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When big trees fall: Damage and carbon export by reduced impact logging in southern Amazonia

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Abstract

We examined carbon export in whole logs and carbon accumulation as coarse woody debris (CWD) produced from forest damage during all phases of the first and second year of a certified reduced impact logging (RIL) timber harvest in southern Amazonia. Our measurements included a 100% survey of roads and log decks, assessment of canopy damage and ground disturbance in skid trails and tree-fall gaps, and measurement of carbon exported from the site in logs. Log deck and road construction crushed one and five trees in the 10–60 cm diameter at breast height (DBH) class per hectare logged, disturbed areas of 24 and 100 $m^2\ ha^{-1}$, respectively, and together disturbed about 1% of the forest. On average 1.1–2.6 trees ha^{-1} were harvested over the two years. Logged gaps constituted the greatest disturbance on an area basis (4–10% of the forest) and CWD generation (1.9–4.4 Mg ha^{-1} logged). In gaps, felled trees severed or crushed 10 trees $\geq$10 cm DBH per tree logged, which corresponded to 1.7 Mg ha^{-1} of CWD per tree logged. Crown height – measured from the first bifurcation to the top of the crown – rather than tree height was the better predictor of gap size formed from tree felling (R^2 = 0.41). Logging activities significantly reduced leaf area in roads, log decks and gaps, with the greatest reduction (48%) in log decks and least in logged gaps and roads (28–33%) compared to undisturbed forest. A total of 37 species were harvested, with 36% of the total trees harvested and 48% of the total carbon exported from the site in three of the most common species. Logging damage produced 4.9–8.8 Mg C ha^{-1} logged of CWD from all phases of the operation. Carbon export in whole logs (2.1–3.7 Mg C ha^{-1} logged) represented 1–3% of the total standing forest carbon $\geq$10 cm DBH (138 Mg C ha^{-1}). The mean carbon ratio (per hectare logged) of C in CWD to C exported in logs was 2.4. The disturbance, damage, carbon export and CWD data we present advances understanding of the effect of selective logging on tropical forest dynamics of the Amazon Basin. Our results indicate that certified timber harvest in Amazonia under RIL is a viable forest management option to reduce damage and CWD production compared to conventional logging (CL) practices; however, the benefits of disturbance reduction from RIL relative to CL are only realized at greater volumes of timber extraction.

Keywords: Gap; LAI; Deforestation; RIL; Selective logging; Forest certification; Primary forest; Amazon; Brazil

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1. Introduction

Carbon flux as necromass is an important component of the regional carbon cycle for mature undisturbed (Chambers and Schimel, 2001) and selectively logged tropical forests (Keller et al., 2004). Selective logging contributes to necromass fluxes through forest damage as well as a net export of carbon as logs. Forest management provides opportunities both to reduce necromass fluxes and to retain carbon stocks in vegetation and soils (Pinard and Putz, 1996). Improved harvest methods such as reduced impact logging (RIL) can lessen damage to the forest (Johns et al., 1996; Pinard and Putz, 1996) and reduce course woody debris (CWD) accumulation (Keller et al., 2004) relative to conventional selective logging (CL). In addition, per volume harvested, RIL may provide an economic advantage to CL (Healey et al., 2000). Few studies have explicitly related ground damage, canopy reduction and log export to carbon fluxes and export on a tree by tree and operation by operation basis. Such values would improve estimates across the Amazon Basin of the level of damage the forests sustain, carbon lost and potential understory and canopy regeneration after selective logging.

In Amazonia, logging intensity (5–90 m^3 ha^{-1}) and forest disturbance vary by region (Barros and Uhl, 1995; Johns et al., 1996; Nepstad et al., 1999; Pereira et al., 2002; Fredericksen et al., 2003). Selective logging, a dominant form of land use in Amazonia, affected 9000–15,000 km^2 in 1996–1997 (Nepstad et al., 1999). Logging and deforestation assume many forms in the frontier regions, including small-scale tree felling opening new areas for subsistence food production and pasture, predatory logging in indigenous reserves and state and national parks, deforestation by ranchers to create large pastures and well-managed forests that closely follow federal logging guidelines and minimize forest perturbations.

Conventional selective logging leaves the forest standing, but no planned efforts are made to reduce residual stand damage. Improved extraction methods such as certified reduced impact logging use reconnaissance and planned logistics to reduce damage to the forest and streams from road and log deck building and tree extraction. Commercial timber inventories of all harvestable trees $\geq$45 cm diameter at breast height (DBH) provide a tool for forest engineers to plan road and log deck density and find desired species quickly, reducing inefficient tree searching common to conventional methods. RIL prescribes vine cutting one or two years prior to logging (e.g. Pinard et al., 1995), which reduces unintentional tree-fall from vine-linked canopies and injury to workers. RIL also employs directional felling to minimize both damage to surrounding vegetation and the size of gaps. Well-planned RIL operations attempt to limit the number of skidder extraction pathways to reduce damage from moving logs to consolidation decks.

Improved extraction methods, such as RIL, result in less canopy damage and lower gap fraction than CL (Pereira et al., 2002), and differences are persistent for several years (Asner et al., 2004a). Logging intensity, species selection and canopy damage from logging have direct effects on stand structure, which in turn influences stand development and subsequent logging cycles. Following selective logging there may be major shifts in species dominance and vine densities, which can reduce tree productivity and the future timber value (Pinard and Putz, 1994).

Market demands by international consumers for sustainably harvested timber has lead to the certification of some forests in Amazonia. Certification places additional management guidelines on forest managers to improve upon RIL methods and further minimize forest damage. Certified timber provides a direct economic incentive to timber companies through premiums paid for timber harvested according to environmentally and socially sustainable guidelines. By adhering to forest management, environmental impact and worker safety guidelines established by certifying agencies, timber companies benefit financially and workers are safer. Forest management improvements under certified RIL may reduce damage and carbon turnover as CWD.

We studied sources of damage in each phase of timber cutting and extraction during two years of a certified RIL timber harvest. Our objectives were to: (1) quantify ground disturbance and tree damage caused by reduced impact logging operations in a forest in southern Amazonia; (2) relate logging damage, including CWD generation from canopy and understory disturbance and tree mortality from tree felling, machine maneuvering, and road and log deck building to carbon export as whole logs; (3) compare carbon export and damage to logging operations in other regions of Amazonia.

2. Methods

2.1. Study site

The study was conducted at Fazenda Rohsamar in southern Amazonia, a 25,000 ha logging concession owned and managed by Rohden Indústria Lígnea Ltda. (10°28′S, 58°30′W). The forest lies adjacent to Rio Juruena in the northwestern region of the state of Mato Grosso in the county of Juruena, Brazil. The regional climate is tropical humid, with 2200 mm of annual rainfall, a dry season from June to October and a mean annual temperature of 24.8 °C. The soils are predominantly dystrophic Oxisols and Ultisols (U.S. soil taxonomy).

The forest is divided into twenty 1000–1400 ha management units, with the remaining areas protected as ecological reserves. Hunting is prohibited and public access to the forest is controlled. Logging began in 1992 using conventional selective logging methods and continued through 2002 with some improvements that minimized forest damage. In 2003, Rohden Indústria was certified by the Forest Stewardship Council (FSC) and began harvesting certified timber. We evaluated logging operations during the first and second year following certification. Having been recently certified by FSC, logging methods at the Rohden forest are transitioning from CL to the improved methods of RIL. Our study focused on two recently logged blocks, Block 5 (1397 ha) harvested in 2003 and Block 18 (1037 ha) harvested in 2004.

