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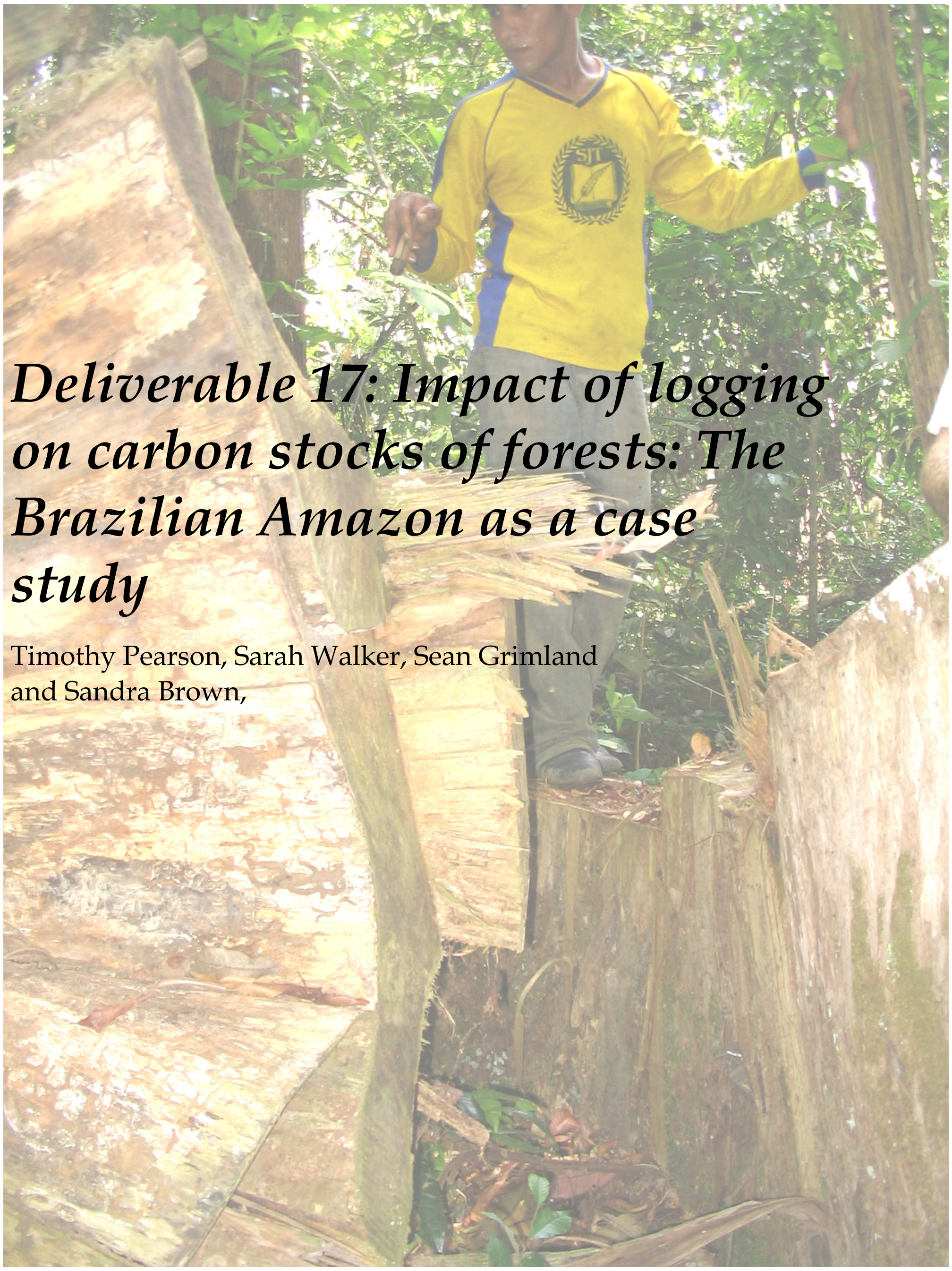

Deliverable 17: Impact of logging on carbon stocks of forests: The Brazilian Amazon as a case study

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Executive Summary

The harvesting of timber from forests is a central part of the economy of tropical nations. Land use change in the tropics contributes up to 25 % of current international CO_2 emissions. Monitoring of logging activities therefore serves an important function. This report develops and presents methods for evaluating the carbon impact of selective logging in the tropics, with the purpose of facilitating the monitoring of forest management and improving understanding of the global carbon cycle.

The aim of the study was to derive factors to link reported data and aerial imagery with carbon impact. Our study site was the Amazon frontier community of Anto, which following Brazilian legislation has the right to deforest 20 % of their land for agriculture and selectively log the remaining 80 %. During the course of the study a methodology was developed that can be applied to other areas and regions practicing selective logging. The size of the gap, and the dimensions of the felled tree and the commercial log, was determined in 105 logging gaps in the Para Province of Brazil, plus we recorded data on all trees severely damaged or killed as a result of the treefall. In addition we calculated the carbon impact of both logging decks and logging roads.

The mean diameter of extracted trees was 86.3 cm and length was 20 m. This compares with 123 cm and 22 m in Congo and 70 cm and 11 m in a similar study in Bolivia. The mean extracted volume per logging gap was 10.7 m^3.

The estimated emissions from logging ten forest blocks (1,000 ha) at the project site are modeled. Also modeled are the avoided emissions from both increasing and decreasing the harvest intensity and the comparison between reduced impact and conventional logging techniques. Stopping logging would result in a saving after 25 years of approximately 1.3 million tons of carbon dioxide equivalent. A twenty percent reduction in intensity would avoid emissions totaling 228 thousand Mg CO_2-e after 25 years. The fact that reduced impact logging is practiced at the site leads to an estimated avoidance of 266 thousand Mg CO_2-e over the twenty-five year model.

