is the incomplete network of logging roads with practically no information on the skid trails. From the analysis of the high resolution imagery, we have shown that emissions from roads are about two times higher than the sum of skids and decks, but as we only analysed one concession it is not clear if this relationship will hold up for other concessions (Table 12). However, if other concessions extract the same amount of timber per ha, it is possible that the emission factors for roads and skids per unit of timber extracted for the other concessions will be similar to those obtained for concession E (we assumed this in the analysis in section 6.1).

From our analysis, we conclude that only the road network can be identified unambiguously in the Landsat type imagery, and that the emissions from roads alone is about 64-73% of the total emissions from infrastructure based on the three concession studies here. Identifying and digitizing skid trails and decks in the WorldView imagery was not without its difficulties and it would not be possible in the Landsat imagery. A network of roads clearly would indicate where logging has or is currently taking place. More detailed analysis using Landsat imagery would be needed to test if the density of roads (length and area per ha of active logging) that is used for estimating the emission factor was related to the extraction rate (cubic meters per ha). To accomplish this task would require the following steps:

1. The acquisition of data bases showing the location of most of the concessions in Berau,
2. The areas and years within the concessions (at least 3-5 years before present) that have been logged and the corresponding extraction rates
3. Landsat imagery at least 90% cloud free, with enough images to fill in the data gaps, for approximately the same time period (close to the end of the logging season)
4. Digitizing the roads (length and width) within the active areas of the concessions and calculating the density based on area of roads per unit area of active areas of concession (as described above and shown in Table 13.
5. Converting the area density of roads to t CO_2 emissions using the carbon stocks of forests. Based on our 2009 field work, we found that combining all the data into one population of interest resulted in an average stock of 346 t C/ha with a 90% CI of ±8% of the mean. Given the low uncertainty in the C stock estimates, we suggest that this value could be used for all concessions (assuming an analysis was made to demonstrate that all forests under concession in Berau are within the same general forest strata).

Contrary to our original plan, we were unable to unambiguously identify the location of logging gaps in the high resolution imagery, thus we have no way of independently estimating the amount of trees felled and extracted or felled only. We can assume that at least one gap would be located at the end of a skid trail (there is also indication of more than one tree), but there were also indications that other gaps existing along a length of trail (e.g. see Figures 12 and 13 in Annex 1). In addition to the roads, we are confident that the location of decks and skid trails were identified correctly, however we do not know to what extent skid trails completely obscured by the forest canopy were missed.

From our analysis, we conclude that to estimate all emissions from logging infrastructure with a high degree of certainty, the following is needed:

- Remote sensing imagery of resolution of about 50-60 c m, or less,

- Imagery of >90% cloud and shadow free (use of multiple images for same time frame could be used; see Annex 1),
- Subsampling of the active area for delineating skid trails by randomly selecting petaks to include about 20% of the active logging area (see Annex 1).

We only were able to analyse one concession (resources and imagery constrained), but it is clear that the method we developed and applied could be repeated for other concessions to develop improved estimates of the baselines for the concessions. Once the baseline emission factors were established for concessions using similar logging practices, the method could then be used to monitor changes in logging practices. (See below for a discussion on possible changes in timber harvesting practices to reduce emissions).

Cost of imagery

From our analysis, one to two high resolution images will cover about one active logging area of a concession. Here are the prices for the high resolution imagery to provide an idea of the cost of one component of the methodology. There are two commercial satellite imagery companies that operate two satellites that capture high resolution data: GeoEye and DigitalGlobe (formerly known as QuickBird). There are two ways to buy imagery, search the archive for what has been captured in the past or to order or 'task' the satellite for imagery in the future. GeoEye defines archive as "> 90 days old". With DigitalGlobe, archive is anything that has been captured and in the archive, even if it was captured yesterday.

At times GeoEye will reduce that 90-day issue, particularly if the purchase is part of a large order or if they are competing with similarly dated DigitalGlobe imagery or if approaching the 90-day threshold. The prices for archived imagery are:

- GeoEye (50 cm) - \$10 per km^2 with 49 km^2 minimum order, so minimum cost is \$490 plus processing costs for a total of \$640.
- DigitalGlobe (60 cm)- \$17 per km^2 for 25 km^2 minimum order size, so minimum cost is \$425 plus processing costs for a total of \$575.

For tasked orders of the imagery, the prices are:

- **GeoEye-1 (50 cm)**
  - Minimum acquisition area: 100 km^2
  - Minimum cost: \$2,500 (100 sq km's * \$25/sq km)
  - Price (Standard Tasking): \$25/sq km for all products
  - Price (Priority Tasking): \$25/sq km for all products PLUS \$3,000 non-refundable tasking fee
- **DigitalGlobe (Quickbird 60 cm)**
  - Minimum acquisition area: 64 km^2
  - Minimum cost: \$1,800
  - Price (Select Tasking): \$20-\$23/sq km depending on product
  - Price (SelectPLUS Tasking): \$40-\$43/sq km depending on product
- **WorldView-2 (50 cm)**
  - Minimum acquisition area: 64 km^2
  - Minimum cost: \$1,800

- Price (Select Tasking): $20-$23/sq km depending on product
- Price (SelectPLUS Tasking): $40-$43/sq km depending on product

One image could in theory cover more than one active area in a concession (about 1,000 to 2,000 ha) thus the cost would be about $1,800-$2,500 for one concession. However, this cost could be lower If monitoring was for neighboring concessions could be covered by one image (images cover 6,400 to 10,000 ha). In addition to obtaining the imagery, there is a cost associated with its interpretation. We estimate that the time to prepare and process the image for analysis and delineate all relevant infrastructure within an active logging area, including subsampling of petaks for skid trails, would take a skilled GIS person about 40 hours for one concession.

7.0 OPPORTUNITIES TO REDUCE EMISSIONS FROM TIMBER HARVESTING.

Here we identify some opportunities that exist for improving forest harvesting practices to reduce the carbon impact.

7.1 Decrease "avoidable" waste

On average about 50% of the tree biomass is left behind in the forest. This includes large pieces of the stump (often parts of the buttress) and the top of the tree. The average volume of the stump pieces (taking into account not all plots did leave stumps pieces) was 1.3 m^3 per plot (0.4 t C), and represented 8% of the volume that was extracted.

The average top diameter (the diameter of the bottom tree crown where the log was cut) of all 380 trees measured in the logging plots was 67 cm with a range of 38 to 148 cm. We made a first order estimate of the amount of merchantable volume in the top if the branches were removed. We first calculated a taper factor for each tree based on field measurements, then for trees with a top diameter > 60 cm and using the taper factor we estimated the length of log between the top diameter and a diameter equal to 60 cm. Using the estimated length and the diameter of the two end of the log we estimated the potential volume assuming a cylindrical log. About 350 trees had top diameters > 60 cm, and the first order approximation of the volume in the crowns (avoidable waste) was 2.1 m^3 per tree, and varied from 1.7 m^3 for concession E to 2.6 m^3 for concession H. The top volume represented about 11.5% of the total timber volume extracted. The total avoidable waste (stump and top) represented 19% of the total timber volume extracted from all four concessions, a significant amount.