2.2. Road and deck frequency and damage

We conducted a 100% inventory of roads and log decks in the two management units. Road and deck location were mapped with a GPS (Garmin 72). Maps of roads and decks were produced using a geographic information system (GIS ArcMap®), and total length and area calculated. For each block, road width was measured at 11 random points and deck size measured every 9th deck for a total of 10 decks. Roads were assigned to three classes: (1) primary, (2) secondary and (3) tertiary based on bifurcations and distance from the primary road. Deck size on the ground and canopy opening above the deck was measured using the "center-point" system (adapted from Runkle, 1982), a system of summing the area of six triangles based on the distance from the center of the deck or canopy clearing to the edge. We measured leaf area index (LAI) in Block 5 at each point (road or deck) using a digital fisheye lens (Sigma 8 mm/F4) attached to a digital camera (Nikon D70). This setup crops the sides of the hemispheric image, giving an incomplete circular image. To resolve this restriction, we shot a second image perpendicular to the first and digitally joined the two paired images using Adobe Photoshop®, thereby creating a complete 180° image. LAI and canopy openness were calculated using the software Gap Light Analyzer (Frazer et al., 1999). This program uses inverse gap fraction analysis to calculate LAI (Norman and Campbell, 1989). Since the analysis assumes diffuse light conditions, we restricted our measurements to times of uniform cloud cover or late afternoon.

2.3. Tree-fall and skid disturbance transects

To determine the percent of the forest disturbed during tree maneuvering by log skidders and tree felling, the frequency of damage (presence or absence) was measured using the line intercept method along 26 transects in Block 5 (total = 7800 m) and 21 transects in Block 18 (total = 5600 m). This sampling represented 5 linear meters of transect per hectare logged for each block. Sampling was stratified across the block to provide full coverage of the 1037–1397 ha blocks; within a stratified area the transect start location was randomly selected. Intersection along a tape was measured for each type of damage (skid trail, gap and undisturbed). In the event of shared damage (i.e. a skid trail intersecting a tree-fall gap), the line intercept was assigned to the initial source of damage (i.e. tree-fall). Transect sections were assigned to three topographic classes, upland, lowland and slope based on estimates of hardwood versus palms, slope and proximity to streams.

2.4. Gap damage

To quantify the effect of tree-fall following logging on the canopy and understory vegetation, we measured damage in 54 logged gaps. Gaps were characterized by measuring the properties of the tree being harvested (tree species, DBH, commercial height, total height, and canopy width and height when prone), and damage to all surrounding trees and trees damaged or killed within each gap (species and number of stems ≥10 cm DBH, type of damage and distance in the clearing from the sawn stump). Gaps were defined as the actual projected canopy as outlined by the remaining canopies rather than the expanded gap (defined by stems of living trees surrounding the gap) (Runkle, 1982). To be certain damage in the gap was created by the logged tree, we restricted our measurements to gaps formed by single logged trees, rather than gaps that contained multiple felled trees. Gap-trees damaged were assigned to one of nine classes based on the severity of damage, ranging from slight bark removal to crushed and prone. When a tree was prone to the ground, DBH was measured at an estimated height of 1.3 m along the stem. Logged-gap size (canopy opening) was measured using the center-point system as described above. LAI measurements were taken in October in the center of 15 clearings and in adjacent undisturbed forest using the same digital fisheye approach as described above. Gap location was recorded with a GPS and transferred to the GIS.

2.5. Skid trail damage

To estimate tree damage due to skidding, we ran 12 transects totaling 1100 m along skid trails. All damaged trees ≥10 cm DBH were measured in each skid trail and the degree of damage recorded with the same system used to measure gap damage. Mean skid trail width was estimated by measuring the width of disturbance at several random points along each trail. LAI measurements were taken in the center of each skid trail and in undisturbed adjacent forest as described above.

2.6. Forest biomass estimates ≥10 cm DBH

Using the commercial timber inventory from Rohden Indústria to identify tree density variation across the blocks, we setup eight long (10 m × 1000 m) and eight short (10 m × 200–500 m) stratified sampling transects within the management units. Prior to logging we measured DBH of all trees and palms with trunks ≥10 cm DBH, lower and upper canopy height, species and location to 10 cm on an *x–y* grid. Height was measured using a Haglöf Vertex III-60 ultrasonic hypsometer (calibrated at ambient temperature). In nested transects (2 m by the length of the transect), we measured DBH at 1.3 cm height of all vines rooted within the transect.

2.7. Carbon calculations

We calculated dry biomass for individual trees and palms with trunks in the belt transects and trees harvested or killed (including trunks severed or crushed) by tree-fall damage, skidding and road and log deck construction using the allometric Eq. (3.2.3) from Brown (1997), with DBH (cm) at 1.3 m height (or immediately above prop-roots or buttresses) as the predictor of kg dry biomass (Eq. (1)). This equation was constructed from measuring 170 trees with a DBH range of 5–148 cm ($R^2 = 0.84$)

$$\text{Tree biomass (kg)} = 42.69 - 12.80\text{DBH} + 1.24\text{DBH}^2 \quad (1)$$

Carbon returned to the soil as necromass (i.e. trees crushed prone to the ground in logged tree-fall gaps) was calculated based on gap damage data from 54 single-tree logged gaps. Gap damage was scaled-up to the block level based on data from the disturbance transects and the commercial inventory of total trees logged, 2.6 and 1.1 trees ha^{-1} harvested in Blocks 5 and 18. We calculated biomass for trees crushed in skid trails and scaled the C data to the block based on skid trail frequency. From the 1 km transect data, we calculated biomass using Eq. (1) and tree density (trees ha^{-1}). We used these measurements to estimate the number and dry mass of trees killed by road and deck construction and total C returned to the soil as necromass. We included only trees 10–60 cm DBH to estimate number and dry mass of trees killed during road construction; we assumed that trees ≥60 cm DBH were avoided.

The tree density and biomass estimates from the 1 km transect data were also used to predict trees damaged at higher harvest intensities. Potential trees damaged included all trees ≥10 cm DBH within a fall radius of a tree that could be damaged by gap formation of the mean gap size. Actual trees damaged were the trees that were physically damaged by directional tree felling. Vine biomass in the belt transects was calculated using the allometric equation from Gerwing and Farias (2000). Estimates of C that remained in the forest from the crowns of logged trees were calculated as the difference between the commercial volume for each bole exported from the forest (converted to biomass based on wood specific gravity) and the total mass of each tree (calculated from mean DBH of harvested trees and Eq. (1)). Commercial volume was measured in logs on consolidation decks and is defined as bole volume from the base of the log to the first bifurcation.

Carbon exported from the site in logs was calculated using the Rohden commercial inventory of the volume of logs transported from the forest to the sawmill for Block 18. The ratio between logs exported and gap frequency for Block 18, together with gap frequency for Block 5 was used to estimate log export from Block 5. Volume estimates were converted to biomass using a combination of literature (Richter and Dallwitz, 2000; IBAMA, 2005; Nogueira et al., 2005) and site-specific wood specific gravity values. To estimate wood specific gravity of seven major commercial species in southern Amazonia, we took wood samples from logs located on consolidation decks. Sample densities were determined at the Universidade Federal de Mato Grosso. For carbon estimates, we assumed carbon was half of the biomass.