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INTRODUCTION

Commercial logging of native forests is integral to the economies, and central to the development, of many tropical nations (FAO 2003). At the Conference of the Parties to the United Nations Convention on Climate Change (UNFCCC) in Montreal in December 2005 there was a concerted international interest in quantifying, slowing and even incentivising the slowing of the rates of deforestation. Deforestation takes two forms. The obvious is the clearance of land for ranching or agricultural production. This form of deforestation is clearly visible from satellite imagery. The more insidious form is forest degradation which occurs through legal and illegal logging and which opens up frontiers for agricultural expansion through the construction of roads and other infrastructure. Internationally there is interest in improved forest management, in particular changes to reduced impact logging, motivated by biodiversity conservation, sustainable forest management, timber certification, and even the potential for increasing forest carbon stocks. The technical problems are not insignificant; to establish and credit any reduction in the rate, the carbon emissions for the business as usual must be well-defined plus the carbon impact of any activities that are taken.

Monitoring changes in carbon stocks serves as a method of assessing the impact of forest management activities, and also helps determine the role forest harvesting plays in the global carbon cycle. Land-use changes in the tropics are a significant source of atmospheric CO_2, contributing up to about 25% of current fossil fuel CO_2 emissions (Prentice et al. 2001). Logging in the tropics tends to be selective, so the impact of harvest is hard to quantify and consequently current estimates of the effects of tropical forest management are likely to be inaccurate.

Monitoring of legal and illegal logging has several purposes. For example, assessments are needed of the integrity of conserved areas, such as National Parks, with regard to incursions by loggers, or, where a logging concession has been granted, there may be a need to assess whether that concession is being fulfilled within the contractual constraints. Alternatively, in the future it is envisioned that a premium will be paid for timber that is certified to come from a sustainably managed forest. To maintain the value of the certification, monitoring would have to be carried out.

In this study we concentrated on carbon stocks, which can be used as a proxy for other monitoring purposes. To monitor logging impacts on carbon stocks, factors are required to link reported data or readily monitored components with the total carbon impact. The two most obvious factors for correlation are volume extracted (which is widely reported) and gap size (which can be determined remotely). Correlation factors can be created through an initial set of ground measurements. To our knowledge only one study has created factors linking gap size or volume extracted with biomass damaged (Brown et al. 2000). 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 gap size or even volume of timber extracted.

This study in Brazil represents the third study on selective logging under USAID Cooperative Agreement No. EEM-A-00-03-00006-00. The first two studies were in the Republic of Congo (Brown et al. 2005) and Chihuahua, Mexico (Pearson et al. 2005).

This study focuses on the logging zones on the property of the community of Anto in Para, Brazil.

In this study we aimed to estimate the net impact of selective logging on the forest carbon stocks by:

- estimating on a gap-by-gap basis extracted volumes, the biomass carbon from the timber tree that remains in the forest, and the incidental carbon damage to surrounding vegetation; and

- creating relationships between volume extracted, the size of canopy gap caused by logging and the carbon impact.

We then discuss how such data and relationships can be used to estimate the impact of logging on the total carbon budget, using such information as timber extraction rates or area and number of felling gaps from aerial imagery.

STUDY AREA

The study area was the 2004-harvest forest zones operated by Antonio Leite in the community of Anto in Para, Brazil (Figure 1). The elevation of the area is approximately 80 meters above sea level, with gentle to flat topography. The mean annual rainfall is about 2,000 mm with a dry season of approximately 5 months in which less than 20 % of the annual rain will fall. The forest concession contains trees in excess of 1.5 m diameter at breast height, reaching heights in excess of 30 m. Trees, with a dbh of between 55 and 180 cm, of approximately 32 timber species are felled.