Given that most of the wood from the concessions is used for wood panels (60-70%) rather than sawn wood, the almost 20% of wood waste is significant and it could be highly marketable. If this wood was removed from the forest instead of being left to decompose, this could potentially reduce the need to fell as many trees as is presently done and instead the same volume could be extracted with a reduction in emissions from gaps and skid trails (fewer skid trails would likely be needed as more volume per tree would be extracted).

What would the actual impact on total emissions be if the 20% waste was removed from the forest instead of being left to decompose? The effect would reduce the number of felled trees and the density of skid trails, but yet the concession would maintain the same level of extracted volume. Based on the emission factors in Table 15 for the concessions F, E, and H, we estimated that emissions would be reduced by about 19 t CO_2/ha on average for each of the three concessions. Using the active logging area of the three concessions for 2009 as an example (Table

1), this could amount to about 18 thousand to 38 thousand t CO_2 per year. The value of this in a carbon market would likely compensate for any extra costs needed to extract all the merchantable timber.

7.2 Reduce impacts from skid trails

- Plan allocation of tree felling operations ahead and plan the location of the skid trails to reduce their length
- Construct trails following the slope contour lines, therefore avoiding sharp turns which enlarge the trail's widths
- Use narrower bulldozer tractors for building the trails
- Pull felled trees onto main haul road by using a system of cables that drag logs out of the forest and therefore substitute the need for building skid trails with tractors.

7.3 Reduce impact from haul roads by:

- Plan roads ahead of time and construct only roads wide enough to serve the purpose of logging the forest, applying the minimum width necessary (2.5 to 3 trucks wide) and length (i.e. roads that only lead to cutting blocks)
- Use only one main road connecting several narrower spur roads designed only to carry logs and logging personnel (i.e. avoid construction of transportation route into the forest)
- Plan route of main roads ahead of time based on the forest inventory for properly allocating roads near the most concentrated areas of harvesting in the forest
- It is not clear if commercial trees in the path of haul road are removed—if not then they need to be during road construction
- Study viability of using helicopter logging and apply where possible; therefore reducing the amount of road construction (and skid trails and decks) to a minimum

7.4 Reduce impacts from logging decks by:

- Plan location of logging decks based on forest inventory results, therefore, establishing logging decks in areas with greatest concentration of logs to be removed and areas identifiable by field observations with lowest carbon stocks and favourable landscape (i.e. flat opened/cleared areas)
- Reduce average area dedicated to logging decks and pile logs higher in each deck
- Harvest commercial trees in the location that logging deck will be constructed

8.0 REFERENCES

Basuki, T. M., van Laake, P. E., Skidmore, A. K., and Hussin, Y. A. 2009. Allometric equations for estimating the above-ground biomass in tropical lowland *Dipterocarp* forests. Forest Ecology and Management, 257 (8): 1684-1694.

Brown, S. 1997. Estimating Biomass and Biomass Change of Tropical Forests: a Primer. For the Food and Agriculture Organization of the United Nations. Rome, 1997. FAO Forestry Paper – 134 pp.

Brown, S., Pearson, T., Moore, N., Parveen, A., Ambagis, S. and Shoch D. 2005. Deliverable 6: Impact of logging on carbon stocks of forests: Republic of Congo as a case study. Report submitted to the United States Agency for International Development; Cooperative Agreement No. EEM-A-00-03-00006-00

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Folster, H., Formard, F., Higuchi, N., Kira, T., Lescure, J. P., Nelson, B. W., Ogawa, H., Puig, H., Riera, B., and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87-99.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: The physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johnson, D. W. and P. S. Curtis. 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140:227-238.

Mokany, K., Raison, R. J., and Prokushkin, A. S. 2006. Critical analysis of root:shoot ratios in terrestrial biomes. Global Change Biology 12: 84-96.

Pearson, T.R.H., Brown, S., Dushku, A. and Walker, S. 2005. Deliverable 13a: Impact of logging on carbon stocks of forests: Chihuahua Mexico as a case study. Report submitted to the United States Agency for International Development; Cooperative Agreement No. EEM-A-00-03-00006-00.

Pearson, T., Parveen, A., Moore, N. and Brown, S. 2006. Deliverable 21: Use of Aerial Digital Imagery to Measure the Impact of Selective Logging on Carbon Stocks of Tropical Forests in the Brazilian Amazon. Report submitted to the United States Agency for International Development; Cooperative Agreement No. EEM-A-00-03-00006-00.

Pearson, T.R.H., Walker, S., Moore, N., Dushku, A., Roshetko, J., Pearson, R., Brown, S. 2007. Deliverable 24: Impact of selective logging on carbon stocks of tropical forests in East Kalimantan, Indonesia. Report submitted to the United States Agency for international Development; Cooperative Agreement No. EEM-A-00-03-00006-00.

Pinard, M.A., and Putz, F.E. 1996. Retaining forest biomass by reducing logging damage. Biotropica **28**: 278-295.

Reyes, G., Brown, S., Chapman, J., and Lugo, A. 1992. Wood densities of tropical tree species. USDA Forest Service. General Technical Report SO-88. 18 pp.

Uhl, C., and Vieira, I.C.G. 1989. Ecological impacts of selective logging in the Brazilian Amazon: A case study from the Paragominas regions of the state of Para. Biotropica 21: 98-106.

Uhl, C., Verissimo, A., Mattos, M.M., Brandino, Z., and Vieira, I.C.G. 1991. Social, economic and ecological consequences of selective logging in an Amazon frontier: the case of Tailândia. Forest Ecology and Management 46: 243-273.

Van der Werf, G. R., D. C. Morton, R. S DeFries, et al. 2009. CO2 emissions from forest loss. Nature GeoScience 2: 737-738.

Verissimo, A., Barreto, P., Mattos, M., Tarifa, R., and Uhl, C. 1992. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. Forest Ecology and Management 55: 169-199.

White, L.J.T. 1994. The effects of commercial mechanized selective logging on a transect in lowland rainforest in the Lope Reserve, Gabon. Journal of Tropical Ecology 10: 313-322.

Winjum, J. K., S. Brown, and B. Schlamadinger. 1998. Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. Forest Science 44:272-284.

Winrock International. 2009. Terrestrial Carbon Standard Operating Procedures. Prepared by: Walker S. M., T. R. H. Pearson, N. Harris, S. Petrova, S. Grimland. 84 pp.

Yamakura, T., A. Hagihara, S. Sukardjo, and H. Ogawa. 1986. Aboveground biomass of tropical rain forest stands in Indonesian Borneo. Vegetation 68: 71-82.

