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Future crop tree damage in a certified community forest in southwestern Amazonia

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Abstract

Field studies in Acre, Brazil assessed logging impacts of a certified community timber management project. The main objectives of the study were: (1) to determine if damage incidence to future crop trees (FCTs; $\geq$20 cm diameter at breast height (dbh)) differs between (a) forest with and without bamboo (*Guadua* spp.), and (b) trees with and without lianas; (2) to what extent harvesting can be conducted more intensely ($m^3 ha^{-1}$), without incurring greater FCT damage; and (3) to what extent marking diminishes FCT damage. Full inventories of FCTs of 50 commercial species complexes were conducted before and after logging in 50 m-radius zones of impact around each designated harvest tree in three 10 ha (200 m $\times$ 500 m) logging blocks. We also mapped all forested areas potentially influenced by logging, including skid trails, log landings and felling gaps, throughout the 30 ha logged.

More than 28% of the forest area was disturbed by logging, with 12.1% in skid trails and 16.8% in gap clearings, indicating that the forest gap mosaic can be significantly altered even when reduced-impact logging guidelines are followed. Overall, 15% of FCTs inventoried were damaged. Damage rates were not significantly reduced by marking treatment, location in bamboo-dominated forest, or liana load on FCT damage. Harvest intensity did not influence the probability of FCT damage. For future studies, it would be prudent to address impacts of timber extraction on other livelihood activities, such as non-timber forest product collection, particularly in such regions as the Brazilian Amazon, where many communities are attempting to integrate a suite of income-generating activities.

Keywords: Bamboo; Community forest management; Forest certification; *Guadua*; Liana; Marking; Reduced-impact logging; RIL; Timber management; Tropical forest

1. Introduction

The guiding principle of sustainability dictates that a commercial forest should be managed to limit as much undesirable damage as possible to the residual stand and overall ecosystem, an essential goal for both economic and ecological reasons (Müller, 1998). Unplanned (conventional) logging results in unnecessary damage to the residual forest and reduces the chances for future timber production (Pinard et al., 1995). Johnson and Cabarle (1993) estimate that 26–75% of future crop trees are injured during typical conventional logging operations.

The most common conventional harvesting method in the tropics is selective logging, whereby only certain trees of sufficient commercial value are harvested from the forest. Uncontrolled selective logging causes extensive canopy cover removal (Johns et al., 1996; Webb, 1997; Whitman et al., 1997; Pereira et al., 2002), soil compaction (Whitman et al., 1997), long-term changes in tree species composition (Molino and Sabatier, 2001; Hall et al., 2003), and reduced faunal diversity (Johns, 1991; Thiollay, 1992). In contrast, controlled selective logging, or reduced-impact logging (RIL), utilizes methods that minimize residual stand damage, such as pre-harvest inventory, mapping, directional felling, liana cutting, and planning of skid trails, log decks, and roads (Dykstra and Heinrich, 1996; Uhl et al., 1997), potentially avoiding some of the post-logging damage noted by other authors (Johns et al., 1996; Pinard and Putz, 1996).

Sustainability of harvesting will ultimately depend on the persistence of future crop trees (FCTs) for the next cutting cycle (Putz et al., 2001). Jackson et al. (2002) report that even RIL

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operations in a Forest Stewardship Council (FSC)-certified timber concession in Bolivia killed or severely damaged an average of 22 trees (≥10 cm diameter at breast height (dbh)) for every one harvested. In the same forest, Krueger (2004) found that flagging reduced damage to FCTs by 20% in felling gaps and by 10% along skid trails receiving 2–10 skidder passes, likely due to improved visibility during on-the-ground operations (Dykstra and Heinrich, 1996).