Differences in gap size, surrounding trees damaged or killed and LAI for each type of disturbance were examined using a one-way analysis of variance (ANOVA). We tested for differences between the means of types of disturbance using a Tukey multiple comparison test ($p = 0.05$). Best subset regression was used to identify the best-fitting regression model to predict gap size from the damage variables measured in each of 54 gaps. Simple linear regression was used to fit a general least squares model of ground disturbance as a function of volume of wood extracted.

3. Results

3.1. Surface disturbance frequency

There were an average of 2.6 and 1.1 trees harvested ha^{-1} in Blocks 5 and 18. At this rate, 16.2 and 9.8%, respectively, of the forest ground area was disturbed by all logging activities (Fig. 1). Gaps formed from tree-fall represented the greatest ground disturbance with a mean of 6.9%. Disturbance was concentrated in upland areas with 10% more logged gaps than lowland areas. Skid trails created from dragging logs to consolidation decks also represented a large part of the damage to the forest, disturbing on average an area 4% greater than disturbance caused by road building. As with gaps, skid trails were less frequent in lowland areas where there are fewer trees harvested. Roads and log decks disturbed less surface area compared to skid trails and gaps.

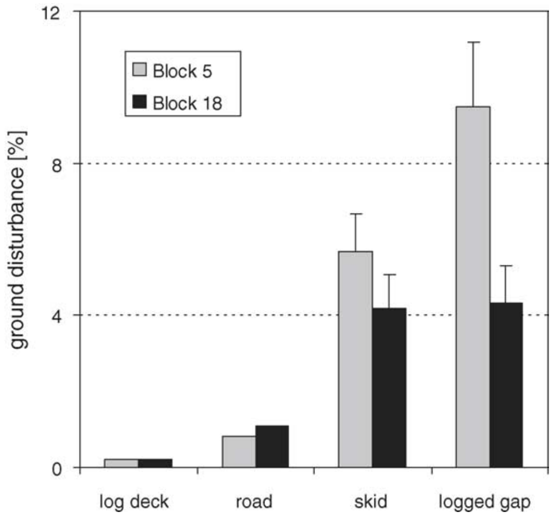

Fig. 1. Frequency of total ground disturbance in Blocks 5 and 18 in Fazenda Rohsamar, southern Amazonia, Brazil. Road, log deck, skidder and logged gap disturbance measured along 47 line intercept transects totaling 13,500 m. Error bars indicate standard error of mean transect values (100% inventory of roads and decks).

3.2. Gap damage

We measured 1031 damaged trees $\geq$10 cm DBH in 54 single tree-fall gaps formed by falling logged trees. Damage to trees in the gaps varied from a slight bump (I) or minor to severe bark loss (II and III), to minor to severe canopy damage (IV–VII), to more acute damage including severing of the trunk (VIII) and crushing the entire tree to the ground (IX) (Table 1). Of the 1031 trees damaged, nearly 50% either had the trunk severed at some height or were crushed to the ground, which is equivalent to 5 trees severed at the trunk and 5 trees crushed to the ground for every tree logged. Damage in these two classes results in tree

Table 1
Gap damage: trees ≥10 cm DBH damaged (by damage class) in 54 single tree-fall gaps formed by trees logged in Block 5 in Fazenda Rohsamar, southern Amazonia, Brazil

Damage class	Descriptor	Percent damaged stems	Stems damaged per tree logged (no. of stems per gap)	Stems damaged per hectare logged (no. of stems ha^{-1})	Mean DBH (cm)	Mean distance from logged tree (m)
I	Tree bumped and at angle	1	1.1	2.9	17.4 ± 2.7	18.8 ± 4.7
II	<2 m bark missing	4	1.5	3.9	20.9 ± 2.5	18.8 ± 2.1
III	>2 m bark missing	2	1.3	3.2	27.0 ± 4.8	20.5 ± 2.1
IV	<25% crown damage	20	4.0	10.4	23.9 ± 1.0	21.8 ± 1.0
V	>25–50% crown damage	10	2.2	5.7	24.3 ± 1.7	21.4 ± 1.1
VI	>50–75% crown damage	7	1.8	4.7	20.4 ± 1.3	23.3 ± 1.2
VII	>75% crown damage	8	2.2	5.6	18.5 ± 1.5	21.0 ± 1.5
VIII	Trunk broken	23	4.7	12.0	19.1 ± 0.9	18.9 ± 0.9
IX	Entire tree crushed to the ground	26	5.1	13.0	18.1 ± 0.7	18.2 ± 0.7
Overall mean (or total)		100	23.9	61.4	20.7 ± 0.5	20.0 ± 0.5

mortality in the absence of stump or stem coppicing. An additional 2 trees per gap, or 8% of the damaged stems suffered from loss of three-fourths or more of the canopy, so that nearly 60% of the trees damaged by tree-fall were severely damaged (classes VII, VIII and IX), i.e. 12 trees per tree harvested. Trees severed or crushed were of intermediate diameter, mean 19 and 18 cm DBH, respectively, well below the mean DBH of trees harvested (75 cm DBH).

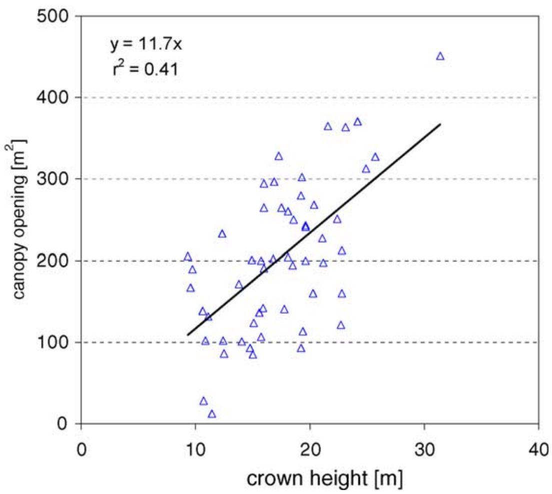

Fig. 2. Tree crown height vs. canopy opening formed during tree felling in 54 single-tree gaps in Fazenda Rohsamar, southern Amazonia, Brazil. Crown height is defined as the height from the first bifurcation to the top of the crown.

The mean canopy opening created by individual falling logged trees was 202.1 ± 12.5 m^2. The total trees killed in gaps and canopy opening was not strongly related to specific species harvested nor tree height. Rather, crown height, the difference between total height and the first bifurcation, most closely correlated with the size of the canopy opening (Fig. 2). This is because as the cut tree fell, there was little damage from the trunk, but extensive damage from the crown crashing through the forest canopy, most commonly resulting in a tear-shaped canopy gap (i.e. the gap was formed primarily by canopy damage mid-way through the fall path, rather than by loss of the logged tree canopy directly above the stump). Larger diameter trees had taller crowns ($y = 0.1x + 8.3$, $R^2 = 0.35$) and greater height ($y = 0.1x + 24.8$, $R^2 = 0.27$). There was no relationship between crown height, tree height or species and the number of stems damaged in gaps.