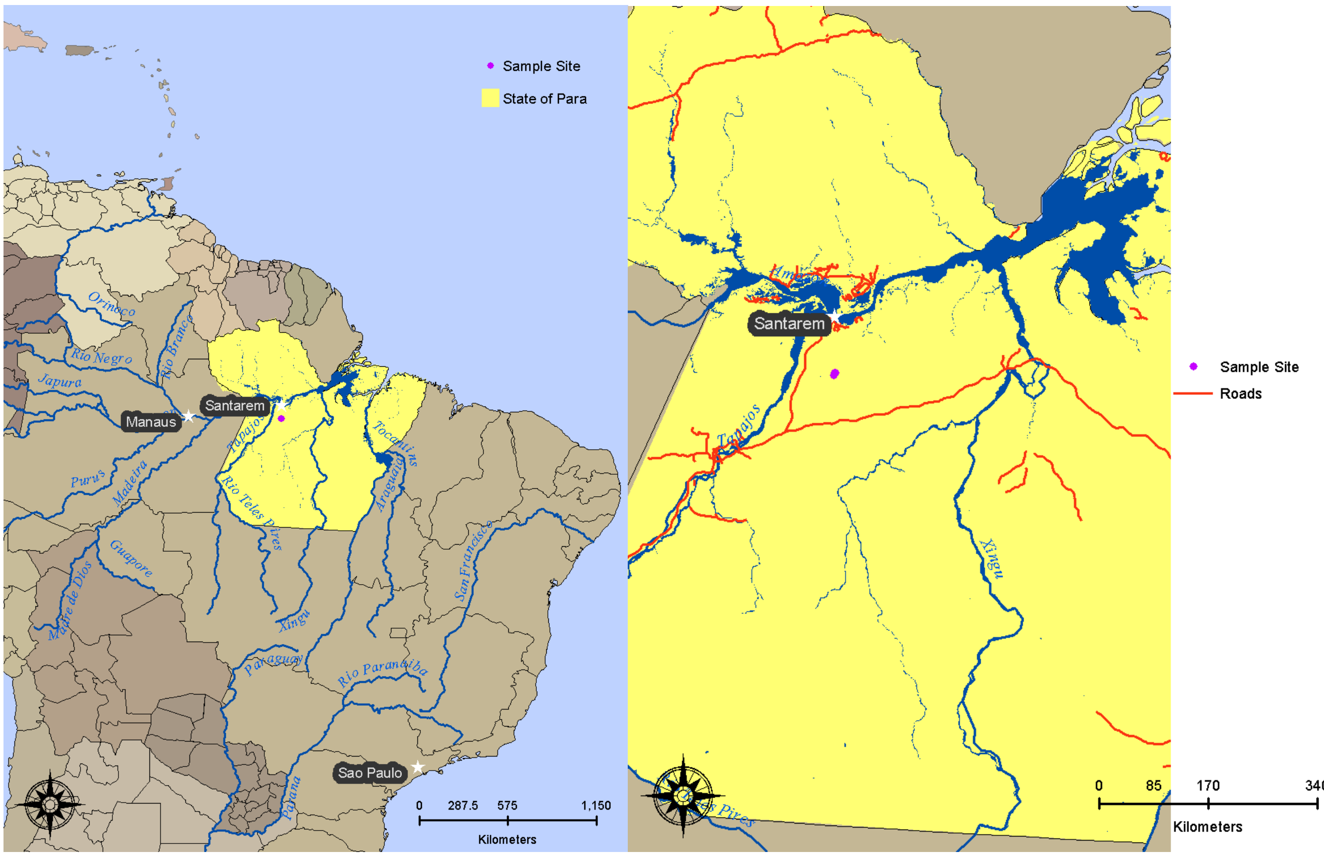


Figure 1. Location of the community of Anto in Para State, Brazil

In the region, logging operations are selective and the trees are felled with a chainsaw (Figure 2) and extracted from the forest by skid trails and roads. Once the timber tree is felled, the crews extract the portion of the tree that is commercially valuable. The skidder follows shortly after and extracts the cut section. The rest of the timber tree (branches, crown, stump) is left behind in the forest, along with other dead trees damaged during felling (Figure 3).

Brazil practices government-induced settlement whereby low income citizens are given land and financial resources to settle in the Amazon rainforest. The settlers practice agriculture and ranching. Of the area of forest give to the new settlers 20 % can be cleared (e.g. Figure 2), the remaining 80 % has to remain under forest. However, sustainable harvesting is allowed in the forested 80 %.

The community of Anto is under the Family Forests Program (e.g. http://www.whrc.org/resources/published_literature/pdf/NepstadetalConsBio.04.pdf). Under this program the community signs a contract with a logging company, the company constructs high quality dirt roads connecting the community with the highway system, it also assists each household in attaining legal tenure of the land. Timber is harvested using reduced impact techniques and the family receives a fair market price for the timber extracted from their land.

Figure 2. Cleared forest at the study site

METHODS

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 3).

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)
[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 (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.

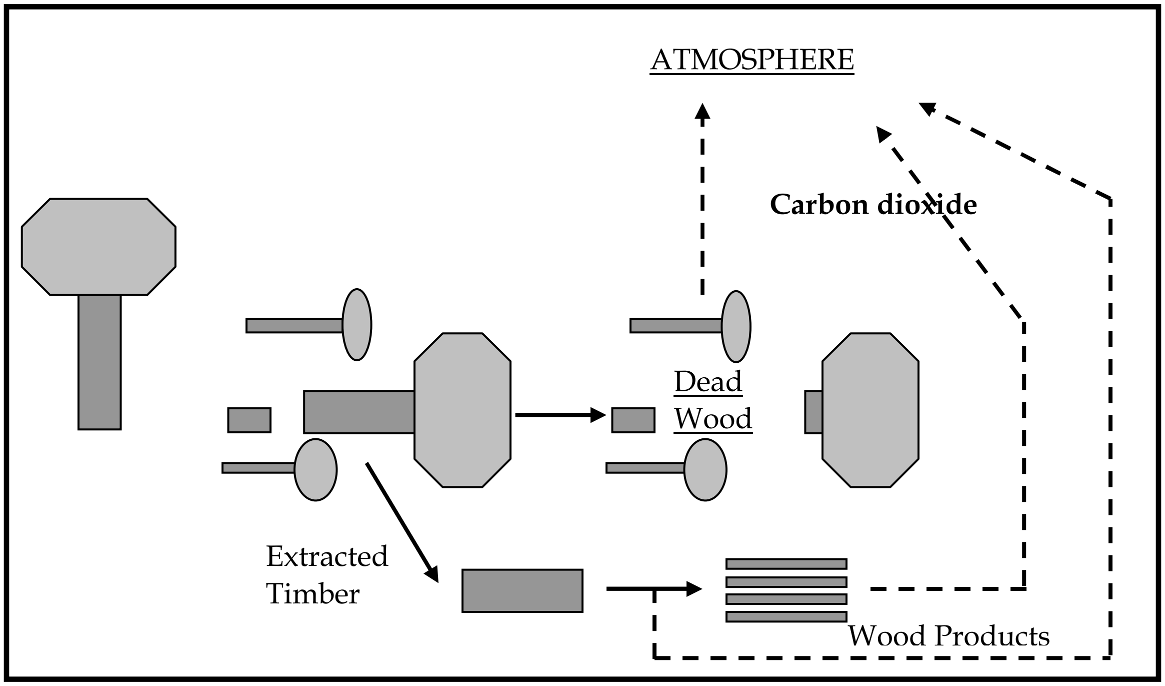


Figure 3. Schematic representation of carbon flow as a result of selective harvest in the tropics

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. We discuss the effect of including decomposition of the dead biomass and the proportion going into long term wood products on the net change in carbon stocks on the forest.