Pre-harvest cutting of lianas on crop trees is considered essential to minimize canopy and FCT damage (Fox, 1968; Appanah and Putz, 1984). On average, lianas connect each canopy tree to anywhere from three to nine others in Amazonian *terra firme* forest (Vidal et al., 1997). During tree felling, this liana connectivity can inadvertently bring down several other trees, endangering workers (Amaral et al., 1998) and creating a far larger gap than occurs when lianas associated with harvest trees are cut prior to harvesting (Appanah and Putz, 1984; Vidal et al., 1997).

Controlling harvest intensities can also reduce damage to residual trees and remaining forested areas (Webb, 1997). Low harvest intensities (few trees harvested per hectare) are common in community-based systems, and are typically considered desirable because they mimic the so-called gap-phase dynamics of the neotropical rainforest (see Brokaw, 1985) by creating small-scale disturbances around the harvested tree (Hartshorn, 1989). Localized logging intensity can vary greatly, depending on spatial and temporal factors, access, equipment, terrain, climate, supplemental treatments, and market acceptance of lesser-known species (Metzger and Schultz, 1984; Sist et al., 1998; Putz et al., 2001).

Mechanisms underlying these residual stand impacts need to be understood in the context of specific local conditions (Sheil and Van Heist, 2000). Community-based conditions are distinct from those of commercial logging operations (Salafsky et al., 1998), suggesting that silvicultural prescriptions tested under industrial settings may not be entirely applicable in smallholder operations (Rockwell et al., 2007). Similarly, commercial species distribution and forest types vary greatly between neotropical regions, such that logging guidelines and silvicultural treatments must be locally-tailored (Putz, 1996).

One forest type receiving little attention is the bamboo-dominated forest of southwestern Amazonia, which covers almost 180,000 km^2 (Griscom and Ashton, 2003). This forest is characterized by a mix of structurally heterogeneous stands without bamboo and patches of trees scattered within dense stands of *Guadua* species (Griscom, 2003). Bamboo-dominated stands are important habitat for many valuable wildlife species, making them focal areas of interest for conservation efforts (Griscom, 2003). Similar to other mast seeding bamboo taxa (Janzen, 1976), some species of *Guadua* undergo a single synchronized reproduction event followed by synchronized mortality, at 25–30 year intervals (Nelson et al., 2001; Nelson and Bianchini, 2005). At least two species, *G. sarcocarpa* and *G. weberbaueri*, have been associated with reduced forest basal area (as compared with neighboring forest patches without bamboo), diminished tree species richness (Silveira, 2001; Griscom, 2003), and increased likelihood of blow-downs (Griscom and Ashton, 2003). If *Guadua* achieves dominance in managed forests, it may competitively exclude commercial tree species and a substantial proportion of the remaining stems may become deformed, due to mass loading (Griscom, 2003; Griscom and Ashton, 2006). Low visibility in some areas of the bamboo-dominated forest also presents an impediment to sawyers trained in directional felling (F. Correa da Cunha, pers. comm.). Combined, these factors present unique challenges for timber management and extraction in bamboo-dominated forest, an ecosystem that many community enterprises cannot avoid.

We evaluated logging damage to FCTs in a certified community forest in Acre, Brazil. To date, few studies have focused on logging damage in smallholder forests and none (to our knowledge) have examined the effects in bamboo-dominated forests. The main objectives of the study were to determine (1) if damage incidence to FCTs (≥20 cm dbh) differs between (a) forest with and without bamboo (*Guadua* spp.), and (b) trees with and without lianas; (2) to what extent harvesting can be conducted more intensely (m^3 ha^{-1}), without incurring greater FCT damage; and (3) to what extent marking diminishes FCT damage.

2. Site description

The Porto Dias Agroextractive Settlement Project (PAE) (S 10°00′40″, W 66°46′26″) is situated in the northeastern corner of the Brazilian state of Acre, and is separated from Bolivia by the Abunã River. The site is defined by red–yellow latisols of low fertility and relatively flat topography, with average annual precipitation of 1890 mm year^{-1}, most of which falls between November and March (Santos, 2000). Three tropical humid *terra firme* forest types are generally recognized in Porto Dias: open canopy forest; open canopy forest mixed with arborescent bamboo (*Guadua* spp.); and closed canopy forest. Three species of *Guadua* are found in the study site: *G. weberbaueri*, *G. sarcocarpa*, and one as-yet unnamed species, which occurs in riverine forest along the Abunã River (M. Silveira, pers. comm.). At the end of 2004, when logging operations commenced, *G. sarcocarpa* underwent a monocarpic dieoff that affected much of the study area.