3.3. Skid trails

Following gaps, skid trails disturbed the greatest surface area (Fig. 1). Mean skid trail width was similar to roads, but damaged few trees (Table 2). Skidding logs damaged intermediate sized trees (mean 18.9 cm DBH) and crushed smaller trees (mean 14.0 cm DBH), but had no effect on large diameter trees nor the forest canopy. The most common damage by skidding was minor bark removal. Trees crushed under the skidder and logs being dragged

Table 2
Skid trails: stems ≥10 cm DBH damaged or crushed to the ground in Block 5 in 12 transects totaling 1100 m along trails created by skidding logged trees from gaps to consolidation decks in Fazenda Rohsamar, southern Amazonia, Brazil

	Stems damaged	Stems crushed	Total
Mean DBH of stem (cm)	18.9 ± 1.4	14.0 ± 0.5	–
No. of stems per 100 m skid trail[a]	16.5 ± 1.4	7.5 ± 0.9	24.0 ± 2.0
No. of stems per hectare logged	26.1 ± 2.2	12.0 ± 1.5	38.0 ± 3.3

[a] Mean skid width 4.0 ± 0.1 m.

represented about half the trees damaged along the skid trails.

3.4. Roads and log decks

Road construction was directly responsible for disturbing an average of 1% of the area logged (2% when including the lateral berm damage), much less than surface disturbance by gaps and skid trails. Disturbance caused by road construction was 84 m^2 the first year (Block 5) and 106 m^2 the second year (Block 18) for each hectare logged (Fig. 3). Including road shoulder area (lateral berm and trees damaged during road construction) more than doubled the total area disturbed (Table 3). Tertiary roads were only slightly narrower than primary and secondary roads, but had lower percent canopy openness, and left no discernable gap above the road (Table 4).

Total surface disturbance by log decks was similar to roads (Fig. 1). Although a greater surface area was covered by roads in 2004 than in 2003, construction of fewer decks per hectare logged reduced the area disturbed by log decks by 8% the second year of the certified harvest (Table 3). Damage to trees in gaps occurred mostly by chance and resulted in partial tree loss, while in skid trails, large trees were avoided by the skidder. Roads and log decks, however, were planned and resulted in the complete removal of all vegetation. Therefore, although the surface area disturbed is less for roads and decks, the intensity of damage is greater since no stems remain.

3.5. Canopy disturbance and leaf area

Leaf area index in October, the end of the dry season, for the undisturbed forest averaged 3.3 ± 0.1. Trees in the region are both evergreen and semi-deciduous during the dry season. All logging activities – road and deck building, skid damage and gap formation – significantly reduced LAI from undisturbed forest levels (Fig. 4). This reduction was moderately low, considering the average canopy opening (202 m^2), which the tree-fall created. Deck construction reduced LAI the greatest of all logging activities, opening the canopy by 23% compared to 6% opening in undisturbed forest. Canopy disturbance above decks produced a mean canopy gap that was 80% of the ground disturbance area. Since deck construction only accounts for 0.2% of all disturbance, this LAI reduction will have less of an effect on the forest than logged gaps, which covered a greater area. Damage caused by tree-fall in logged gaps reduced LAI by 0.9 from values measured in undisturbed forest and opened the canopy by 18%. The canopy gap opening from tree-fall represented half of the gap ground disturbance per hectare. In total, logging activities (deck and road construction, logged gaps) resulted in a 12% weighted mean canopy reduction for the forest.

3.6. Forest structure and biomass

Total biomass (276.2 ± 12.1 Mg ha^{-1}) for all trees and palms with trunks ≥10 cm DBH in the 16 belt transects representing 11.1 ha sampled was equally distributed among the tree DBH classes (Table 5). There were significantly more stems in the 10 to <30 and 30 to <60 cm DBH classes than the ≥60 class ($p < 0.001$). These values were used to compute tree loss and CWD contributions in roads and log decks.

3.7. Carbon as course woody debris

On a per hectare basis, carbon returned to the soil as CWD – severed or crushed trees – was greatest for trees killed by tree-fall, followed by the CWD of residual canopy from the logged tree (Table 6). Skid trails and decks each contributed about 8–23% of the

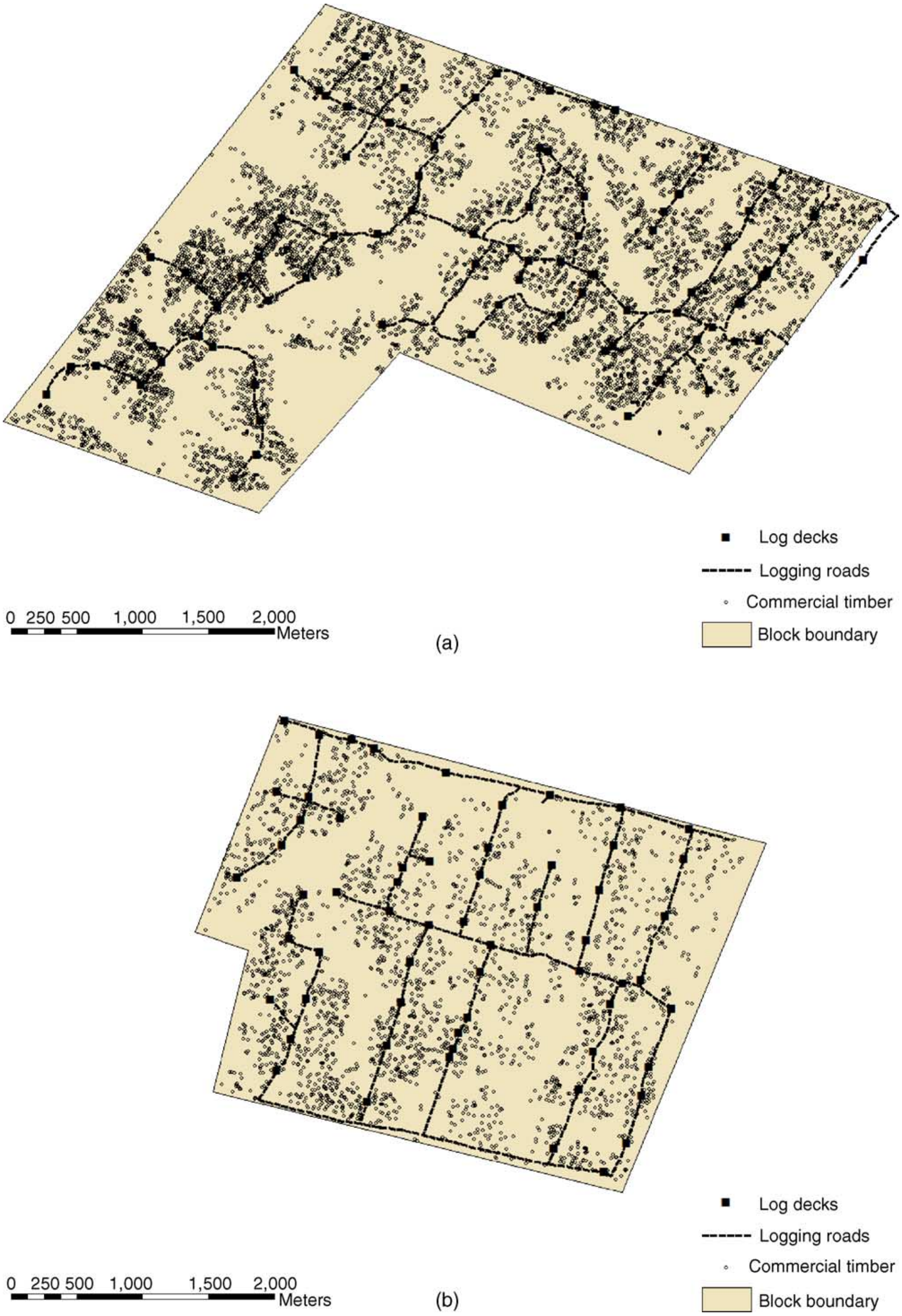

Fig. 3. Roads (- - -) and log decks (■) constructed to access trees in two management units: (a) Block 5 (1397 ha) and (b) Block 18 (1037 ha) in Fazenda Rohsamar, southern Amazonia, Brazil. Circles (○) indicate the location of individual marketable trees ≥45 cm DBH.