Field measurements

Timber extraction

A total of 105 selective logging gaps were examined in Para province, Brazil in August 2005 (Figure 4).

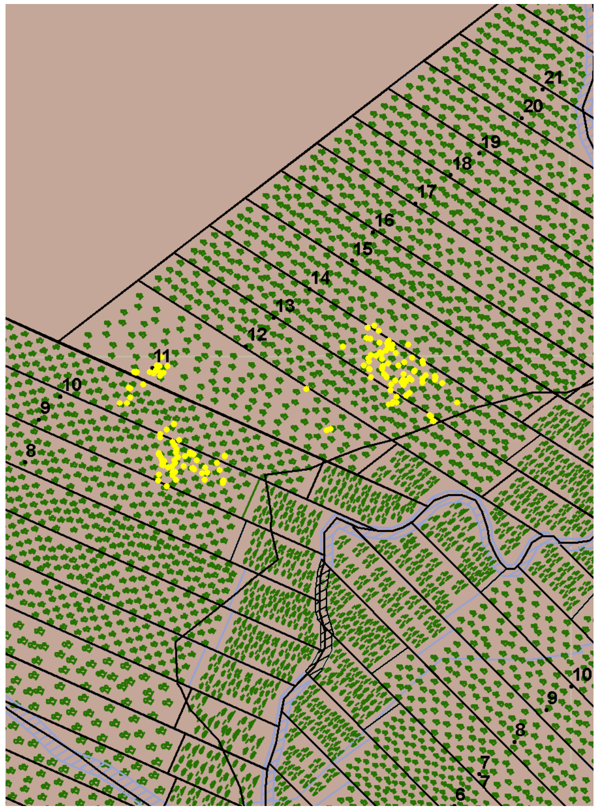


Figure 4. The site of logging gaps measured in the field by the Winrock team in August 2005. Each of the numbers represents a property owned by a single household in the community. Each block has access to the road and the river

In all cases the commercial log had already been removed leaving the stump (Figure 5) and the crown (Figure 6) of the tree. Four measurements were taken on each timber tree: the diameters at both the stump and crown ends of each commercial log, the distance between the stump and crown (length of timber log) and the height of the stump.

Figure 5. 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 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 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) to the dbh (from Chave et al. 2005). 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.

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.

Figure 6. The crown of a felled timber tree and incidental damage caused during the felling of the tree

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.

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.

As logging had occurred up to one year previously it was not possible to record the impact of skid trail construction. Skidders avoid large trees so damage is limited to small diameter trees which do not persist for extended periods as downed dead wood (Figure 7).

Figure 7. A skid trail

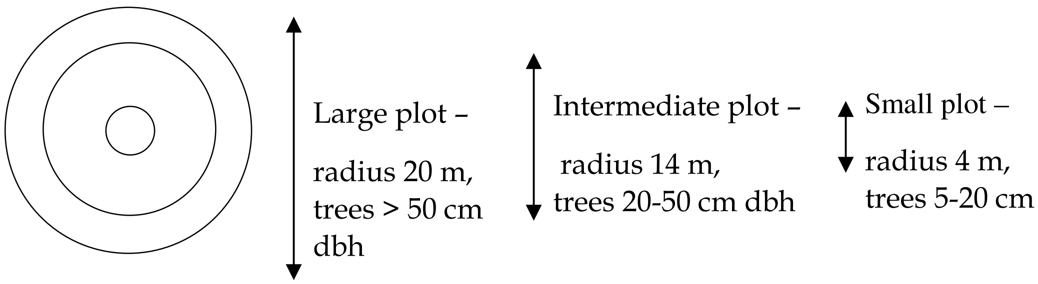
Roads are also used to transport the logs. We aimed to calculate the impact of logging roads through correlating area of roads (measured using imagery), with a measured stock for unlogged forest per unit area. The mean width of road was recorded with 85 measurements (Figure 8).

Figure 8. A log extraction road

Logging decks are a feature of the harvesting the practices in the Brazilian Amazon. Logging decks exist where logs are piled after skidding for subsequent loading on trucks (Figure 9). The area of 4 separate logging decks was recorded.

Figure 9. A logging deck

In Brazil we estimated a mature forest stock by measuring 10 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 Brazil 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.

RESULTS

Timber extracted

In the 105 logging impact plots examined in Brazil, 123 trees had been harvested. Eighty-nine of the logging impact plots consisted of a single harvested tree (e.g. Figure 10), and sixteen plots had more than one tree harvested in an area (14 consisted of 2 trees, and 2 plots consisted of 3 trees). Examining the records of the logging operator, across 5 blocks around which we worked, 32 species were harvested. By far the most common species was *Manilkara huberi* representing 58 % of all trees harvested.

The mean size of the logging gaps was 340 m^2, with a range of 0 (closed canopy) to 1,436 m^2. The zero for the area of a logging gap in Brazil represents four sites where the treefall failed to do sufficient damage to the surrounding canopy to cause an opening or where the opening had been closed in the year between logging and measurement. The mean dimensions of the logged timber trees were 123 cm dbh (range 57-179 cm), with a 18 m bole length (range 5.4-34.6 m), an extracted volume of 9.1 m^3 per tree (Table 1) and an extracted biomass carbon of 3.7 Mg/tree..

Table 1. Components measured/estimated from the logging operations in the CIB concession. All values are mean ± 95 % confidence interval. (The volume per gap is higher than volume per tree because in 19 plots more than 1 tree was felled.)

