3.0 METHODS

3.1 General Approach

The carbon impact of logging is calculated as the difference in carbon stocks between a forest that has been harvested and one that is not. Our method is to focus on the logging gaps. 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. 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, will be much larger. It is more appropriate to measure the change in live and dead biomass pools due to logging directly in the harvesting gaps. The change in live and dead biomass between the with- and without-logging cases is a result of the extraction of timber and damage to residual trees from the logging activities.

Estimating the carbon impact is more complex than just recording the change in live biomass. Ultimately, the entire timber tree and all trees incidentally damaged will be oxidized. However, in the immediate term carbon that progresses from live to dead wood is only emitted once decomposition has occurred, and the portion of the timber tree that is converted to long term wood products will not be emitted for the life time of the products (Figure 2).

The difference in carbon stocks between with- and without-logging scenarios equals:

(biomass carbon removed during logging + biomass carbon damaged/dead as a result of logging**)**
– (damaged/dead biomass carbon –decomposition of damaged/dead biomass)
– (wood products biomass carbon – wood products decomposition**)**

[Equation 1]

An additional term could be added if it was found that there was a growth differential between the logged area and adjacent unlogged areas (we assumed there is none; the term would consist of adding or subtracting the growth differential per year for the given area of logging gaps for the given number of years of growth difference). We also assume that selective logging has no impact on soil carbon over a large concession because of the small area impacted.

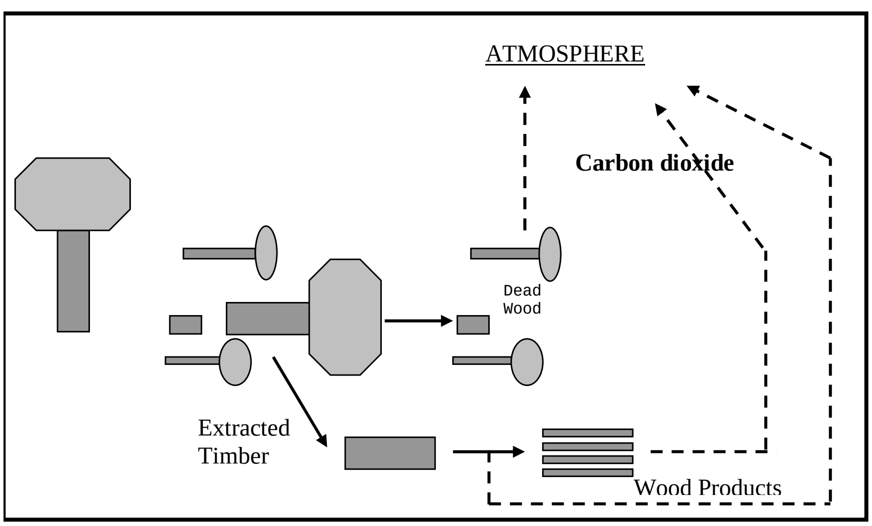


Figure 2 Schematic representation of carbon flow as a result of selective harvest in the tropics

In this study we focused on the carbon impact of felling and extracting the timber. We did not trace the processes of decomposition of dead wood or wood products, nor was the conversion efficiency of processing mills included. Instead we estimated factors to determine the volume and biomass carbon extracted from the forest and the biomass carbon remaining in the forest to decompose.

Correlations are then made between the data on loggings gaps, roads and skid trails collected from aerial imagery and the carbon emissions resulting from selective logging that these aerial data represent.

4.0 FIELD MEASUREMENTS

4.1 Timber extraction

Selective logging gaps were examined in East Kalimantan, Indonesia in August 2006 (Figure 3). The gaps were located in the Aditiya Kirana Mandiri forestry concession. Gaps formed by trees felled in both 2005 and 2006 were measured, however the focus of this report will be the 56 gaps measured for tree felled in 2006. Analysis of results from plots produced in 2005 were all so different from those in 2006 that we believe are due to the rapid closing of the canopy and the uncertainty in whether all damaged and dead trees were included or not (similar problems were found for Brazil; Pearson et al. 2006a).