Porto Dias encompasses approximately 22,145 ha, and is divided among *colocações*, or individual family landholdings organized around pre-existing rubber trails (roughly 300 ha each). Cash has been customarily earned from harvest of *Bertholletia excelsa* (Lecythidaceae; Brazil nut) and *Hevea brasiliensis* (Euphorbiaceae; rubber), but in recent years families have turned to logging as an alternative income source. The Center for Amazonian Workers (CTA), a local non-governmental organization, has been instrumental in developing the management framework of the Multiple-Use Community Forest Management Project, initiated in 1995, with the first timber harvested in 2000. The Institute of Forestry and Agricultural Management and Certification (IMAFLORA), a formal partner of the U.S.-based Rainforest Alliance's SmartWood Program, certified the logging operation using FSC criteria in 2002, distinguishing it as the second FSC-certified community timber management project in Brazil. One current condition for retaining certification is implementation of a special monitoring program in bamboo-dominated forests. Resident landholdings serve as the timber management areas, and in compliance with federal regulations, only 10% may be cleared for agricultural activities and 5% must be set aside for preservation (no harvesting of trees). Thus, most timber project members have at least 255 ha available for timber management, of which 10 ha is harvested in a given year, resulting in a 25-year logging rotation.

3. Methods

3.1. Forest management and harvesting operations

One year prior to harvest, tree species ≥35 cm dbh were mapped in each logging block. After crop tree selection, an annual operating plan was submitted to the Brazilian Institute of the Environment and Renewable Resources (IBAMA), which reviewed the plan to ensure compliance with federal standards (e.g., acceptable basal area removed, minimum diameter cut of ≥45 cm dbh, desired residual stand species distribution, and crop tree proximity to water sources). Logging is generally carried out in the driest part of the year, and in 2004 was conducted between October and November. Approximately 12–16 major timber species are harvested in Porto Dias (Table 1) at a low cutting intensity (1–3 trees ha^{-1} or approximately 10 m^3 ha^{-1}). Sawn board and artisan products from the community sawmill are primarily sold to the domestic certified market in southern Brazil.

Project members, extensively trained in RIL techniques, carried out inventories, selection of crop trees, assessment of defects in crop trees, directional felling, and skid trail planning. Skidding was the only logging activity contracted to outsiders, although each landowner flagged skid trails to be used by the tractor operator. Pre-existing skid trails were also re-opened to access new areas that were located next to previous logging blocks. An agricultural tractor (Valmet 128) that had been adapted for skidding operations was used to extract logs (E. Araújo, pers. comm.). All three logging blocks were located close to existing roads, so boles were eventually skidded to log decks adjacent to these routes.

3.2. Experimental design and pre-logging inventory

The greatest amount of FCT damage during logging occurs in areas closest to felled crop trees and skid trails (Johns et al., 1996). Therefore, observations of logging impacts were concentrated in a 50 m radius (hereafter referred to as ‘‘zone of impact’’) around each designated harvest tree in each of the 10 ha (200 m × 500 m) logging blocks in three landholdings scheduled for 2004–2005 harvest (Barrinha I, Barrinha III and Palestina). A full inventory of all commercial FCTs ≥20 cm dbh was conducted in the zones of impact. Fifty tree species or species complexes (i.e., a group of congeners whose taxonomy is currently unresolved) were selected for study based on their potential importance as commercial timber sources (Table 1; Ribeiro et al., 1999; Lorenzi, 2000). Due to external market demands, however, only a subset of these species are exploited on a regular basis in Porto Dias, most commonly *Amburana cearensis*, *Cedrela* spp., *Peltogyne* spp., *Dipteryx* spp., *Apuleia leiocarpa*, *Tabebuia* spp., *Aspidosperma vargasii*, and *Hymenaea intermedia*. For our study, the definition of FCTs was broadened to account for all species of commercial timber value, both current and future (Table 1). When proper field identification was questionable, species were verified at the Federal University of Acre herbarium in Rio Branco, Acre, Brazil.