Table 3
Roads: total length, area and trees damaged (10–60 cm DBH) in roads constructed; Log decks: ground area disturbed, trees killed and canopy reduction (openness) resulting from log deck building in two 1000–1400 ha logging blocks in Fazenda Rohsamar, southern Amazonia, Brazil

	Block 5 (2003)	Block 18 (2004)
Roads		
Road per hectare logged (m ha^{-1})	19	24
Total road + shoulder per hectare logged (m^2 ha^{-1})[a]	200	252
Trees eliminated per hectare logged (no. of trees ha^{-1})[b]	4.3	5.4
Log decks		
Number of log decks per 100 ha logged	6.4	5.9
Mean deck size (m^2)	339 ± 31	N.D.
Mean deck canopy gap (m^2)	291 ± 44	N.D.
Deck area per hectare logged (m^2 ha^{-1})	21.6	19.9
Deck canopy opening per hectare logged (m^2 ha^{-1})	18.5	17.1
Trees eliminated per hectare logged (no. of tree ha^{-1})[b]	1.1	1.0
Canopy openness (%)	23.7 ± 1.8	N.D.

[a] Road + shoulder represents the roadbed plus the lateral berm and tree damage in the adjacent forest. Road values are based on mapping all roads in each block by GPS and length computed in ArcMap. Log deck values are mean ± S.E. (n = 10). N.D. indicates no data were available.
[b] Calculated from the area affected and the tree density for the diameter class 10–60 cm DBH based on data for the same forest.

CWD as damage in gaps from falling trees. The wood remaining from the residual canopy from each logged tree was about 60% of the wood produced as CWD from crushed or severed stems in each gap. The residual canopy, trees severed or crushed to the ground in gaps, decks, roads and skid trails returned an overall mean 6.9 Mg C ha^{-1} logged to the soil as CWD.

3.8. Total C loss via whole log export

A total of 37 species were harvested in Block 18, with 36% of the total trees harvested and 48% of the total carbon exported from the site in three of the most common species (Table 7). *Bagassa guianensis* Aubl. (Moraceae), locally called *garrote*, was harvested in the greatest quantity, followed by *Vataeropsis speciosa* Ducke. (Fabaceae) locally called *Angelim amargoso* and *Goupia glabra* Aubl. (Celastraceae) locally called *cupiúba*.

There were about 8.5 stems ha^{-1} ≥45 cm DBH in the commercial timber inventory classified as ‘‘potentially’’ marketable. Of these stems, only about 3.5 stems ha^{-1} ≥45 cm DBH could currently be sold on the market. An additional self-imposed minimum DBH restriction of ≥60 cm DBH because of low heartwood to sapwood ratio placed by Rohden Indústria on some dominant species such as *B. guianensis* and *Vataeropsis speciosa* further lowered harvest rates to 1.1–2.6 stems ha^{-1}.

Total mean C export for Blocks 5 and 18 in whole logs harvested and taken off-site was 2.1–3.7 Mg ha^{-1} logged. This corresponds to 1–3% of the total aboveground C in trees and palms ≥10 cm DBH (138 Mg C ha^{-1}). Total mean C export in boles plus

Table 4
Roads: mean (±S.E.) disturbance and canopy reduction following logging road building in Block 5 in Fazenda Rohsamar, southern Amazonia, Brazil

Road class	Road width (m)	Percent of the total roads	Road + shoulder width (m)[a]	Canopy gap (m)[b]	Canopy openness (%)
1	4.3 ± 0.2	48	10.1 ± 0.5	4.0 ± 2.7	14.2 ± 1.1
2	5.1 ± 0.2	33	9.8 ± 0.9	4.8 ± 2.3	17.0 ± 3.0
3	3.9 ± 0.3	19	11.8 ± 2.1	0	11.5 ± 2.4
Overall mean	4.5 ± 0.2	–	10.6 ± 0.6	2.9 ± 1.3	14.2 ± 1.4

[a] Road + shoulder represents the roadbed plus the lateral berm and tree damage to the adjacent forest.
[b] Canopy gap is a linear measurement parallel to and directly above the road width measurement (perpendicular to the road).

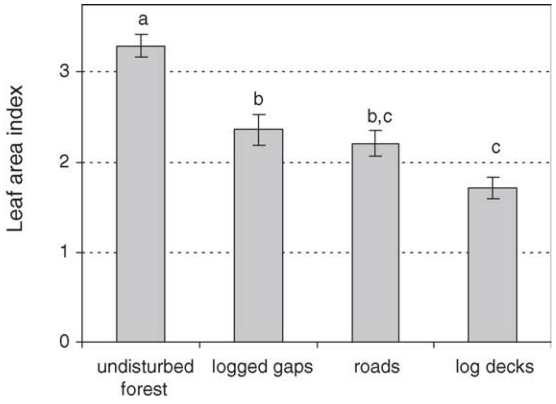

Fig. 4. Leaf area index in October, one year following selective logging in logged gaps ($n = 15$), roads ($n = 11$), log decks ($n = 10$) and adjacent undisturbed forest ($n = 50$) in Fazenda Rohsamar, southern Amazonia, Brazil. Bars represent standard error. Columns with different letters are significantly different ($p = 0.05$).

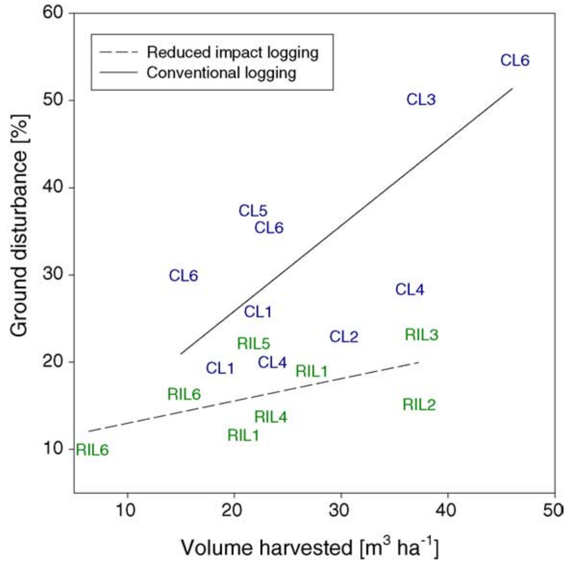

Fig. 5. Ground disturbance (%) by volume harvested ($m^3\ ha^{-1}$) under conventional and reduced impact logging. Conventional logging (CL) data from: (1) Asner et al. (2004b); (2) Johns et al. (1996); (3) Kammesheidt et al. (2001); (4) Pereira et al. (2002); (5) Hendrison (1990); (6) Jonkers (1987). Reduced impact logging (RIL) data from: (1) Asner et al. (2004b); (2) Johns et al. (1996); (3) Kammesheidt et al. (2001); (4) Pereira et al. (2002); (5) Hendrison (1990); (6) this study. Data from Pereira et al. (2002) and Asner et al. (2004b) lacked data for disturbance in tree-fall gaps; for graphing purposes, we added percent gap disturbance to their values based on the mean ratio of volume harvested to gap disturbance for all values of CL and RIL, 0.47 and 0.38, respectively.

flux as CWD from all sources of damage was 7.0–12.5 Mg C ha^{-1} logged. The mean ratio for the CWD generated from all logging phases to carbon exported from the forest as logs was 2.4 for the two blocks.