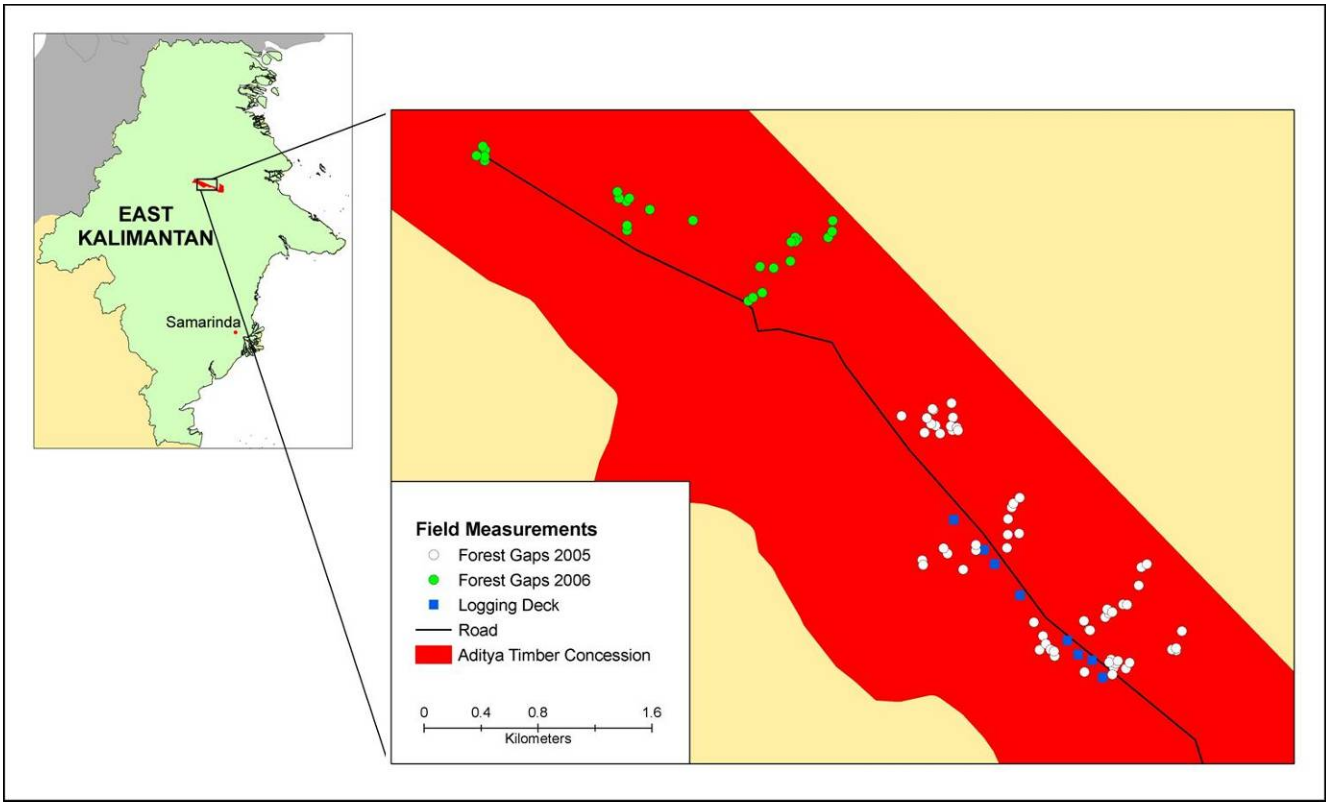


Figure 3 The site of logging gaps measured in the field by the Winrock team in August 2006

Figure 4 The stump of a felled timber tree

Volume of the extracted log was calculated by multiplying length by the average of the cross-sectional areas at the foot and crown ends of each log. Biomass of the commercial log was calculated by multiplying the estimated volume by the wood density. A species-specific density was used when the species was identified or a mean tree density for tropical Asian species when the species was not known (0.60 Mg m^{-3}; Brown 1997). Here and throughout this study carbon is approximated as biomass x 0.5.

We estimated the total aboveground biomass of the felled tree by applying a general moist tropical biomass regression equation that incorporates the dbh and specific gravity of the wood given the higher than average wood density in the region (Biomass (kg) = exp{-1.864 +2.608*ln(dbh) + (ln(wood density))}; r2 = 0.996; n = 1,502; range = 5-156 cm dbh) (from Chave et al. 2005). Several trees that we measured exceeded the maximum size of the trees that the equation was built on and, because of the nature of the equation, substitution of diameters that exceed the maximum size into this equation would greatly over-estimate the biomass. Following the recommendation of Brown (1977), we used Eq. 3.2.3 in that report for trees with diameters greater than 160 cm as the function behaves better in these larger classes. Finally 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.

The area of the logging gaps was estimated 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 to estimate the area were recorded.