	Mean	95 % CI
DBH (cm)	86.3	±3.38
Commercial log length (m)	19.7	±0.88
Volume / tree (m^3)	9.1	±0.89
Volume / gap (m^3)*	10.7	±1.31
Extracted biomass carbon (t C) / gap	4.28	±0.51
Damaged biomass carbon (t C) / gap	5.77	±0.91
Extracted timber as % of total tree biomass	50.7 %	±2.6

Figure 10. A logging gap at the study site

Incidental damage

During measurements in 2005, 458 trees were recorded as severely damaged in the 105 logging impact plots. Of the damaged trees, 85 % had their stem snapped and 15 % were uprooted. Fifty percent of the damaged trees were measured in the minimum diameter class (10-19.9 cm).

Damage per Mg (1 Mg= 1 metric ton) extracted ranged from 0.40 to 6.82. Analysis of the logging impact plots with more than one harvested tree showed no significant difference from single stump plots (ANOVA; $p>0.05$). Mean amount of biomass carbon damaged per Mg C extracted was 1.21 for the multi-stem plots and 1.53 for single stump plots (confidence intervals overlap: 1.21 ± 0.26, 1.53 ± 0.20). The contribution of crown and stump biomass (i.e. portions of the tree not extracted at harvest) to total damage carbon biomass was high (77.8 % ± 3.4; mean ± 95 % confidence interval). On average, the amount of damage per Mg of timber extracted was 1.48 Mg.

Factors

In the Brazilian Amazon, every cubic meter of timber extracted was equivalent to 0.40 Mg C extracted. In terms of damage, 0.58 Mg C were damaged and left to decompose in the forest for each cubic meter of commercial timber (Table 3, Figure 2). For every square meter of gap area 0.043 m^3 or 17.27 kg C were extracted, and 23.24 kg C were damaged and left to decompose in the forest (Table 2).

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 CIB concession, Republic of Congo. One Mg = one metric ton

	Factor	95% CI
Mg C extracted / m^3 extracted	0.40	±0.01
Mg C damaged / m^3 extracted	0.58	±0.06
Mg C damaged / Mg C	1.48	±0.17
m^3 extracted / m^2 of gap area	0.0432	±0.0088
Kg C extracted / m^2 of gap	17.27	±3.78
Kg C damaged / m^2 of gap	23.24	±5.02

Logging Roads and Decks

From 10 plots in mature unlogged forest we estimated a carbon stock equal to 218.1 Mg C/ha ± 66.1 (n = 10, mean ± 95 % confidence interval). This is equal to 0.022 Mg C per m^2 area.

From 85 measurements of road width, the mean width is equal to 5.56 m ± 0.34 (mean ± 95 % confidence interval). Therefore, using the per m^2 carbon estimate, 1.8 km of roads are equivalent to 1 ha of forest or 218 Mg C.

From four measurements of deck area, the mean area is equal to 538 m^2 ± 34 (mean ± 95 % confidence interval). Using the mean forest carbon stock determined above this is equal to a mean of 11.8 t C ± 8.7 (mean ± 95 % confidence interval calculated using a Monte Carlo iterative procedure) per logging deck.

DISCUSSION

Comparison between selectively logged sites

Brazil represents the fifth site examined by Winrock for the impact of selective logging on carbon stocks (Table 3). In terms of mean breast height diameter and log length, Brazil is second only to the massive forests in the Congo basin.

Table 3. Comparison of mean data collected for five selective logging study sites

	Congo	Brazil	Bolivia	Belize	Mexico
DBH (cm)	123	86	70	62	38
Log length (m)	22	20	11	10	12
Volume per tree (m^3)	21	9	4	3	1
Mg C Incidental damage/ Mg C extracted	0.65	0.33	1.17	0.93	0.06
Extracted biomass carbon per gap (Mg)	6.8	4.3	1.2	0.8	0.2
Damaged biomass carbon per gap (Mg)	10.8	5.8	6.1	2. 8	0.3
Extracted as % of total	50	51	40	34	44
Mg C damaged / Mg C extracted	1.7	1.5	2. 8	3.1	1.4
Mg C extracted / m^3 extracted	0.27	0.40	0.30	0.30	0.38
Mg C damaged / m^3 extracted	0.46	0.58	0.83	0.92	0.54
Kg C extracted / m^2 gap area	12.10	17.27	1.77	N/A	N/A
Kg C damaged / m^2 gap area	18.52	23.24	4.14	N/A	N/A
M^3 extracted / m^2 gap area	0.044	0.043	0.006	N/A	N/A

A number of studies on logging practices in the Brazilian Amazon have been conducted. In the Southern Amazon, Feldpausch et al. (2005) reported a mean dbh of 75 cm and mean volume of approximately 5.8 m^3 per tree. Verissimo et al. (1992) studied logging in Eastern Para state and reported a mean dbh between 73 to 75 cm, a log length of 16-20 m and extracted volume of 5.2-6.4 m^3 per tree. More comparable in terms of diameter of logged trees was the study of Uhl and Vieira in Northern Para with a mean DBH of harvested trees of 87 cm but the extracted volume of 6.6 m^3/tree is lower than the current study. Uhl et al. (1991) again in eastern Para report an extracted volume per tree of 8 m^3.

The prevailing pattern among the five tropical sites considered in Table 3 is: the larger the logs, the greater the proportion of total tree biomass that is extracted. Also larger trees seem to cause less incidental damage (damage to the surrounding vegetation) per biomass extracted. Brazil does not follow this trend. It has a higher extracted proportion than Congo and half the rate of incidental damage of Congo.