Sample sizes in the logging blocks (i.e., the number of zones of impact) depended on the abundance of crop trees, with a total of 18 zones of impact and 161 FCTs in Barrinha I, 20 zones of impact and 216 FCTs in Barrinha III, and 12 zones of impact and 109 FCTs in Palestina. In 2004, before logging operations commenced, the following data were noted for FCTs: species, location (x, y coordinates), dbh (diameter at 1.3 m or above the buttresses).

3.3. Area disturbed

All primary and secondary skid trails and treefall gaps were mapped using a compass and meter tape. The size of treefall gaps was estimated using the ‘‘center-point’’ system (modified from Runkle, 1992). From a point in the approximate center of each treefall gap, compass angles in eight different directions were measured to the edge of intact canopy (Johns et al., 1996). This information was then entered into ArcGIS 9.0 (ESRI, Redlands, CA), to calculate area of the resulting polygon. The ground area transformed by the total length of skid trails was determined using modified methods from Johns et al. (1996), with skid trail width measured at the beginning and end of each straight segment of trail. Trail width measurements were also taken at each bend to account for potential tractor maneuvering. This information was then combined with total skid trail length (estimated using pre-harvest inventory maps) in ArcGIS 9.0.

3.4. Description of FCT environment

Zones of impact (both in areas of high and low harvest intensity) naturally fell in locations where bamboo was present and in areas where it was absent. Location in bamboo-dominated stands was positive when at least one culm of *Guadua* spp. was located within 2 m of the FCT trunk (adapted from Griscom and Ashton, 2003). Liana occurrence was positive when at least one liana (≥1 cm dbh) connected to the FCT canopy. No lianas were cut prior to logging operations. To detect harvest intensity impacts, zones of impact were established in locations scheduled to receive a locally high cutting intensity (≥3 trees ha^{-1}), and also in areas of locally low intensity cutting (1–2 trees ha^{-1}). This design allowed for establishing a harvest intensity gradient in each logging block, but did not necessarily allocate the treatments evenly across the logging blocks, because the abundance and distribution of crop trees varied greatly between landholdings.

Table 1
Commercial timber species inventoried during 2004 logging operations in the PAE Porto Dias, Acre, Brazil. For those species harvested in 2004, total raw volume harvested is given. Nomenclature follows Killeen et al. (1993)