4.1.1 Incidental-damage measurements

Damaged trees were those trees that were severely impacted by tree fall. Damage trees were classified as either 1) snapped stem or 2) uprooted. To estimate the amount of damaged vegetation in each plot, the general biomass equation (see above) was applied to measurements of dbh of the damaged trees. The minimum breast height diameter for measurement was 10 cm. During the felling of a large timber tree it is possible that large branches could be broken off from neighboring surviving trees. However, careful inspection in each plot to the best of our ability recorded such events in only two plots; in this case the biomass carbon of the branches was also estimated based on volume estimation and subsamples for wood density.

The total damage caused by logging was calculated as the sum of the biomass of the crown and stump of the felled tree, plus the biomass of snapped and uprooted trees and large broken branches.

Figure 5 A felled timber tree and incidental damage caused during the felling of the tree

4.1.2 Estimation Factors

To estimate carbon impact from readily available indicators, we created factors 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.

4.1.3 Skid trails, Logging Roads and Logging Decks

An additional carbon impact results from the construction of roads and skid trails for extracting timber from the forest (Figure 6).

Figure 6 A skid trail

Logs are dragged out of the forest on skid trails. The impact of skid trails was estimated per unit of length with the assumption that all vegetation in the path of the skidder will be killed. The length of skid trails was determined from the imagery and the width of skid trails from 79 measurements in the field.

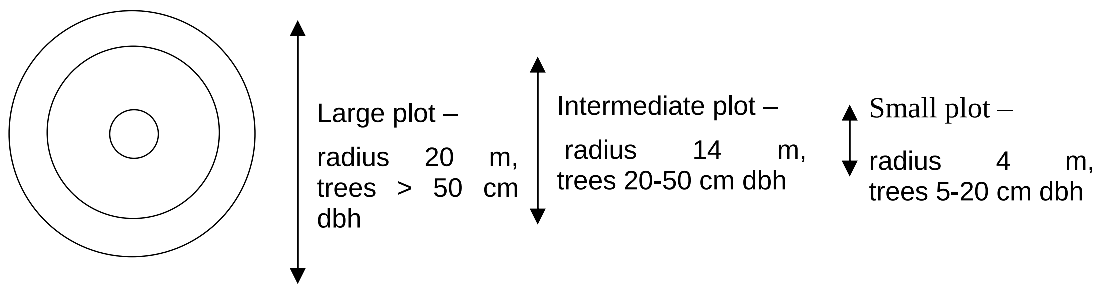
After being skidded out of the forest, logs were piled on logging decks. To create the logging decks the forest operators would entirely clear a patch of forest. The mean size of logging decks was determined from measurements of 16 logging decks.

Roads are used to transport the logs. We also calculated the impact of logging roads by correlating area of roads (measured using imagery), with a measured carbon stock for unlogged forest per unit area. The mean width of road was recorded with 61 measurements (Figure 7).

Figure 7 A log extraction road

In E. Kalimantan we estimated a mature forest stock by measuring 16 nested plots in forest that had not yet been logged. The schematic diagram below represents a three-nest circular sampling plot that we used in E. Kalimantan for biomass determination.

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 expansion factors occurs by calculating the proportion of a hectare that is occupied by a given plot. As an example, if a series of nested circles measuring 4 m, 14 m and 20 m in radius were used, their areas are equal to 50 m^2, 616 m^2 and 1,257 m^2 respectively. The expansion factors for converting the plot data to a hectare basis are 198.9 for the smallest, 16.2 for the intermediate and 8.0 for the largest nested circular plot.



5.0 AERIAL DIGITAL IMAGERY DATA

The digital imagery system (camera, navigational equipment, real time GPS, and computers) that we used to collect data can be loaded onto nearly any single engine aircraft that can fly at low altitudes and at relatively slow speeds for image acquisition (a Cessna 206 was chartered for this project). The imagery system can be flown under cloud cover, flown at high temporal frequency, and viewed as automatically georeferenced strips in a standard computer with GIS (Geographic Information System) software.

5.1 Aerial Data Collection

Aerial imagery was collected over the Aditya forest concession on both August 15th and December 4th 2006. The imagery consists of a total of 566.4 km of flight lines flown at 1039 m above the ground and covering a total area of almost 50,000 hectares.