Brazil also has the lowest total damage per extracted biomass of all the tropical sites studied. In a study in Sabah Malaysia, Pinard and Putz (1996) recorded 2.3 Mg damaged per Mg extracted from conventional logging. Feldpausch et al. (2005) in southern Amazonia produced an extimate of 2.4 Mg damaged per Mg extracted.

The damage values are highest in the studies in Central and South America, followed by Malaysia, and by Congo. One explanation may be the extracted proportion of the timber tree. In Bolivia, the mean bole length was only 10.8 m and the proportion of the total aboveground tree biomass that was extracted was just 40.1 %. In Belize, the mean bole length was just 9.8 m and the proportion extracted was 34.3 %. In Belize, therefore, there was a smaller proportion extracted and consequently a higher amount of damage per extraction. In Malaysia the timber trees were tall dipterocarps, consequently the bole lengths at Pinard and Putz's study site averaged 17.0 m (Tay 1996) and in the conventional logging areas the extracted proportion was 49 % of the preharvest biomass (Pinard and Putz 1996), resulting in lower mean damage per Mg extracted. Finally in Congo the mean bole length was 22 m and over 50 % is extracted leading to lower mean damage per extraction – 1.7 (Figure 11). The study of Feldpausch et al. (2005) does not report log length but does include the mean dbh of felled trees and the value of 75 cm fits in with the sites studied by Winrock.

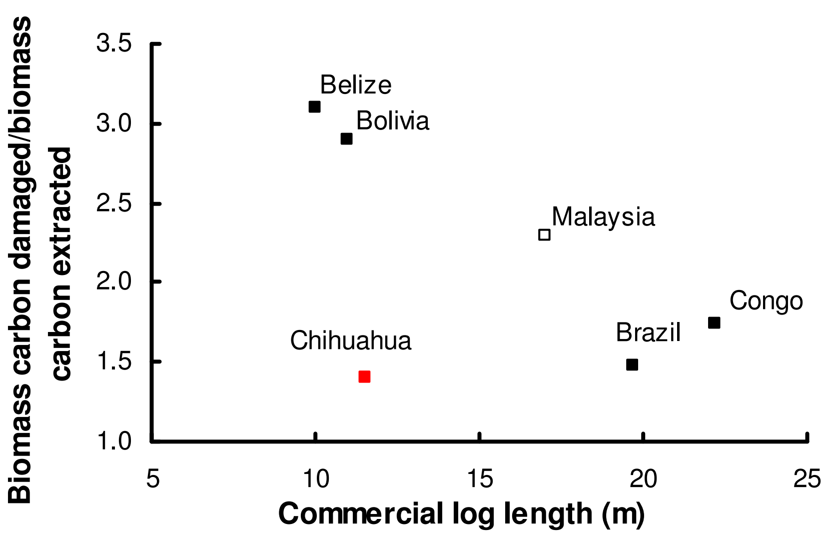


Figure 11. Relationships for five pantropical sites and Chihuahua, Mexico between commercial log length and the ratio between biomass carbon extracted and damaged

The forests of Chihuahua in Mexico clearly do not follow the pattern of the tropical sites (Figure 11). The site, however, is not comparable due to being a coniferous forest located outside the tropics. A detailed discussion on Chihuahua can be found in a previous deliverable to USAID (Pearson et al. 2005).

The tropical sites of Belize, Bolivia, Malaysia and the Republic of Congo fall on a line predicting biomass carbon damaged per biomass carbon extracted from the commercial log length. However, the current study in Brazil, like Chihuahua Mexico, falls outside of this line. The reasons for this non-compliance have been already identified: The site in Brazil had lower than predicted incidental damage per extracted biomass and had a higher extraction proportion than predicted.

Other studies in the literature also recorded the number of trees damaged during logging (incidental damage in this study). Verissimo et al. (1992) reported 27 trees severely damaged per tree extracted, Uhl et al. (1991) similarly measured 29 trees severely damaged per extracted tree. In contrast in the current study the total was just 4.5 trees damaged per tree extracted. The study site did feature reduced impact logging and the damage caused along skid trails and logging roads are not included but it is clear that significantly less damage was recorded than in the alternative studies.

Extrapolating from DBH or log length, we might expect an additional 0.4 to 0.5 Mg C in incidental damage per extracted biomass carbon beyond that which was recorded in this study. This addition, alone, would be enough to place this study on the predicted line defined by the other tropical sites.

From the other sites we would also predict an extraction proportion that is lower than that recorded in the Republic of Congo. If a lower proportion is extracted this predicts a higher proportion as damage and consequently a higher damage ratio. The reasons for this variation in extracted proportion are not immediately clear but could include a lower boundary for top diameter extraction in Brazil. In the Republic of Congo the mean top diameter was 90 cm and the minimum was 56 cm. In Brazil the mean was 62 cm and the minimum was 41 cm.

The reasons for the difference in incidental damage may be more clear. For logistical reasons (the Government of Brazil was not granting licenses to harvest trees to timber operators at the time of our visit), the sites included in the current study were logged 12 months previously. In the 12 months after harvest small diameter and rapidly decomposing trees, killed by treefall, may have disappeared. In addition, 12 months of growth in the treefall gap leads to substantial vegetation growth which may have shielded damage and led to incomplete damage accounting.