ANNEX 1: SPATIAL ANALYSIS OF LOGGING IMPACTS IN CONCESSION E, EAST KALIMANTAN INDONESIA

SUMMARY

Two high resolution satellite images were acquired that cover 70% of the 2010 logging area inside the concession E, East Kalimantan Indonesia. The 2010 logging area also known as a RKT is divided into 26 sub-blocks known as petaks. Nineteen of the petaks are completely contained inside the satellite imagery, with 18 petaks showing signs of logging. By using two images taken within three days of each other, we were able to get 94% cloud free coverage of the 18 petaks, 7 of which are 100% cloud free. From these seven, four (20% of the area represented by the 19 petaks) were chosen at random to study the impacts of logging. All skid trails and logging decks contained inside each block and the main haul roads throughout the satellite imagery were digitized. The total length and area of skid trails and roads, and area of decks was calculated. The associated carbon impacts were calculated using field data derived biomass values.

The sum of the length of the digitized haul roads is 23,604 meters, and an average width of 27 m resulting in a haul road area of 65 hectares. The carbon impact of a haul road based on satellite imagery is 776 tons carbon per km length. The total length of skid trails for the four petaks was 17,592 meters. Width of skid trails was not calculated due to canopy coverage. Using the field data derived average skid trail width of 5.7 meters; the area covered by skid trails in the imagery is almost 10 hectares. The carbon impact of a skid trail based on combination of satellite imagery (length) and field data (width) is 88.5 tons carbon per km. The total number of logging decks digitized was 36 with an average area of 0.09 hectares. The carbon impact of a logging deck based on satellite imagery is 25 tons carbon.

The emission factors, expressed on a per cubic meter extracted basis, are: 1.44 t CO_2/m^3 for roads, 0.65 t CO_2/m^3 for skid trails and 0.07 t CO_2/m^3 for logging decks.

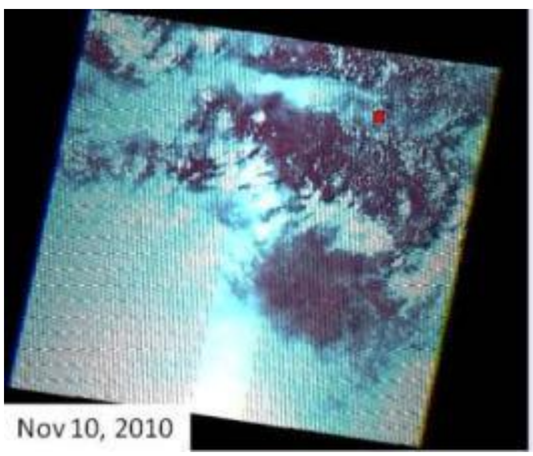
STUDY OBJECTIVES

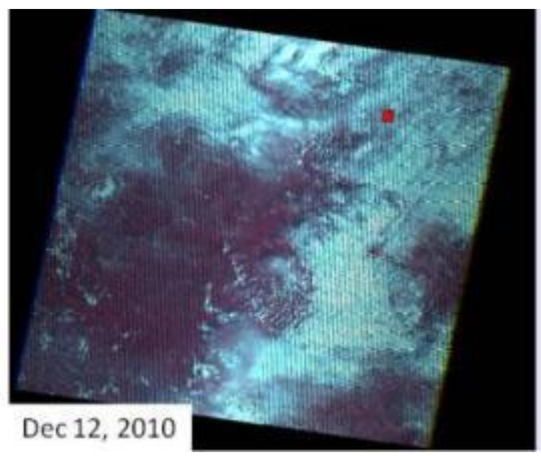
This report builds on a previous one that presented the results of the field data. To complete the assessment of emission factors, additional data are needed in relation to logging infrastructure such as skid trails, logging decks, and haul roads, and that these items be associated with timber extraction rates. The original plan was to collect high resolution imagery (about 10 cm) but due to logistical issues the mission had to be canceled. So we proposed an alternative plan of purchasing and interpreting high resolution satellite imagery (about 2m or less resolution) and determine if this could then be used with Landsat type imagery to extrapolate over larger areas.

The goal is to determine if it is possible to develop a method for monitoring emissions reductions achieved by shifting to reduced impact logging practices using a combination of very high and medium resolution remote sensing data sources (e.g. GeoEye and Landsat) and field sampling. Here we report on the remote sensing data analysis.

We planned to use remote sensing imagery to obtain data on logging infrastructure and tree gap size, density, and distribution across the landscape. We proposed to determine if it is possible to develop a method to distinguish between conventional logging practices vs. improved logging practices (e.g. RIL, HCVF, monocable winch logging) using remote sensing data. Our plan was to use a combination of free data such as Landsat along with very high resolution commercial satellite data, to identify an affordable and scalable mix of data sources and analytical methods to achieve credible monitoring of emissions reductions achieved through the switch to improved logging practices. However, as we will detail below, our plan encountered problems. The main problems were related to the acquisition of cloud free data for the time period of interest (October-December 2010). For the imagery to be useful in the analysis of emission factors, it needed to be collected over areas of the four concessions that were in process of being logged or had been logged in 2010. Upon enquiry with the concessionaires, two of the four had plans to log in 2010 (concessions E and G), and an order was placed to cover the logging areas in these two concessions as well as cover logged areas from previous years. Even though we submitted our request to the imagery provider well in advance of the needed dates and the provider confirmed that this should not be a problem, it turned out that other demands (US Government) on the satellite overrode our request and thus we were able to obtain data that covered only one of the four concessions of interest .

With respect to Landsat—the archives were searched and colleagues contacted and only three images were available that covered our area of interest and time period and they were more than 50% covered with clouds over the area of interest, and thus we were unable to analyse them.





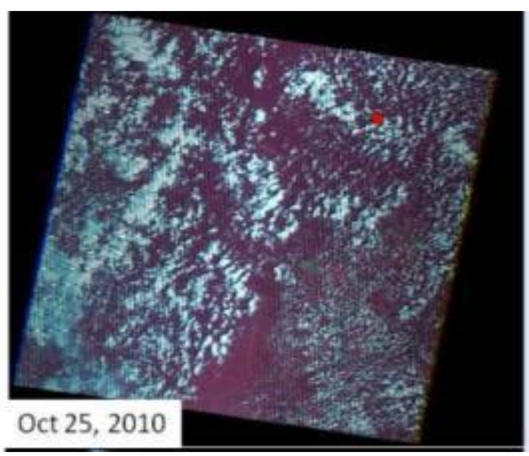


***Figure 1**. The three available Landsat images that covered the area and dates of interest. The small red square represent the concession area of interest (see Figure 2).*