4. Discussion

4.1. Harvest intensity and damage

Gaps and skid trails represented the greatest surface disturbance but lower damage intensity than roads and log decks, where all stems are eliminated. In general, the forest of this study was harvested at rates below the limits set by RIL and forest certification. The harvest rates we report (1.1–2.6 trees ha^{-1}; 6.4–15.0 $m^3\ ha^{-1}$) were lower than RIL logging in eastern Amazonia, where rates ranged from 3 to 4.5 trees ha^{-1}, or from 23 to 37 $m^3\ ha^{-1}$ (Johns et al., 1996; Asner et al., 2002). These low harvest rates resulted in low total ground disturbance (10–16%) in the forest of our study. RIL has been reported to reduce both canopy damage and ground disturbance compared to CL (e.g. Hendrison, 1990). A review of the literature indicated total ground disturbance can vary from 13 to 55%, all at higher rates of wood volume harvested than our site. Comparing RIL to CL, RIL causes much less ground disturbance than CL, but only at higher volumes of timber extraction (Fig. 5).

When big trees fall, however, damage occurs to the surrounding vegetation, even at low harvest rates and with the aid of directional felling to minimize damage. The disturbance in road, deck area and skid area we measured (1.0, 0.2 and 4.9%, respectively) were very similar to other sites (Pereira et al., 2002) that had higher harvest rates, indicating that more decks and roads are unnecessary with increasing harvest rates. Even in the absence of additional road building, the geometry of a falling tree demands that an increase in the number of trees harvested would increase ground disturbance, placing our forests at disturbance levels found in some CL. Improved directional felling might offset some additional damage to surrounding trees at higher harvest rates; however, the physical surface area occupied by prone canopies, and thus total surface disturbance, still increases with additional tree felling.

Table 5
Forest structure and tree characteristics by DBH class for all commercial and non-commercial species of trees and palms with trunks ≥10 cm DBH for 16 transects totaling 11.1 ha in Blocks 5 and 18 for Fazenda Rohsamar, southern Amazonia, Brazil*

	10 to <30 cm DBH	30 to <60 cm DBH	≥60 cm DBH	Total	F	p
n	3950	742	133	4825	–	–
DBH (cm)						
Mean	16.3	39.3	78.6	–	–	–
S.E.	0.1	0.3	1.4			
Median	14.8	37.3	75.0			
Height to canopy (m)						
Mean	11.4 a	15.3 b	20.2 c	–	179.4	<0.001
S.E.	0.2	0.2	0.5			
Median	10.5	15.0	19.8			
Tree height (m)						
Mean	16.6 a	25.8 b	35.0 c	–	516.3	<0.001
S.E.	0.3	0.2	0.7			
Median	15.9	25.5	34.2			
Density (no. of trees ha^{-1})						
Mean	435 a	68 b	12 c	519	664.3	<0.001
S.E.	15	3	1	15		
Median	430	68	12	503		
Minimum	355	48	4			
Maximum	554	88	21			
Total (%)	84	13	2			
Biomass (Mg ha^{-1})						
Mean	89.0 a	102.3 a	84.9 a	276.2	1.7	n.s.
S.E.	2.6	5.2	10.3	12.1		
Median	89.5	103.5	78.7	278.1		
Minimum	70.9	68.0	31.2			
Maximum	106.0	35.4	151.4			
Total (%)	31	37	31			

* Values followed by different letters (a–c) indicate significant differences between DBH class (Tukey test, $p < 0.05$).

Table 6
Coarse woody debris: mean C (Mg ha^{-1}) returned to the soil as necromass following logging and damage in: (1) tree felling gap formation (trees killed by tree-fall), (2) residual canopy from the felled tree, (3) road, (4) deck construction (whole trees plowed to the ground) and (5) skid maneuvering during logging in Fazenda Rohsamar, southern Amazonia, Brazil

	Block 5 (2003)	Block 18 (2004)	Mean
Gap-trees killed by tree-fall	4.4	1.9	3.2
Gap-residual canopy	2.8	1.2	2.0
Road	0.8	1	0.9
Log decks	0.2	0.2	0.2
Skid	0.6	0.6	0.6
Total	8.8	4.9	6.9

Damage estimates for roads and log decks include only trees 10–60 cm DBH killed (larger trees were avoided during construction).

Increasing harvest intensity by harvesting additional species or reducing the minimum diameter harvested to include additional trees would increase both the number of stems damaged per hectare (Fig. 6) and total gap area per hectare logged. For example, reducing the minimum DBH logged from ≥75 to ≥60 cm would provide twice the stems available for harvest, but nearly triple the number of stem per hectare damaged in gaps of timber and non-timber species. Stems damaged in gaps would be primarily in the 10 to <30 cm DBH class (Fig. 6). Likewise, reducing the minimum DBH logged from ≥75 to ≥65 cm would more than double the gap area per hectare, but the damage would be reduced when selecting fewer marketable species. These values should be considered when estimating harvest rates and logging cycles to sustain timber yields over time.

Table 7

Timber harvest: trees logged, mean DBH, annual volume, wood specific gravity, carbon in boles exported, total carbon (bole + canopy) in trees harvested and canopy carbon that remained in the forest (Mg ha^{-1}) for 10 of 37 most common species in Block 18 in Fazenda Rohsamar, southern Amazonia, Brazil

Common name	Scientific name	Family	Logged (trees ha^{-1})	DBH (cm)	Volume (m^3 ha^{-1})	Specific gravity (g cm^{-3})[a]	C export in logs (Mg ha^{-1})[b]	Total C in trees logged (Mg ha^{-1})[c]	C in residual canopy (Mg ha^{-1})[d]	Wood density source
Garrote/tatajuba	*Bagassa guianensis* Aubl.	Moraceae	0.18	75	1.4	0.66	0.4	0.6	0.1	Nogueira et al. (2005)
Angelim amargoso	*Vataeropsis speciosa* Ducke.	Fabaceae	0.11	71	0.7	0.65	0.2	0.3	0.1	This study
Cupiúba/copiúva	*Goupia glabra* Aubl.	Celastraceae	0.11	80	0.6	0.77	0.2	0.4	0.1	This study
Caixeta/marupá	*Simarouba amara* Aubl.	Simaroubaceae	0.08	73	0.3	0.39	0.1	0.2	0.2	Richter and Dallwitz (2000)
Angelim pedra	*Dinizia excelsa* Ducke	Mimosaceae	0.08	66	0.4	0.70	0.1	0.2	0.0	This study
Jatobá/jutai	*Hymenaea* sp.	Fabaceae	0.07	75	0.3	1.03	0.2	0.2	0.1	This study
Cachimbeiro	*Couratari* sp.	Lecythidaceae	0.06	75	0.6	0.61	0.2	0.2	0.0	Richter and Dallwitz (2000)
Cerejeira/imburana	*Amburana acreana*	Fabaceae	0.06	77	0.4	0.52	0.52	0.2	0.2	IBAMA (2005)
Canela bosta	*Ocotea corymbosa*	Lauraceae	0.04	75	0.2	0.49	0.04	0.1	0.1	Nogueira et al. (2005)
Cedro rosa	*Cedrela odorata*	Meliaceae	0.04	75	0.2	0.52	0.05	0.1	0.1	IBAMA (2005)
Total (of 37 species harvested)			1.1	–	6.2	–	2.2	3.3	1.2	
Mean (of 37 species harvested)			–	75	–	0.68	–	–	–	

Total and mean values represent all 37 species harvested.