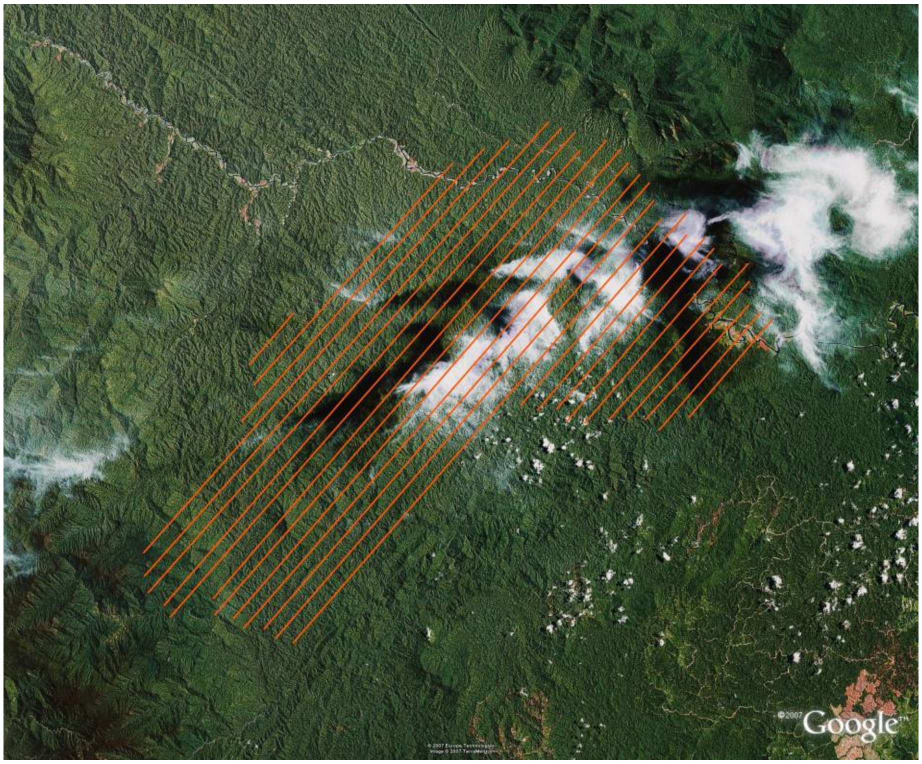


Figure 8 The flight lines over the Aditya forest concession in East Kalimantan, Indonesia

6.0 RESULTS

6.1 Timber extracted

Of the 56 forest gaps caused by logging during 2006, one was formed by four overlapping felled trees, one by three overlapping felled trees, eight by two overlapping felled trees and 46 by single felled trees.

The mean diameter at breast height of the felled trees was 104.2 cm and the mean length of extracted logs was 18.3 m (Table 1). On average 55% of the total biomass of each tree was extracted. The biomass that was left in the forest to decompose was the average remaining 45% of each tree plus all vegetation accidentally snapped or uprooted by the timber treefall.

Table 1 Components measured/estimated from the logging operations in the Aditya concession. All values are mean ± 95 % confidence interval. (The volume per gap is higher than volume per tree because in 10 plots more than 1 tree was felled.)

	Mean	*95 % CI*
DBH (cm)	104.2	*9.1*
Commercial log length (m)	18.3	*1.4*
Volume / tree (m^3)	13.6	*3.3*
Volume / gap (m^3)	16.7	*4.7*
Extracted biomass carbon (t C) / gap	4.8	*1.3*
Damaged biomass carbon (t C) / gap	7.3	*2.7*
Extracted timber as % of total tree biomass	55	*5*

Figure 9 A logging gap at the study site

6.1.1 Incidental damage

A mean of 3.3 t/ha ± 2.1 (mean ± 95% confidence interval) of incidental damage was caused in each logging gap. This incidental damage was comprised of trees snapped or uprooted by the timber treefall plus large branches knocked down by the treefall. On average 41% of the total damage (dead wood directly resulting from the harvesting operations left in the forest to decompose) was derived from the incidental damage and 59% from the stump and top of the timber tree. For the multiple felled tree gaps the incidental damage proportion was 40% of total damage.

6.1.2 Factors

From the analysis, correlation factors were created both for comparison with other similar datasets and correlation with timber inventory data and/or aerial imagery.

On average, a mean of 1.69 t C were left as dead wood in the forest to decompose (damage) for each t of wood extracted (Table 2).

For correlation with inventory data, 0.28 t C were extracted per cubic meter extracted and 0.66 t C were left to decompose per ton extracted.

Examining the gap sizes, the mean area of the felling gaps was calculated as 666 m^2 ± 2.1 (mean ± 95% confidence interval). The average size for single felled trees was 517 m^2 and the average across the multiple felled tree gaps was 1,350 m^2. From these data it was possible to derive that for each square meter of measured gap area, 0.033 m^3 were extracted equal to 9.54 kg C extracted and 12.70 kg C left in the forest as dead wood to decompose.