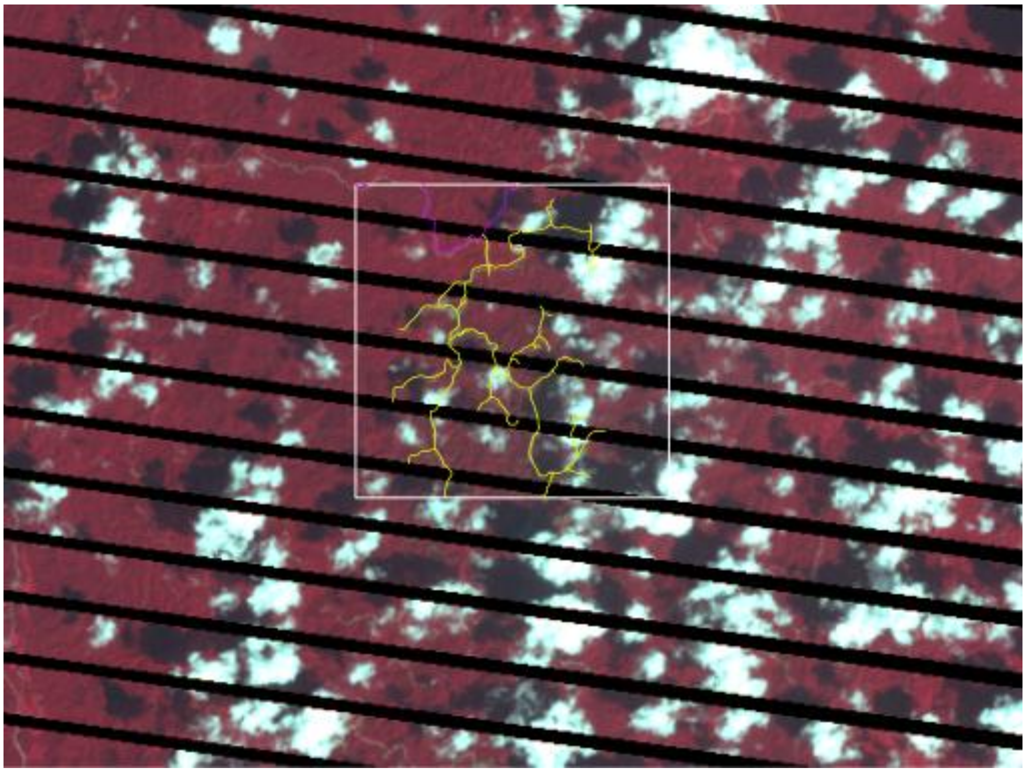


***Figure 2**. A zoomed in version of the October 25 image (most cloud free) overlain with a rectangle outlining the area of interest. Logging roads are clearly observable (outlined here with data extracted from the high resolution image), but after removing clouds, shadows, and the missing data (a common problem with recent Landsat imagery), the remaining proportion of the image is too small to obtain any meaningful results.*

APPROACH

Study Site

Concession E is located in East Kalimantan, Indonesia, in Berau (Figure 3 and 4). The 2010 cutting area, known as a RKT, is located in the southwestern corner of the concession. The area is divided into 26 cutting blocks, known as 'petak', covering 1,834 ha (Figure 5).

Figure 3. Overview of project location within East Kalimantan

Figure 4. Condition of the concession area circa 2009 pre-logging (jpg file downloaded from Google Earth. The line in the top of the rectangle is a road from the adjacent logged area.

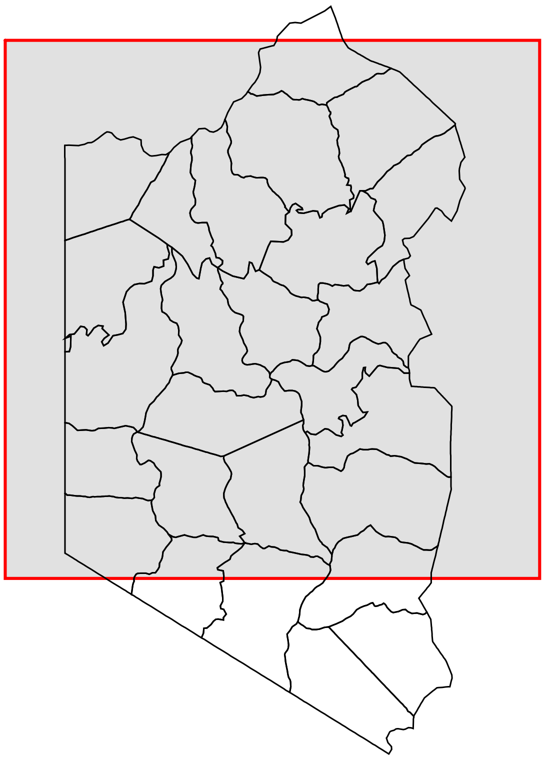


Figure 5. Boundary of satellite imagery in red and 2010 RKT with cutting blocks (petaks) outlined in black.

High Resolution Imagery

Winrock was able to purchase from DigitalGlobe two images from the WorldView-2 satellite. The images are 4 band multi-spectral, pan-sharpened to 0.6 meter resolution. The images were acquired by the satellite on November 9 and November 12, 2010. The imagery covers 2,499 hectares. The logging in this RKT began March 1, 2010 and finished at the end of November 2010 (personal communication with Bambang Wahyudi of TNC Berau).

The images were overlain with a Digital Elevation Model (DEM) to obtain information on elevation and slope. Elevation inside the boundary of the satellite imagery ranges from 57 to 276 m above sea level, with an average of 163 meters and a slope of less than 21% (Figure 6). Two rivers are visible in the imagery. There was one existing road before the logging began, it skirts the northern border of the 2010 logging areas and is not included in any of the analysis. All the new roads however, do originate from the existing road. There are no villages or settlements inside the 2010 RKT.