[a] Specific gravity data are defined as the oven-dry mass per unit of green volume.

[b] Carbon estimate based on volume and specific gravity measurements.

[c] Carbon estimate based on mean DBH and Eq. (1).

[d] Calculated as the difference between the volume exported in logs and the total C estimate for individual trees.

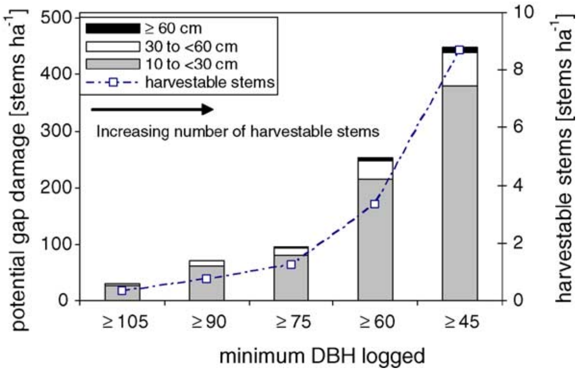

Fig. 6. Potential gap damage to surrounding stems from tree-fall and available harvestable stems based on the commercial timber inventory of stems for Block 5 (≥45 cm DBH is the minimum classified as potential timber; the mean DBH harvested was 75 cm) in Fazenda Rohsamar, southern Amazonia, Brazil. Ten percent of all timber species are protected from harvest as seed trees. Columns indicate potential stems damaged in gaps by DBH class; the dashed line shows the number of harvestable stems available for logging.

Localized timber availability may vary greatly within the forest based on topography and lowland areas. The harvest rates for our forest may appear lower than the true intensity based on harvestable area. Block area is defined by the area perimeter. A buffer zone of 50 m on each side of streams where cutting trees is prohibited reduces the harvestable area by about 25% (Feldpausch et al., in preparation). Furthermore, dense vine tangles (locally called *cipozal*) and lowland areas could additionally reduce the actual harvestable area for each block and thereby underestimate the harvest intensity of upland areas.

4.2. Changes in forest structure

Logging activities removed large diameter trees as timber, damaged intermediate and killed smaller trees. When building roads, bulldozer operators avoid large trees (>60 cm DBH) and plow down intermediate and smaller trees. Skid operators dragging logs to consolidation decks have more autonomy than bulldozer operators, with fewer restrictions on where they move, a more maneuverable machine that allows them to avoid larger trees, and rubber tires that substantially reduce soil perturbations. In tree-fall gaps, the smaller individuals were crushed prone (mean 18 cm DBH), while larger, more robust trees suffered slight or moderate damage. Such changes will alter stand competition and available light. The mortality rate is unknown as some severed stems may survive or crushed trees resprout. For logged stems, stump and root sprouting will be important for the recovery of some species (Rijks et al., 1998; Kammesheidt, 1999). Biomass in the forest prior to logging was distributed approximately evenly among each of three DBH classes, 10–30, >30–60 and >60. The death of smaller stems (<20 cm DBH) through damage and larger stems (>75 cm DBH) through logging shifts the size class in disturbed areas of the forest to a modal distribution dominated by intermediate sized stems (20–75 cm DBH).

Several methods can be used to evaluate canopy damage, for example, inverse gap fraction analysis to calculate LAI from hemispheric images as used in this study or estimated from remotely sensed imagery such as Landsat TM. Instruments such as the LI-COR LAI-2000 may be more accurate at capturing canopy structure at large plot or stand scales, while hemispheric images may be better for quantifying the distribution of canopy gaps (Rhoads et al., 2004). The LAI hemispheric method in this study was able to draw strong distinctions between types of damage – gap, log deck and road – and undisturbed forest (Fig. 3). These data could help to inform remotely sensed data and improve delineation of selectively logged forests by serving as LAI GIS training data.

Determining forest damage from Landsat ETM+ images remains difficult when the gap fraction is less than 50% (Asner et al., 2002). Johns et al. (1996) reported 10 and 19% canopy reduction in planned and unplanned logging. Log decks, the greatest concentrated disturbance we measured, occupied only 0.2% of the area and reduced canopy openness above the deck by 16%. Log decks do provide readily identifiable remotely sensed evidence of logging, but efforts have proven unsuccessful to relate log deck frequency to the intensity of logging (Asner et al., 2002). This is probably because in unplanned logging the frequency or size of decks is independent of the intensity of logging. Even in well-managed forests, however, increasing the volume harvested does not translate to more roads and decks. Our canopy reduction and ground damage estimates linked to measurements of log export provide a tool to estimate carbon turnover and export on a larger scale for other logged forests. The challenge remains to successfully relate LAI and gap fraction changes following logging to remote estimations of the intensity and area of forest disturbed.

Increased disturbance in logged areas has both positive and negative effects on forest regeneration dynamics. For example, with higher irradiance litter is dryer, promoting ground fires (Cochrane et al., 1999); vines often dominate, reducing the growth of tree species (Alvira et al., 2004); in highly disturbed areas long-lived pioneers may persist to the detriment of late successional species and seedlings planted by the timber company. Increased irradiance will also increase net primary productivity and liberate the growth of small diameter stems. Irradiance in the forest of our study will be greatest in log decks, where canopy openness increased the most relative to undisturbed forest values. Log decks are also the largest concentrated disturbance both to the soil surface and to the canopy, which create an artificially large gap above a large swath of soil removed and compacted from machinery and log placement. Scarification in gaps by skidders, however, resulted in increased commercial tree regeneration in Bolivian Amazonia (Fredericksen and Pariona, 2002).

4.3. Carbon export and turnover

Carbon exported as whole logs in the forest in our study in Mato Grosso was lower than rates observed for logging operations in Pará State (Pereira et al., 2002). The amount of timber harvested from the forest depends on sustainable harvest guidelines, but also on market demand. Prior to the mid-1980s, as few as four species were logged in some areas (Kammesheidt, 1998). Currently, the market in southern Amazonia supports at least 37 species (Table 7). As markets evolve, the volume of timber harvested will increase, resulting in greater logging intensity, C export and CWD generation.

Carbon returned to the soil as necromass (4.9–8.8 Mg C ha^{-1} logged) in gaps, roads, skid trails and decks represented 2.4 times the carbon taken off site in logs. Keller et al. (2004) reported values of 16–22 Mg C ha^{-1} for CWD in forests with much greater logging intensity (23.1 m^3 ha^{-1}) one year following logging in eastern Amazonia (their CWD classes 1–3). Adjusting for differences in harvest rates (23.1 m^3 ha^{-1} versus 6.2 m^3 ha^{-1}) indicates CWD generation was approximately equal per volume harvested between Block 18 in our study and their sites (0.8 Mg C m^{-3} harvested).