Table 2 Estimation factors for linking volume extracted and/or area of canopy gap with extracted volume and biomass carbon and damaged biomass carbon from logging operations in the Aditya concession, East Kalimantan, Indonesia.

	Factor	*95% CI*
t C extracted / m^3 extracted	0.28	*0.003*
t C damaged / m^3 extracted	0.63	*0.196*
t C damaged / Mg C extracted	1.69	*0.3*
m^3 extracted / m^2 of gap area	0.033	*0.011*
Kg C extracted / m^2 of gap area	9.54	*3.03*
Kg C damaged / m^2 of gap area	12.70	*2.99*

6.1.3 Logging Roads, Skid Trails and Decks

Across the sixteen closed forest plots the average forest carbon stock was estimated to be equal to 212 t C/ha ± 66 (mean ± 95% confidence interval), with a range of 115 - 643 t C/ha. This forest carbon stock was then combined with the area of roads, skid trails and logging decks to calculate the total logging impact.

Measurements of 16 logging decks gave an average area of 1,550 m^2/deck. This gives a mean carbon impact of deck creation equal to 33.4 t C/deck ± 19.0 (mean ± 95% confidence interval).

Seventy-nine skid trail widths were measured giving a mean of 8.9 m wide. This gives a mean carbon impact of skid trail creation equal to 0.19 t C/m of skid trail ± 0.08 (mean ± 95% confidence interval).

Sixty-one road width measurements gave a mean of 10.2 meters. The average impact of road creation is therefore equal to 0.21 t C/m of logging road ± 0.08 (mean ± 95% confidence interval).

6.2 Analysis of Aerial Imagery

From the 566 km of flight lines that were flown, the following results were recorded:

The area over the 2006 Aditya concession was examined, this totaled approximately 651 ha. A total of 41 logging gaps were recorded in the imagery with an average size of 631 m^2.

A total of 18 logging decks were recorded along a total of 6.6 km of roads. Skid trail length totaled 483 m.

Applying the factors in Table 2 gave a total carbon impact recorded in the imagery of 2,676 t C with a 95 % confidence interval equal to 12% of the mean. Fifty-two percent of the total carbon impact was caused by the roads with just 9% in the logging gaps (Table 3).

Figure 10 A logging road with skid trails emerging from it.

Table 3 The total carbon impact and the carbon impact per hectare as calculated from aerial imagery analyzed for 2006 concession area in Kalimantan

	Total carbon impact		**Impact per ha of concession**	
	t C	**95% CI**	**t C/ha**	**95% CI**
Extracted biomass carbon	247	68	0.38	0.10
Damaged biomass carbon in logging gap	350	73	0.54	0.11
Damaged biomass carbon in skid trails	97	43	0.15	0.07
Biomass carbon impact of logging decks	601	340	0.92	0.52
Biomass carbon impact of logging roads	1,001	362	1.53	0.56
TOTAL	**2,296**	**886**	**3.52**	**1.36**

7.0 DISCUSSION

7.1 Comparison between selectively logged sites

Measurements in the Aditya forest concession in East Kalimantan revealed a mean size of 104 cm diameter at breast height for harvested trees and mean extracted log length of 18.3 m. The mean volume per tree was 13.6 m^3 and at the felling gap level the mean biomass extracted was 4.8 t C/gap with 7.3 t C/gap left as dead wood directly resulting from the tree felling. The measurements allowed calculations linking extracted carbon and resultant dead wood/damage carbon with extracted volume and size of felling gap.

The study in Indonesia represented the sixth set of similar measurements taken by Winrock (Table 4). In terms of the size of felled trees and proportion of the tree in commercial logs, the forests in Indonesia were exceeded only by the forests in the Congo Basin. Although having a lower mean diameter and volume the felled trees in Brazil represented a longer mean log length.