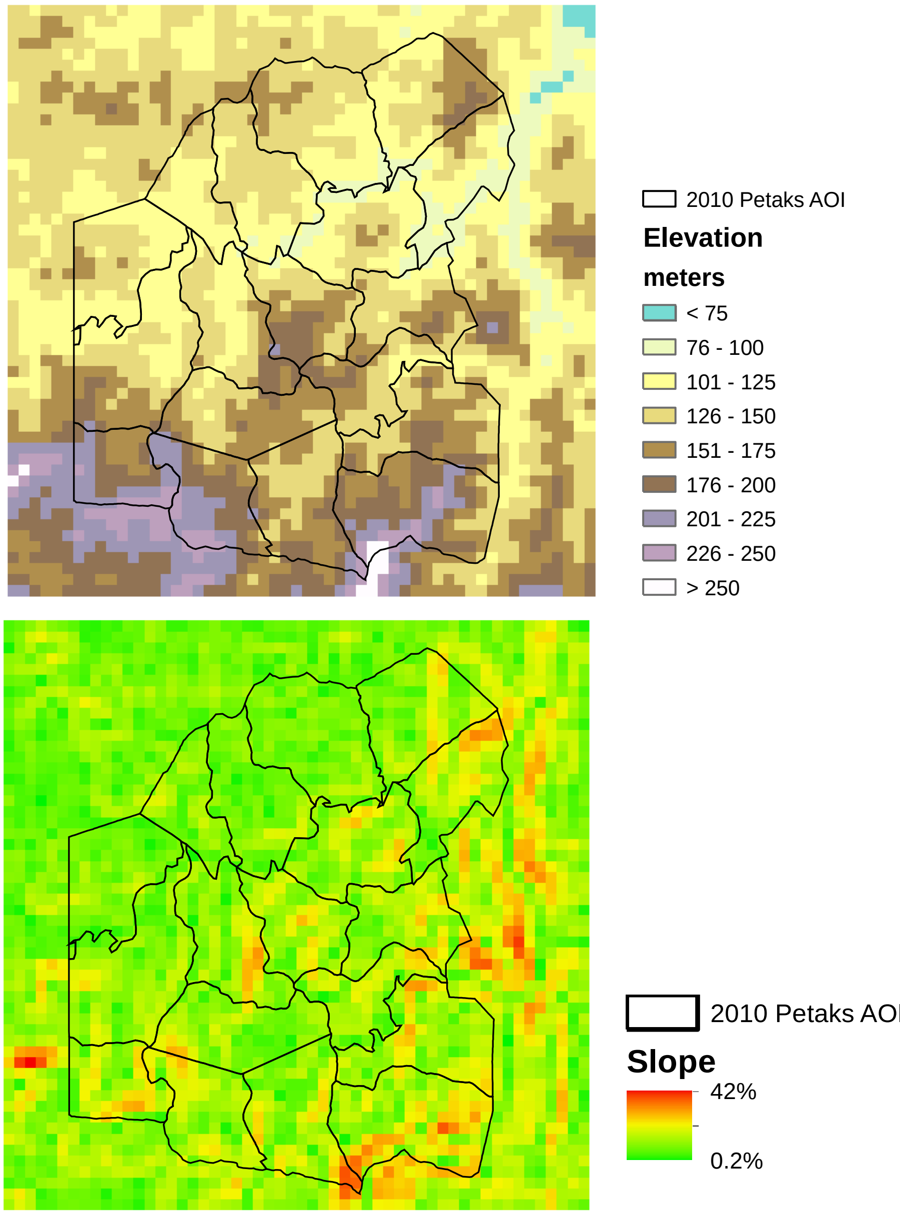


Figure 6. Elevation (top) and slope (bottom) of the lands inside in the project area of interest

2010 Logging Practice

The 2010 RKT totals 1,834 hectares and is comprised of 26 petaks (Figure 5), 19 of which are completely contained within the boundary of the satellite imagery. Of those 19, 18 petaks showed signs of logging and cover an area of 1,290 ha. The one petak with no signs of logging was excluded from the sample. Only 7 out of the 18 petaks are fully free of cloud cover or cloud shadows and therefore suitable for this analysis (highlighted in Table 1). These 7 petaks cover 432 ha of forest, or 33% of the area of interest encompassed by the images. Four petaks were chosen at random using Microsoft Excel's random number generator from the eligible seven. The four petaks chosen were 135, 141, 143, and 148. These four petaks cover 249 hectares of lowland tropical forest, and represent 58% of the cloud/shadow free petaks, and 20% of the total petak area encompassed by the RS images (Figure 7).

Table 1. Percentage of petaks that is free of clouds or shadows

Petak No.	% Cloud/Shadow Free
132	95.27%
134	83.66%
135	100.00%
136	100.00%
138	96.15%
140	95.11%
141	100.00%
142	100.00%
143	100.00%
144	87.86%
145	98.53%
146	86.10%
147	99.28%
148	100.00%
149	100.00%
150	95.71%
151	83.33%
152	90.19%
	94.53%

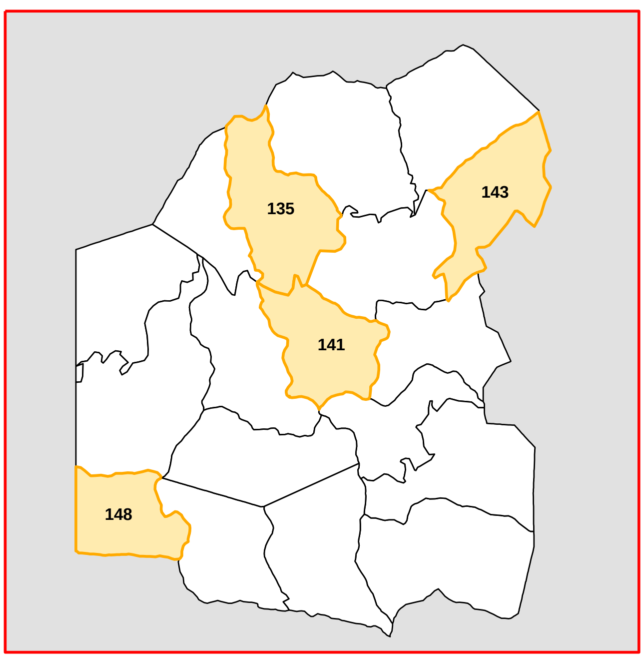


Figure 7. The eligible petaks with the four chosen petaks highlighted in orange.

The area of each petak in the area of interest (Figure 7) ranges between 47 to 103 ha (Table 2). The total area of cloud/shadow free petaks is about 25% of the total area of the 2010 concession block.

Table 2. The area of the 2010 logging areas (ha) and the volume of timber extracted (data are from the concessionaire, personal communication 2/2011).

Petak No.	GIS Calculated Area (ha)	Volume (m^3/ha)
132	77.63	40.9
134	94.43	15.0
135	75.74	29.6
136	46.81	23.3
138	71.74	17.0
140	73.01	45.0
141	59.47	27.8
142	73.60	24.6
143	64.55	28.8
144	61.14	30.9
145	50.19	56.8
146	73.29	47.7
147	103.48	41.0
148	48.88	38.7
149	62.52	42.9
150	77.41	35.8
151	79.42	54.8
152	96.88	46.2
	1,290.2	Ave=36