We did not estimate carbon loss in vines cut prior to logging and vines torn from the trees and killed during tree-fall, so actual C flux in CWD is higher than estimated. Vine biomass averaged about 15 Mg ha^{-1}. Given the overall area disturbed during logging (13%), the C generated in CWD from killed vines would be 0.5 Mg ha^{-1} if, for example, 50% of all vines were killed. Considered together with the pre-logging practice of vine cutting, changes in vine ecology for the forest may be great. For example, eight years after vine cutting in a RIL forest in eastern Amazonia, there was an 85% reduction in vine basal area, biomass and LAI, and a 14% reduction in vine species richness (Gerwing and Vidal, 2002).

4.4. Improving forest management

Large gains in disturbance and CDW reduction could be made by pre-harvest planning, training and improved communication on the ground. The 100% pre-logging commercial timber inventory ($\geq$45 cm DBH) and stream mapping are essential tools for forest managers to plan roads and log deck locations. Forest managers need training and access to new resources such as digital elevation models, remotely sensed imagery and GIS software to place roads and decks only were needed (Fig. 3). The RIL and FSC guidelines prescribing vine cutting as a silvicultural practice help to reduce damage (Vidal et al., 1997), but the cost of vine cutting, US$ 13.50–16.00 ha^{-1} (Johns et al., 1996; Perez-Salicrup et al., 2001), representing about 8% of profits (Vidal et al., 1997), may be prohibitive for some operations. By combining vine cutting activities with other operations, such as timber marking and stand inventories, the cost may be reduced. Furthermore, increased income from premiums paid for certified timber should help to offset the additional costs of improved logging methods.

Tree densities and location of valuable timber species vary greatly across the forest making roads and log decks unnecessary in many areas (Fig. 3). Road length, disturbance frequency and damage can be reduced by building straighter roads. Along each road, log decks can be selectively located in naturally occurring clearings to minimize disturbance, but still need to be placed near the area where trees are being felled. Reductions in disturbance by building fewer log decks from the first to the second year of certified timber harvest demonstrate the practical aspects of improving forest management.

The area of ground disturbance as gaps, relatively high considering our low logging intensity compared to other RIL operations, represented the greatest disturbance of all activities, indicating additional training may be necessary to minimize damage. Improved directional felling, the felling of trees in the bearing least likely to damage surrounding trees, could reduce damage. Stand density, however, is responsible for much of the damage sustained in gaps. Denser forests will have more stems damaged from tree-fall. Our results indicate the size of the crown controls damage more than tree height, so that forests with taller crowns, rather than taller trees will have greater damage from felling. A topic receiving little attention to date is the effect of logged tree canopy residue or ‘‘slash’’ on seedling regeneration in gaps. Canopy residue covers a substantial area of the soil in gaps, and as such, reduces the surface available for seedling regeneration. Utilization of second-grade residual canopy wood with the use of small mobile in forest sawmills could increase the volume of wood harvested with little additional forest disturbance while freeing soil surfaces for seedling regeneration in gaps.

Skid trail disturbance, 5% of the logged area and nearly identical to Pereira et al. (2002) at higher harvest rates, represents a field method that could be improved. Adequate planning and pre-marking skid trails, and better communication between the log spotter and the skid operator would reduce skidder meandering and restrict skidder movement to fewer skid trails. Skidders disturbed an area 70% of felled tree-fall gaps but produced less damage (~20%) compared to gaps. From a management perspective, skid trails can be thought of as a replacement for roads. They provide access to the felled tree, kill relatively few trees, and do not generate the damage of roads. Skid disturbance has the advantage of creating potentially beneficial disturbance that could stimulate seeding growth, without the intense damage found in gaps and log decks.

4.5. Adopting RIL and certification

An important consideration in the adoption of RIL and certification is the effect of harvesting on growth and value of residual stems. Damaged individuals have higher rates of mortality (Clark and Clark, 1991). Minimizing stand damage increases the value of future timber. For example, basal scarring during skidding and crown breaking during felling have major impacts on future growth, health and value. Furthermore, destroying versus releasing seedlings from growth constraints for the regeneration of high-value species can change future stand composition and value. Timber certification together with RIL methods has the potential to facilitate regional economic development through timber premiums and improved future harvests while mitigating C loss from total deforestation.

The benefits in terms of carbon retention of improved logging operations are only realized when the forest remains standing. Threats from fire in selectively logged forests become greater (Cochrane et al., 1999; Nepstad et al., 1999; Siegert et al., 2001) as CWD accumulates (Keller et al., 2004). Changes in the current political and social environment in the frontier regions of Amazonia would make adoption of certified RIL more favorable. Strengthened frontier management (Nepstad et al., 2002), such as reducing corruption and illegal logging, improving land tenure and forest management is needed to make RIL viable to retain forest carbon stocks. Carbon credits allocated for carbon preserved during RIL is an option to add value to the forest (Smith and Applegate, 2004). Illegal logging and bribes, as reported by timber companies in the region, are a disincentive for the companies to adhere to environmentally sustainable guidelines.

Brazil, the greatest world consumer of tropical timber, annually consumes 34 million m^3 of timber (Carneiro et al., 2002). Certified timber currently commands a very small percentage of the total timber harvested in Amazonia, with only 10 native forest and 9 plantation companies certified (Bezerra, 2004). The certified timber market is growing as international consumers seek sustainably harvested timber. This growing market provides an alternative to the domestic market and could provide important external inputs in Brazil's growing economy. The market for certified timber has nearly doubled in five years, with US$ 379 million of exports in 1998 growing to US$ 630 million in 2003 (Bezerra, 2004).

5. Conclusions

Our results contribute to a growing body of research evaluating selective logging. Although there have been several studies examining forest damage during logging, none have explicitly computed carbon budgets for all phases of the logging operation. This study provides harvest intensity, ground disturbance, residual tree damage and carbon export data to further improve estimates of the effect of certified selective logging in tropical forests of the Amazon Basin. These data also lend support to ecological, meteorological, biogeochemical, modeling and remotely sensed studies of land cover/use change in Amazonia.

Our results could improve regional estimates of carbon removed from the forest and returned to the soil as CWD for other selectively logged forests. This is important since the area of forest degraded by logging in Amazonia is nearly as great as the area deforested (Nepstad et al., 1999). Gaps and skid trails represented the greatest surface disturbance and gaps the greatest source of CWD per hectare logged. To minimize surface disturbance and damage, improvements in directional felling and communication between the log spotter and skidder operator are needed. In the absence of additional planning and training, increases in the volume harvested would increase damage from gaps and skid trails but not roads and log decks.

The sustainability of selective logging is still unknown (Pinard and Putz, 1996; Fredericksen and Mostacedo, 2000). Studies throughout the Amazon Basin indicate that RIL disturbs the forest less than CL. Comparison of our results to other studies indicates RIL results in less disturbance than CL only at higher timber volumes harvested. To reduce the environmental impact of logging and improve profits, tools need to be developed to assist forest managers in predicting the harvestable area and in planning extraction. Certified RIL methods being adopted by timber companies in Amazonia can minimize disturbance relative to CL. Disturbance reduction under RIL will occur primarily in skid trails and gaps, but only with pre-harvest planning, training of loggers, and application of RIL methodologies in the field.

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