Table 4 Comparison of mean data collected for six selective logging study sites

	Congo	Brazil	Indo-nesia	Bolivia	Belize	Mexico
DBH (cm)	123	86	104	70	62	38
Log length (m)	22	20	18	11	10	12
Volume per tree (m^3)	21	9	14	4	3	1
t C Incidental damage/ t C extracted	0.65	0.33	0.69	1.17	0.93	0.06
Extracted biomass carbon per gap (t)	6.8	4.3	4.8	1.2	0.8	0.2
Damaged biomass carbon per gap (t)	8.6	5.8	7.3	6.1	2. 8	0.3
Extracted as % of total	59	51	55	40	34	44
t C damaged / t C extracted	1.4	1.5	1.7	2.8	3.1	1.4
t C extracted / m^3 extracted	0.27	0.40	0.28	0.30	0.30	0.38
t C damaged / m^3 extracted	0.38	0.58	0.63	0.83	0.92	0.54
Kg C extracted / m^2 gap area	12.10	17.27	9.54	1.77	N/A	N/A
Kg C damaged / m^2 gap area	15.14	23.24	12.70	4.14	N/A	N/A
m^3 extracted / m^2 gap area	0.044	0.043	0.033	0.006	N/A	N/A

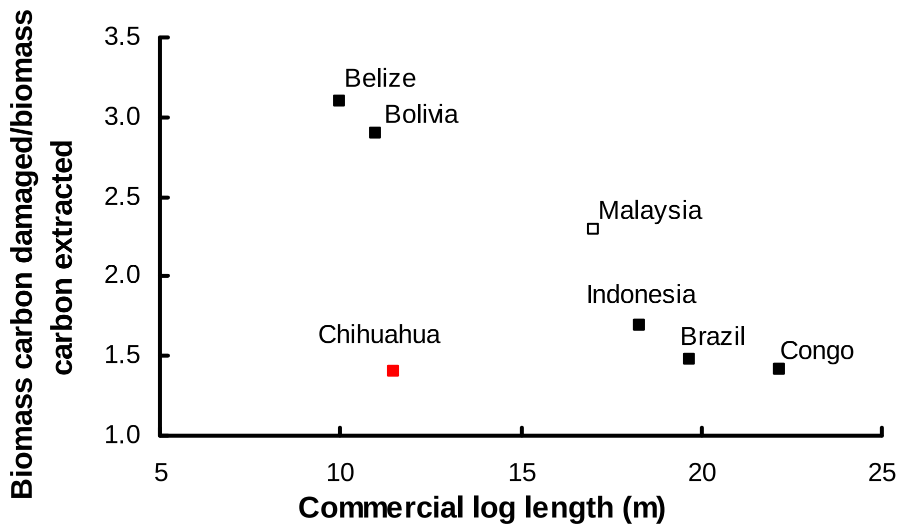


Figure 11 Relationships between commercial log length and the ratio of biomass carbon damaged to biomass carbon extracted for six pantropical sites and Chihuahua, Mexico.

The relationship between mean commercial log length and the ratio of damaged/dead biomass to extracted wood biomass is shown for the six Winrock measured sites plus one site derived from the literature (Figure 12; Sabah, Malaysia: Tay 1996, Pinard and Putz 1996). For the six tropical sites there is a clear trend of an increasing amount of damaged/dead wood biomass relative to extracted biomass with decreased commercial log length.

The forests of Chihuahua in Mexico clearly do not follow the pattern of the tropical sites (Figure 12). The site, however, is not comparable because it was a pine forest located in montane subtropical area. A detailed discussion on Chihuahua can be found in a previous deliverable to USAID (Pearson et al. 2005a).

7.2 Scaling factors

Estimation factors are presented that link volume extracted to biomass carbon extracted and biomass carbon damaged (Table 2). Volume extracted is a standard reported measure for forestry operations around the world. A potential problem could exist, however, with relying on reported volumes as: not all trees cut are extracted (up to 7 % of felled trees were not extracted in the Eastern Amazon; Holmes et al. 1999); records of extraction in some cases may be poor; and illegal extractions cannot be monitored. As an alternative, estimation factors are also detailed relating area of damage to extraction and carbon damage(Table 4). These factors could be used in combination with aerial imagery to create a record not subject to the same problems.

Ground measurements also created factors linking the number of loggings decks, and the length of roads and skid trails with the carbon impact in terms of biomass carbon of dead wood generated. These facets can then be analyzed from aerial imagery or from harvesting plans to give the total carbon impact of forestry operations.

7.4 Impact of logging on the carbon budget

Equation 1 represents the total impact of logging on the forest carbon budget. In this study we have developed methods for determining the biomass carbon extracted and the biomass carbon damaged/dead as a result of logging. Additional components in the budget include delayed mortality of damaged trees, and finally the consideration of the decomposition/oxidation of damaged biomass and the long term products arising from the extracted biomass.