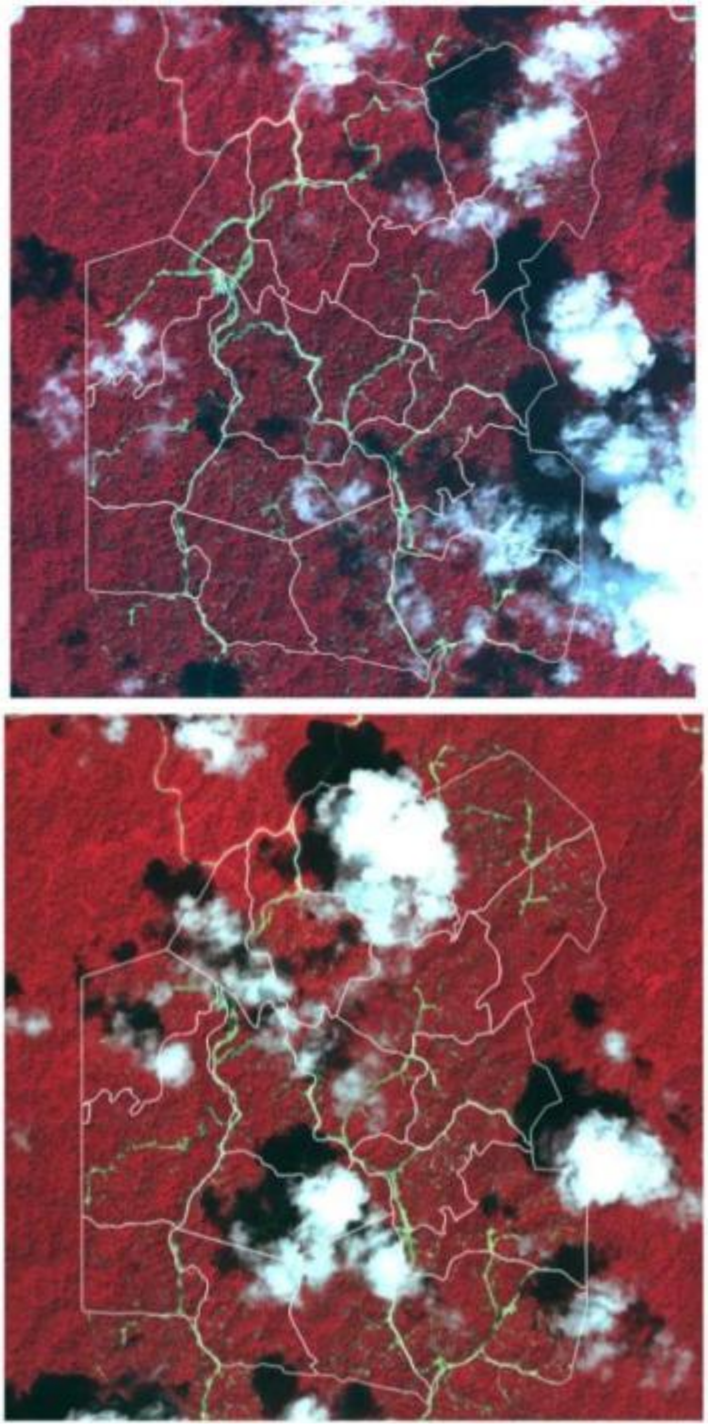


Figure 8. November 9 (top) and 12 (bottom), 2010 false color image from the WorldView 2 satellite with an overlay of the borders of the pateks and haul roads.

RESULTS

Main Roads

The main roads that run throughout the 18 petaks inside the WorldView images were digitized via a "heads-up method" (Figure 9 and 10). The total length was 23,604 meters. The width of the roads in the imagery was calculated by digitizing 431 lines across the main roads (Figure 11). The result is an average of 27.4 m in width, but varied from about 14 to 48 m wide. With the width and length of the roads known, the total area was estimated to be 64.73 hectares. The carbon stock of the forests in concession E, based on the 2009 field work, was 283 t C/ha. Using that value the digitized main roads have a carbon impact of 776 tons carbon per km and a total impact of about 18,300 tons carbon. The emission due to roads on a per ha of all petaks in the area of interest was 14.2 t C. The average volume extracted for all 18 petaks in the area of interest was 36 m^3/ha (Table 2), thus **emission factor for roads was 1.4 t CO_2/m^3 extracted**.

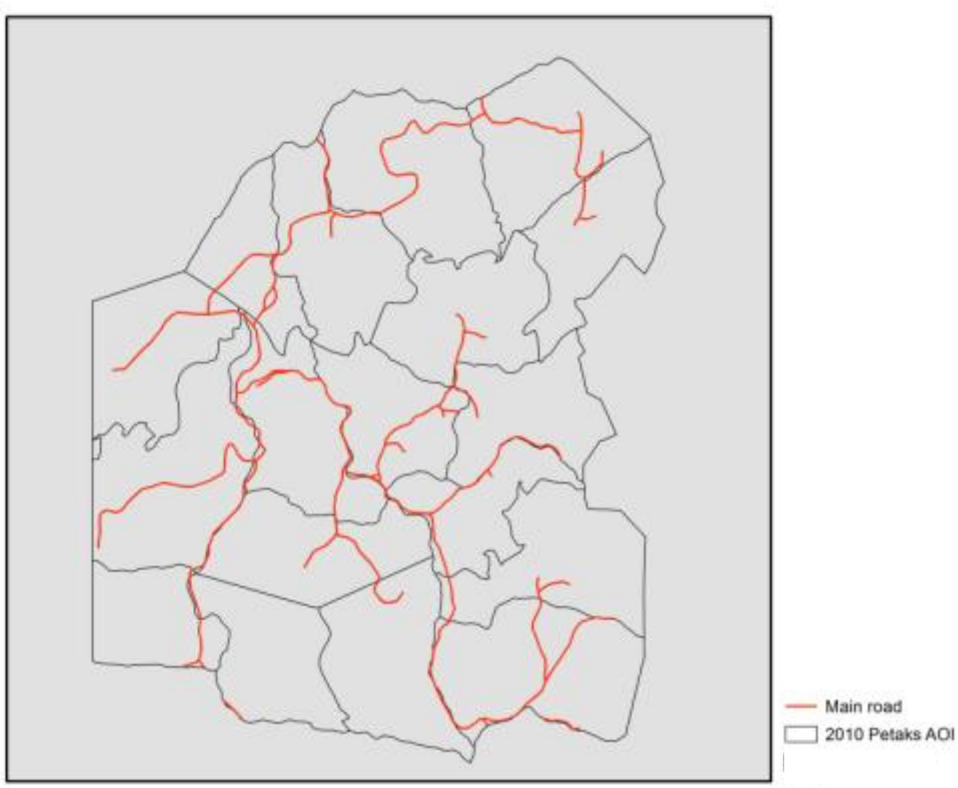


Figure 9. Main roads in the project area of interest (AOI).