Alternatively, the difference between Brazil and the other sites studied could merely lie in logging methodology. The methods in Brazil could be considered reduced impact logging (RIL). Pinard and Putz (1996) compared the carbon impact of conventional logging (CL) and reduced impact logging (RIL). The authors found that incidental damage (damage to non-harvested surrounding vegetation which results in coarse woody debris) was 2.4 times higher under CL than under RIL: 1.3 Mg incidentally damaged / Mg extracted under CL, and 0.5 Mg damaged / Mg extracted for RIL. Given that the logging practices at the Brazil study site were RIL this would be an additional explanation for the lack of conformity of the site with the studies of Belize, Bolivia, Sabah (CL) and Congo. If the incidental damage in Brazil were increased by the same ratio as in Sabah, then under CL practices 0.80 Mg C would be incidentally damaged / Mg C extracted and the damage ratio would increase to 1.94 Mg C / Mg C extracted. This value approximates the relationship which would be expected for the site in Figure 11.

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 (Table 2) relating area of damage to extraction and carbon damage. These factors could be used in combination with aerial imagery to create a record not subject to the same doubts (aerial imagery has been collected over the Brazil sites and are in process of being interpreted).

For skid trails we were unable to estimate a mean carbon damage due to the time elapsed since harvest. Any impact, however, will be low because skid trails are narrow and skidders detour around large trees. For example, in the Republic of Congo, where the mean log had a diameter greatly in excess of the logs in Brazil (1.2 m vs. 0.9 m), Winrock recorded a mean impact of just 6.8 kg per m of skid trail.

For a given area of logged forest, with its associated number and area of roads, it could be argued that the carbon impact of the roads is also low. In Brazil the roads are a mean of 5.56 m wide so that construction of 1.8 km of forest results in the clearance of 1 hectare of forest. As the property blocks are an average of 2,500 m deep by 400 m wide, no road should be more than 2.5 km long, which would equal 1.4 ha of forest or 303 Mg C.

An additional component of the carbon budget that was not a common practice in Congo or Mexico was the presence of logging decks. Across the sites we visited there were an average of two logging decks per property block or 1,076 m^2 per 100 ha or 23.6 Mg C per 100 ha, which is equal to 0.24 Mg C per ha of logging area.

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 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 minorly 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).

Modeling a change in harvest practices in Brazil

Across the logging blocks considered in Brazil the mean extraction of 2.1 trees per hectare or 19.5 m^3 per hectare which compares with a mean across tropical forest in Latin America of 8 m^3/ha (FAO 1993), or 6.4 – 15 m^3/ha in the study of Feldpausch et al. (2005) in the southern Amazon, 16 m^3/ha or 38

m^3/ha in Eastern Para (Uhl et al. 1991, Verissimo et al. 1992) or 52 m^3/ha in northern Para (Uhl and Vieira 1989). An extraction of 19.5 m^3 per hectare is proportional to an extracted biomass carbon of 7.4 Mg and a biomass carbon of 11.3 Mg left as dead wood in the forest.

The decomposition coefficient for dead wood is assumed to 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. One road and four logging decks are constructed for every two blocks. The conservative decomposition rate of 0.05 is adopted.

After 25 years a total of 488,500 m^3 would have been harvested with emissions totaling 355 thousand tons of carbon or 1.3 million tons of carbon dioxide (1 ton of carbon = 3.667 tons of carbon dioxide) (Table 4, Figure 12).

Table 4. The modeled extraction of timber and emissions from an annual harvest of 1,000 hectares

Year	Volume Extracted	Mg C in Wood Products	Emissions Extracted Carbon	Mg C in Dead Wood	Emissions Dead Wood	Emissions Roads and Logging Decks	TOTAL Emissions
1	19,540	3,095	4,721	10,767	567	1,751	7,039
2	39,080	6,190	9,473	21,533	1,700	3,502	14,675
3	58,620	9,285	14,256	32,300	3,400	5,253	22,909
4	78,160	12,381	19,071	43,066	5,667	7,004	31,742
5	97,700	15,476	23,917	53,833	8,500	8,755	41,172
6	117,240	18,571	28,794	64,599	11,900	10,506	51,200
7	136,780	21,666	33,703	75,366	15,866	12,257	61,826
8	156,320	24,761	38,642	86,132	20,400	14,008	73,050
9	175,860	27,856	43,613	96,899	25,500	15,759	84,872
10	195,400	30,951	48,616	107,665	31,166	17,510	97,292
11	214,940	34,046	53,649	118,432	37,400	19,261	110,310
12	234,480	37,142	58,714	129,198	44,199	21,012	123,925
13	254,020	40,237	63,810	139,965	51,566	22,763	138,139
14	273,560	43,332	68,937	150,732	59,499	24,514	152,950
15	293,100	46,427	74,096	161,498	67,999	26,265	168,360
16	312,640	49,522	79,286	172,265	77,066	28,016	184,367
17	332,180	52,617	84,507	183,031	86,699	29,767	200,973
18	351,720	55,712	89,759	193,798	96,899	31,518	218,176
19	371,260	58,808	95,043	204,564	107,665	33,269	235,977
20	390,800	61,903	100,357	215,331	118,999	35,020	254,376
21	410,340	64,998	105,704	226,097	130,898	36,771	273,373
22	429,880	68,093	111,081	236,864	143,365	38,522	292,968
23	449,420	71,188	116,490	247,630	156,398	40,273	313,161

24	468,960	74,283	121,930	258,397	169,998	42,024	333,952
25	488,500	77,378	127,401	269,164	184,165	43,775	355,340