Missing from this analysis is a verification of the mortality of the severely damaged trees or an indication of the mortality of trees with minor damage. It could be expected that a proportion of snapped and uprooted trees would resprout. Pinard and Putz (1996) found that 82 % of trees that were snapped had resprouted 8-12 months after logging. Our own plots in Bolivia were revisited four years after logging (Brown et al. 2003), and we found that 64 % of snapped trees and 12 % of uprooted trees had resprouted. However, we would argue that, in terms of carbon, whether or not a tree resprouts is immaterial as the biomass present aboveground in the tree still enters the dead wood pool. A more serious missing factor may be lack of mortality data on minor damaged trees. In Bolivia, 283 trees or an additional 28 % were impacted in a minor way, 80 (28 %) of these trees had died by the time of remeasurement four years later but the carbon impact is low because all had a dbh of less than 50 cm and 79 % had a dbh of less than 20 cm.

For conservation purposes, for the monitoring of concessions, and for forest certification, the destination of the dead wood and the extracted timber is less important. It matters, however, for carbon analyses. The immediate impact of logging to the atmosphere is diminished when it is considered that neither the dead wood pool in the forest, nor the extracted timber, in the form of the long-term product pool, are instantaneously oxidized. Instead, a proportion is oxidized each year forming a diminishing additional atmospheric input. It is not practical to track the decomposition of dead wood or wood products. Instead, decomposition/oxidation is modeled as a simple exponential function based on mass of dead wood/wood products and a decomposition coefficient (proportion decomposed per year).

7.3 Modeling a change in harvest practices in East Kalimantan

Examining the Aditya harvesting records across three logging units, the mean extraction rate was 26.3 m^3 ha^{-1} (range 20.1 – 30.9 m^3 ha^{-1}) from an average of 2.7 trees extracted per hectare. This compares with a mean across tropical forest in Asia of 33 m^3 ha^{-1} (FAO 1993). In Sabah in Northern Borneo, Pinard and Putz (1996) recorded much higher extracted volumes of between 54 and 175 m^3 ha^{-1}. An extraction of 19.5 m^3 per hectare is proportional to an extracted biomass carbon of 7.4 t and a biomass carbon of 17.4 t left as dead wood in the forest.

The decomposition coefficient for dead wood can range from 0.05 – 0.12/yr based on literature sources for the tropics (Brown 1997, Delaney et al. 1998). An efficiency of 40% is assumed for the conversion of logs to long-term wood products and a conservative retirement rate of 0.01 (Winjum et al. 1998).

Here a harvest scenario is modeled. Annually, ten blocks of 100 hectares are harvested. The carbon emissions from roads, skid trails and logging decks were calculated from the average extraction per hectare from the Aditya concession records and the density of roads, decks and skid trails recorded by the aerial imagery. The conservative decomposition rate of 0.05 is adopted.

After 25 years, a total of 657,500 m^3 would have been harvested with net emissions totaling 451,497 tons of carbon or 1.7 million tons of carbon dioxide (1 ton of carbon = 3.667 tons of carbon dioxide) (Table 5, Figure 13).

Table 5 The modeled extraction of timber and emissions from an annual harvest of 1,000 hectares

Year	Volume Extracted	t C in Wood Products	Emissions Extracted Carbon	t C in Dead Wood	Emissions Dead Wood	Emissions Roads, Skid Trails and Logging Decks	TOTAL C Emissions
1	26,300	2,041	4,439	15,741	828	2,604	7,871
2	52,600	4,083	8,899	31,481	2,485	5,207	16,591
3	78,900	6,124	13,379	47,222	4,971	7,811	26,160
4	105,200	8,165	17,880	62,962	8,285	10,414	36,579
5	131,500	10,207	22,401	78,703	12,427	13,018	47,846
6	157,800	12,248	26,943	94,443	17,397	15,622	59,962
7	184,100	14,289	31,506	110,184	23,197	18,225	72,928
8	210,400	16,330	36,089	125,924	29,824	20,829	86,742
9	236,700	18,372	40,693	141,665	37,280	23,432	101,406
10	263,000	20,413	45,318	157,406	45,565	26,036	116,919
11	289,300	22,454	49,963	173,146	54,678	28,640	133,281
12	315,600	24,496	54,629	188,887	64,619	31,243	150,491
13	341,900	26,537	59,316	204,627	75,389	33,847	168,551
14	368,200	28,578	64,023	220,368	86,987	36,450	187,460
15	394,500	30,620	68,750	236,108	99,414	39,054	207,218
16	420,800	32,661	73,499	251,849	112,669	41,658	227,825
17	447,100	34,702	78,268	267,589	126,753	44,261	249,281
18	473,400	36,743	83,057	283,330	141,665	46,865	271,587
19	499,700	38,785	87,867	299,070	157,406	49,468	294,741
20	526,000	40,826	92,698	314,811	173,975	52,072	318,744
21	552,300	42,867	97,549	330,552	191,372	54,675	343,597
22	578,600	44,909	102,421	346,292	209,598	57,279	369,298
23	604,900	46,950	107,314	362,033	228,652	59,883	395,849
24	631,200	48,991	112,227	377,773	248,535	62,486	423,249
25	657,500	51,033	117,161	393,514	269,246	65,090	451,497