Figure 10. Portion of the satellite imagery showing the details of the main roads in the project area of interest

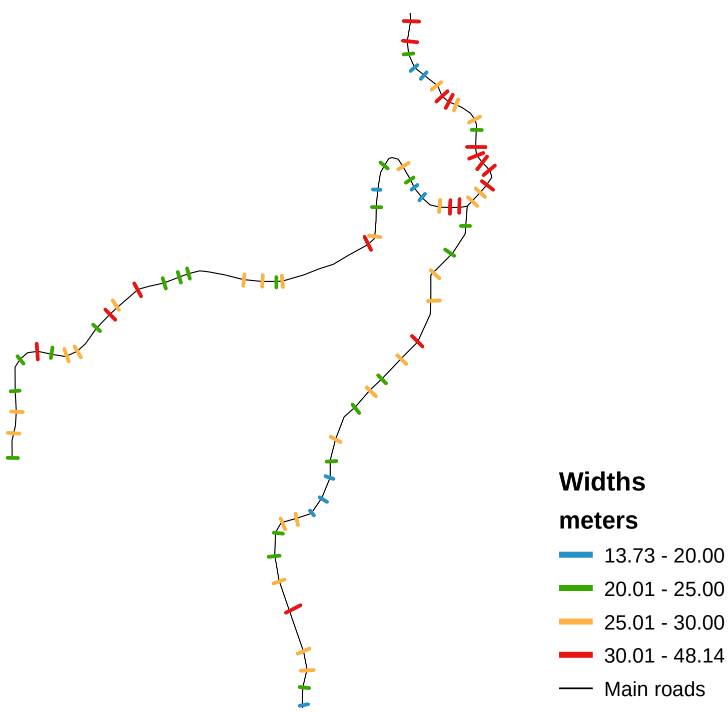


Figure 11. Sample of the road widths

Skid Trails

For each of the four chosen petaks, all the skid trails were digitized via a heads-up method (examples in Figure 12 - 14). Rules for what a skid trial is versus a logging gap, deck, or main road were established as:

- Width <10 meters
- Roads with bare soil that are not the main road
- Shadow areas that appear to connect bare soil roads
- Roads or paths that lead to clearing (gap)

Skid trails were connected when parts were invisible as they passed under the canopy. The lengths of the skid trails inside each petak are relatively similar to each other (about 4 to 5 km or so, Table 3), as are the extraction rates per petak reported by the concession for 2010 (28-39 m^3/ha of timber). It was difficult to discern the total width of skid trails because the canopy coverage prevented full visibility. Using the field data derived average skid trail width of 5.7 meters; the area covered by skid trails in the imagery is about 10 hectares. In a related study by B. Griscom who collected more detailed measurements along skid trails, he found that trees larger than 50 cm or so would be avoided by the skidders, thus we adjusted the biomass plot data obtained from the 2009 field work to account for this resulting in a carbon stock value of 155.9 t C/ha. Thus the carbon impact of a skid trail based on combination of satellite imagery (length) and field data (width & biomass) is 88.5 t C/km. The carbon impact is a total of 1,557 tons for the four petaks with an average of 389 tons C/per petak.

Table 3. Remote sensing derived skid trail impacts

Petak	Skid Trail Length (m)	Area of Skids Trails (ha)	Density of skids (km/ha petak)	Carbon Impact (t C)
135	4,574	2.60	0.06	405
141	4,316	2.45	0.07	382
143	4,935	2.80	0.08	437
148	3,767	2.14	0.08	333
	17,592	9.98	0.07	1,557

The average density of the skid trails was 0.07 km/ha of petak, and varied little across the four petaks (Table 3). The **emission factor for skid trails is 0.73 t CO_2/m^3 extracted.**