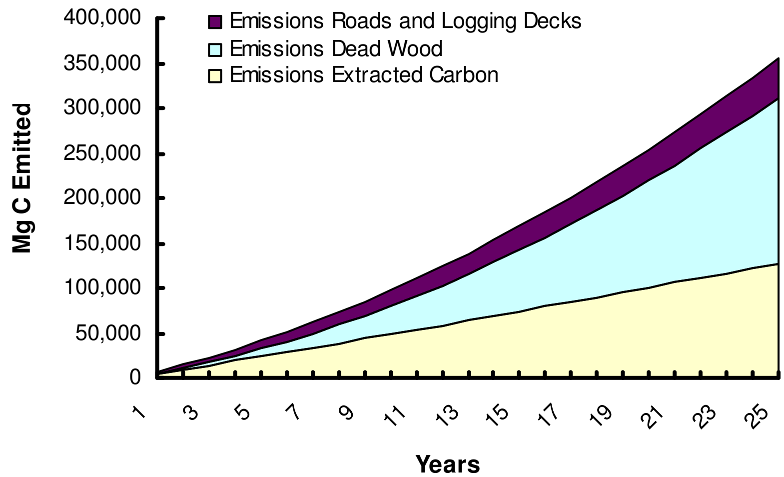


Figure 12. The modeled emissions through 25 years of harvest

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 19.5 m^3 per hectare to 15.6 m^3/ha (20 % reduction) and the second scenario is a doubling in intensity to 39.1 m^3/ha. After 25 years emissions equivalent to 1.3 million tons of carbon dioxide were estimated for the status quo, 1.0 million tons of carbon dioxide equivalent for the 20 % reduction and 2.4 million tons of CO_2-e for the doubling in intensity (Figure 13).

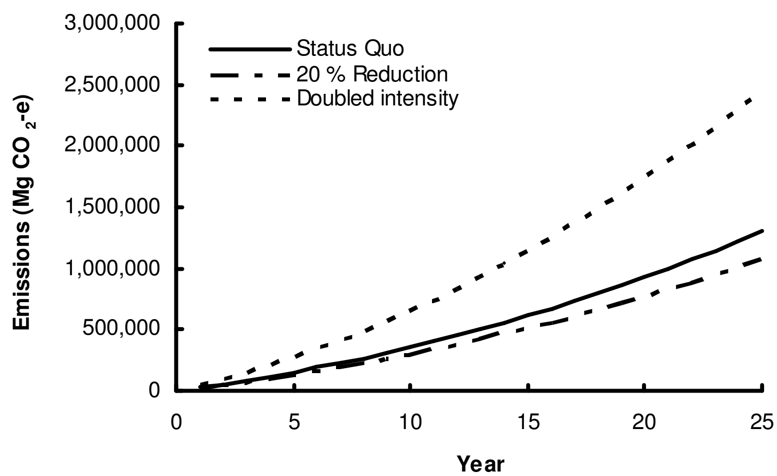


Figure 13. The modeled emissions of both the status quo and the alternative scenarios of a 20 % reduction in logging intensity and a doubling of logging intensity

The emissions from roads and logging decks remain constant through all three scenarios as it is envisaged that the change would be in choice of species harvested rather than in area logged.

The harvesting procedures utilized in the study area in Brazil would be considered as reduced impact logging (RIL). The additional emissions that might result if a more conventional form of logging were practiced can be estimated from the literature as is described above. Applying the higher damage ratio to the logging model illustrates the carbon advantage of RIL practices over CL practices.

Excluded from these calculations is a consideration of the relative area of roads and logging decks under CL and RIL. Typically under RIL the area of each of these components is reduced, further increasing the avoided emissions.

Gullison and Hardner (1993) reported that damage can be decreased by 25 % by requiring that roads and skid trails be linear (based on a study in Bolivia). In a study in Paragominas in Para, Brazil, Pereira et al. (2002), for the logging year 1996 (representing > 75 % of the area incorporated in the study), determined that 32.5 m^2 of roads were created for each extracted tree but 20 m^2 / tree under RIL. This represents a 40 % decrease in impact. Applying the more conservative 25 % of Gullison and Hardner (1993) represents an avoided emission of RIL vs CL under the current model of 35 thousand Mg CO_2-e after 25 years.

The data of Pereira et al. (2002) also suggest a decrease in logging decks from 24.3 m^2 / tree to 19.9 m^2 / tree from CL to RIL (in 1996), which is equivalent to an 18 % decrease in damage or 3.9 thousand Mg CO_2-e after 25 years.

Including each of these components produces an estimated avoided emission equivalent to 107 thousand Mg CO_2-e after 15 years and 266 thousand Mg CO_2-e after 25 years for a switch from conventional to reduced impact logging with no change in extracted volume (Figure 14).

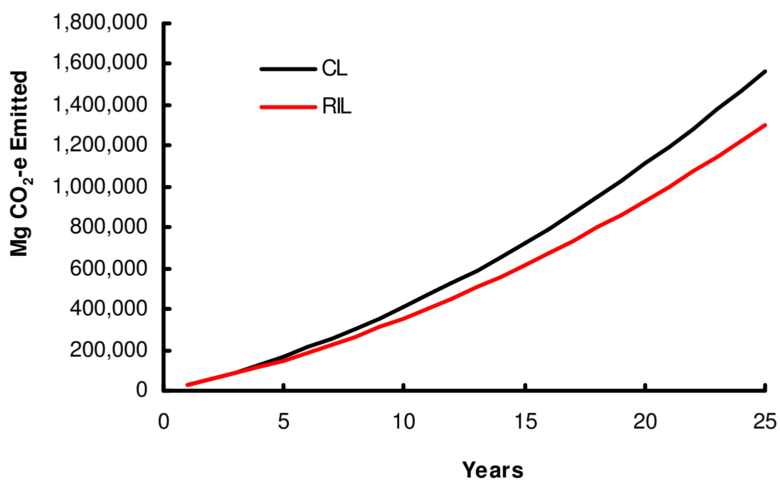


Figure 14. A comparison between the estimated emissions following the extraction of 234 thousand cubic meters of logs under conventional logging and reduced impact logging scenarios

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