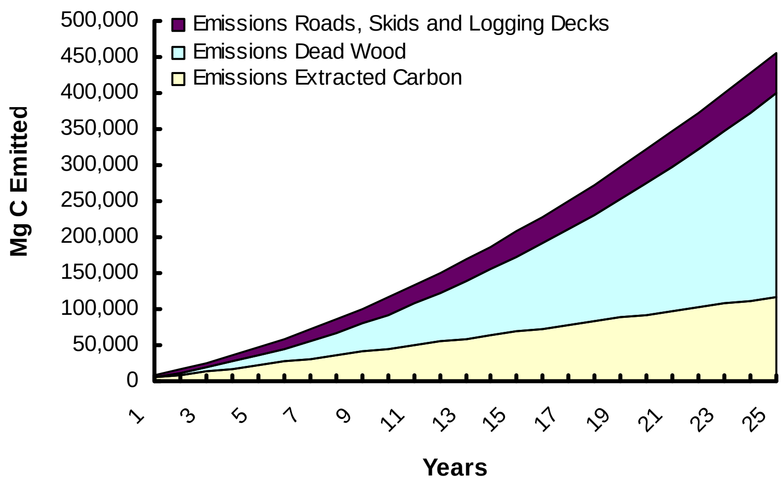


Figure 12 The modeled emissions through 25 years of harvest

To illustrate the impacts of changes in harvesting practices two alternative scenarios were modeled over the same 25 year period. The first alternative scenario is a reduction in harvesting intensity from 26.3 m^3 per hectare to 21.0 m^3 ha^{-1} (20 % reduction) and the second scenario is a doubling in intensity to 52.6 m^3 ha^{-1}. After 25 years emissions equivalent to 1.7 million tons of carbon dioxide were estimated for the status quo, 1.3 million tons of carbon dioxide equivalent for the 20 % reduction and 3.3 million tons of CO2-e for the doubling in intensity (Figure 13).

Figure 13 The modeled emissions of both the status quo and the alternative scenarios of a 20 % reduction in logging intensity and a doubling of logging intensity

7.4 Efficacy of aerial imagery

Interpretation of the aerial imagery revealed an estimated extraction equal to 1.31 m^3/ha from an estimated 0.10 trees/ha. This compares to the average extraction rate for tropical forest in Asia of 33 m^3 ha^{-1}, or the mean rate in Sabah in Malaysian Borneo of between 54 and 175 m^3 ha^{-1}. Finally, examination of the harvesting records for Aditya reveals extraction rates across three subunits of 26.3 m^3 ha^{-1} from a mean of 2.7 trees per hectare. There are two possible explanations for the differences between the aerial imagery estimates and recorded estimated by Aditya.. First that the harvesting for the year was not completed at the time of flying over the concession. This is likely for the time of the flight (August 15^{th}). To verify this we went back and looked at the number of logging gaps for 2005 where we can be confident that the logging is completed and we make the assumption that the gaps will all still be visible after a year of surrounding canopy regrowth. In the adjacent 397 ha logged in 2005 just 20 logging gaps were recorded suggesting a lower rate of extraction than in the 2006 zone. This indicates a rapid rate of gap closure and the more likely explanation that a proportion of the gaps were not identified in the imagery.

The conclusion is therefore underreporting by the aerial imagery. We argue that this implies no implicit flaw in the remote sensing imagery. While in the previous studies under this agreement (Pearson et al. 2005b, 2006), the imagery was collected at a 10 cm resolution, the analysis in Indonesia was conducted a reduced resolution of 25 cm. The reason for this was an incorrect alignment in the Geographic Imagery Systems (GIS) that were used in the planning of the flight paths. Ten centimeter data were collected but outside of the logging area. At the lower imagery resolution it is likely that a significant number of gaps were overlooked as well as a significant proportion of skid trails.

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