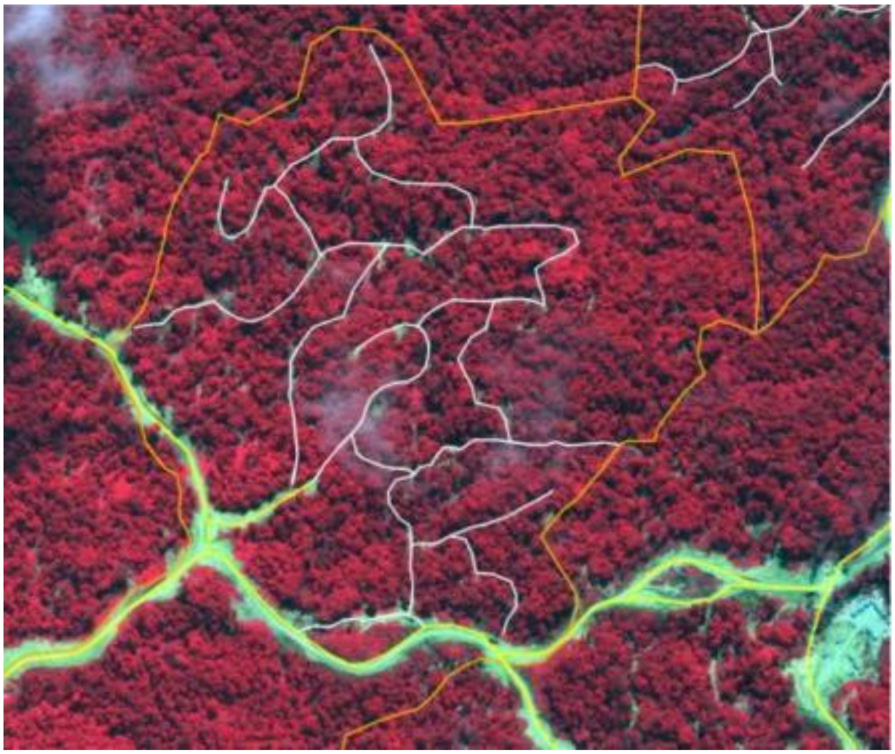


Figure 12. Skid trails in petak 135

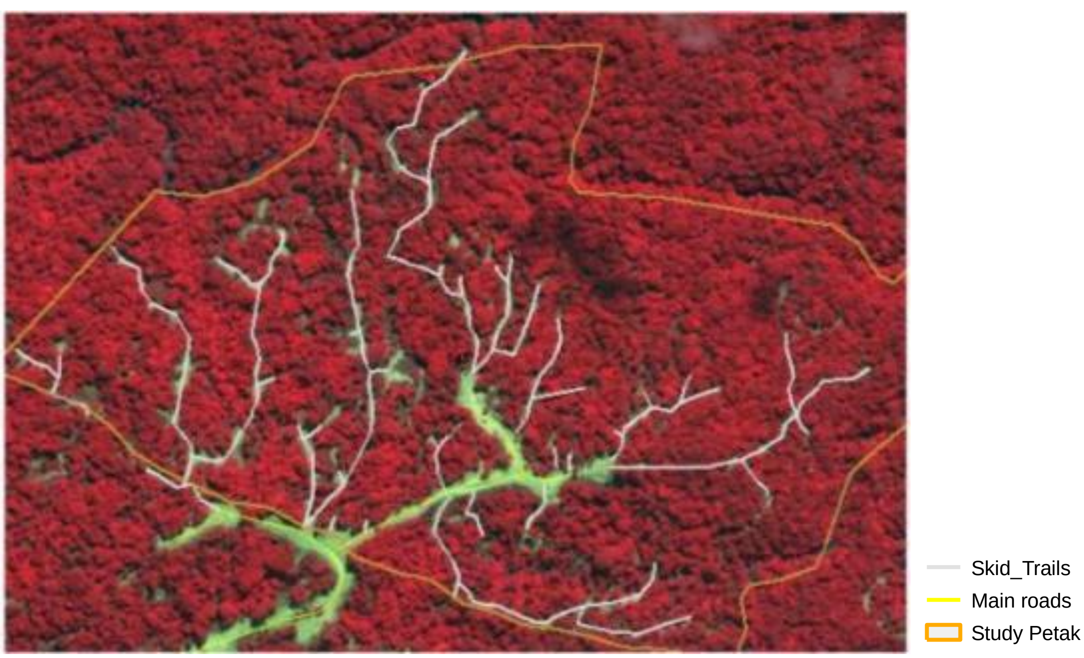


Figure 13. Skid trails in petak 143

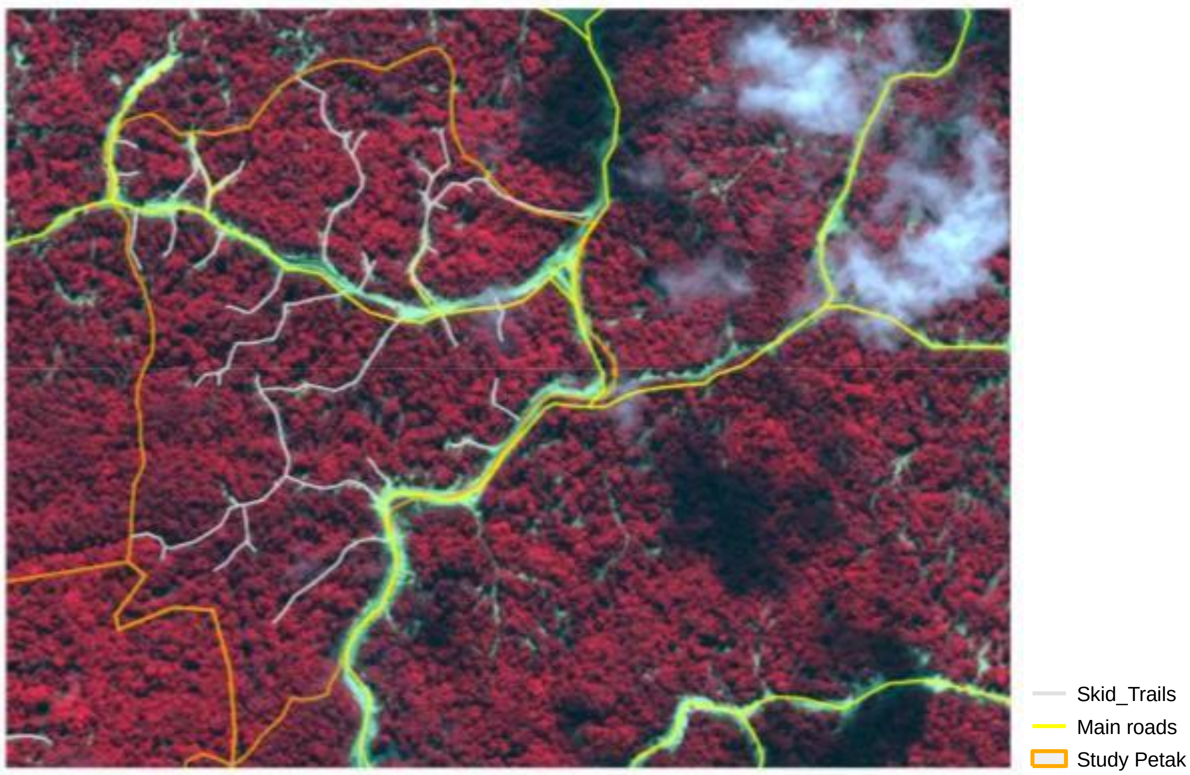


Figure 14. Skid trails in petak 141

Decks

Logging decks across the entire imagery boundary were digitized and the rules for logging decks are:

- Cut out areas along main roads that have logs
- Cut out areas along main road that look similar in shape/area to those that have logs
- Areas along main roads with logs but the road is not appreciably wider are excluded
- Open areas where large amounts of debris are evident were excluded

The total number of logging decks that meet the criteria was 36 with an average area of 0.09 ha, a maximum of 0.25 ha and a minimum of 0.04 ha (CV 60%, 90% CI of +/-16% mean), and a total area of 3.2 ha. The density of decks was 0.0025 ha per ha of all 18 petaks. There was another 34 'decks' or locations with stacked logs that do not meet the above criteria, mainly because the logs are stacked along the road but the road was not wider to accommodate the logs (Figure 15). Using the carbon stock value for forests in concession E based on the 2009 field work (283 t C/ha), the total carbon impact of the 36 decks was 905 t C, with an average carbon impact of a logging deck of 25.2 tons carbon. **The emission factor for logging decks was 0.07 t CO_2/m^3 extracted.**

Figure 15. Logging decks, a) ineligible b) eligible

Summary of emission factors

The density of the infrastructure is calculated based on two measures: area and length (roads and skid trails) per unit area of the petaks (Table 4). For roads and logging decks the total area used is that of all 18 petaks (1,290 ha) and for skid trails, the area used is that of the four randomly selected petaks (249 ha).

Based on length only, skid trails are about four times denser than roads, but because roads are much wider than skid trails, the density of roads based on area is about 1.25 times larger than for skid trails. The density of logging decks is more than an order of magnitude lower than either roads or skid trails.

To estimate the emission factors for the logging infrastructure on a per unit timber extraction basis, we combined the estimated carbon emissions per unit area of petak (all 18 for roads and decks and the 4 sampled one for the skid trails) with the amount of timber volume extracted per ha of petak for each petak (obtained from the concessionaire) (Table 4). As expected roads have the highest emission factor at almost double that for skids, and logging decks are more than an order of magnitude lower than either roads or skids.

Table 4. Density (km/ha or m2/ha) and emission factors (t C/m3 and t CO2/m3) for logging infrastructure in the concession E based on imagery and field data

	Density-length (m /ha of petaks)	Density-area (m^2/ha of petaks)	Emissions factor (t C/m^3)	Emission factor (t CO_2/m^3)
Roads	18.3	502	0.39	1.44
Skid trails	70.7	401	0.20	0.73
Logging decks	-	25	0.02	0.07

For questions or comments contact:

Dr. Sandra Brown Director and Chief Scientist, Ecosystem Services Unit

office 703.302.6578 | cell 703.470.9430 | fax 703.302.6512 | sbrown@winrock.org

2121 Crystal Drive, Suite 500 | Arlington, VA 22202, USA | **www.winrock.org/ecosystems/**