Scientific name	Common name	Family	Total volume harvested (m^3)[a]
Astronium Jacq sp.	Aroeira preta	Anacardiaceae	
Astronium lecointei Ducke	Aroeira	Anacardiaceae	1.8
Aspidosperma C. Martius & Zucc. sp.	Carapanaúba amarela	Apocynaceae	
Aspidosperma megalocarpon Müll. Arg	Carapanaúba preta	Apocynaceae	
Aspidosperma spp.	Pereiro	Apocynaceae	
Aspidosperma vargasii A. DC.	Amarelão	Apocynaceae	9.7
Geissospermum Allemao sp.	Quariquara amarelo	Apocynanceae	
Jacaranda copaia (Aubl.) D. Don	Marupá	Bignoniaceae	
Tabebuia cf. impetiginosa (C. Martius ex DC.) Standley	Ipê roxo	Bignoniaceae	
Tabebuia Gomes ex DC. spp.	Ipê amarelo	Bignoniaceae	2.9
Tetragastris altissima (Aubl.) Swart	Breu vermelho	Burseraceae	
Amburana cearensis (Allemao) A. C. Smith	Cerejeira	Fabaceae	56.6
Andira A. L. Juss. spp.	Angelim branca	Fabaceae	
Apuleia leiocarpa (Vogel) J. F. Macbr.	Cumaru cetim	Fabaceae	23.4
Copaifera cf. *langsdorfii* Desf.	Copaiba preta	Fabaceae	
Copaifera L. sp.	Copaiba branca	Fabaceae	
Diplotropis cf. purpurea (Rich.) Amshoff	Sucupira preta	Fabaceae	
Dipteryx Schreber sp.	Cumaruzinho	Fabaceae	6.1
Dipteryx spp.	Cumaru ferro	Fabaceae	65.0
Enterolobium cf. schomburgkii (Benth.) Benth.	Fava orelhinha	Fabaceae	7.7
Hymenaea intermedia Ducke	Jatobá	Fabaceae	
Hymenaea L. sp.	Jutaí da folha grande	Fabaceae	
Hymenaea parvifolia Huber	Jutaí	Fabaceae	19.5
Hymenolobium Benth. sp.1	Angelim da mata	Fabaceae	
Hymenolobium Benth. sp.2	Angelim pedra	Fabaceae	
Hymenolobium Benth. sp.3	Favela preta	Fabaceae	
Hymenolobium cf. excelsum Ducke	Angelim preto	Fabaceae	14.1[b]
Martiodendron elatum (Ducke) Gleason	Pororoca	Fabaceae	
Myroxylon balsamum (L.) Harms	Bálsamo	Fabaceae	2.5
Parkia pendula (Willd.) Benth. ex Walp.	Angico vermelho	Fabaceae	
Peltogyne Vogel sp.	Roxinho da folha grande	Fabaceae	
Peltogyne spp.	Roxinho	Fabaceae	
Vatairea Aubl. sp.	Sucupira amarela	Fabaceae	
Mezilaurus itauba (Meissner) Taubert ex Mez	Itaúba	Lauraceae	
Cariniana Casar sp.	Tauarí churu	Lecythidaceae	
Couratari Aubl. spp.	Tauarí	Lecythidaceae	
Carapa guianensis Aubl.	Andiroba	Meliaceae	
Cedrela fissilis Vell.	Cedro branco	Meliaceae	1.7
Cedrela odorata L.	Cedro rosa	Meliaceae	4.4
Brosimum uleanum Mildbr.	Manitê	Moracae	9.4
Clarisia racemosa Ruiz & Pavon	Guariúba amarela	Moraceae	
Minquartia guianensis Aubl.	Quariquara branca	Olacaceae	
Manilkara Adans. spp.	Maçaranduba	Sapotaceae	6.5
Pouteria cf. reticulata (Engler) Eyma	Abiurana preta	Sapotaceae	
Pouteria Aubl. sp.1	Abiurana roxo	Sapotaceae	
Pouteria Aubl. sp.2	Abiurana abiu	Sapotaceae	
Simarouba amara Aubl.	Marupá preto	Simaroubaceae	
Qualea cf. tesmanni Mildbr.	Catuaba	Vochysiaceae	3.5
Vochysia Aubl. sp.	Cedrinho	Vochysiaceae	
Vochysia spp.	Guaruba	Vochysiaceae	

[a] Volume was estimated on the log landing after harvest using a cone formula based on length, and basal and apical diameter.
[b] Volume recorded under one common name, but likely reflects more than one species of *Hymenolobium*.

3.5. Marking treatment

About half of all inventoried FCTs in each of the four logging blocks were marked with a single band of orange paint 20 cm wide at approximately 1.7 m above the ground (adapted from Krueger, 2004). All FCTs within the zone of impact of each targeted harvest tree were either marked or left unmarked, stratifying the treatment between regions of low and high crop tree density (Fig. 1). We chose not to randomly assign the marking treatment because the highly visible presence of even one marked FCT in the vicinity of unmarked FCTs could induce the logging crew to alter their

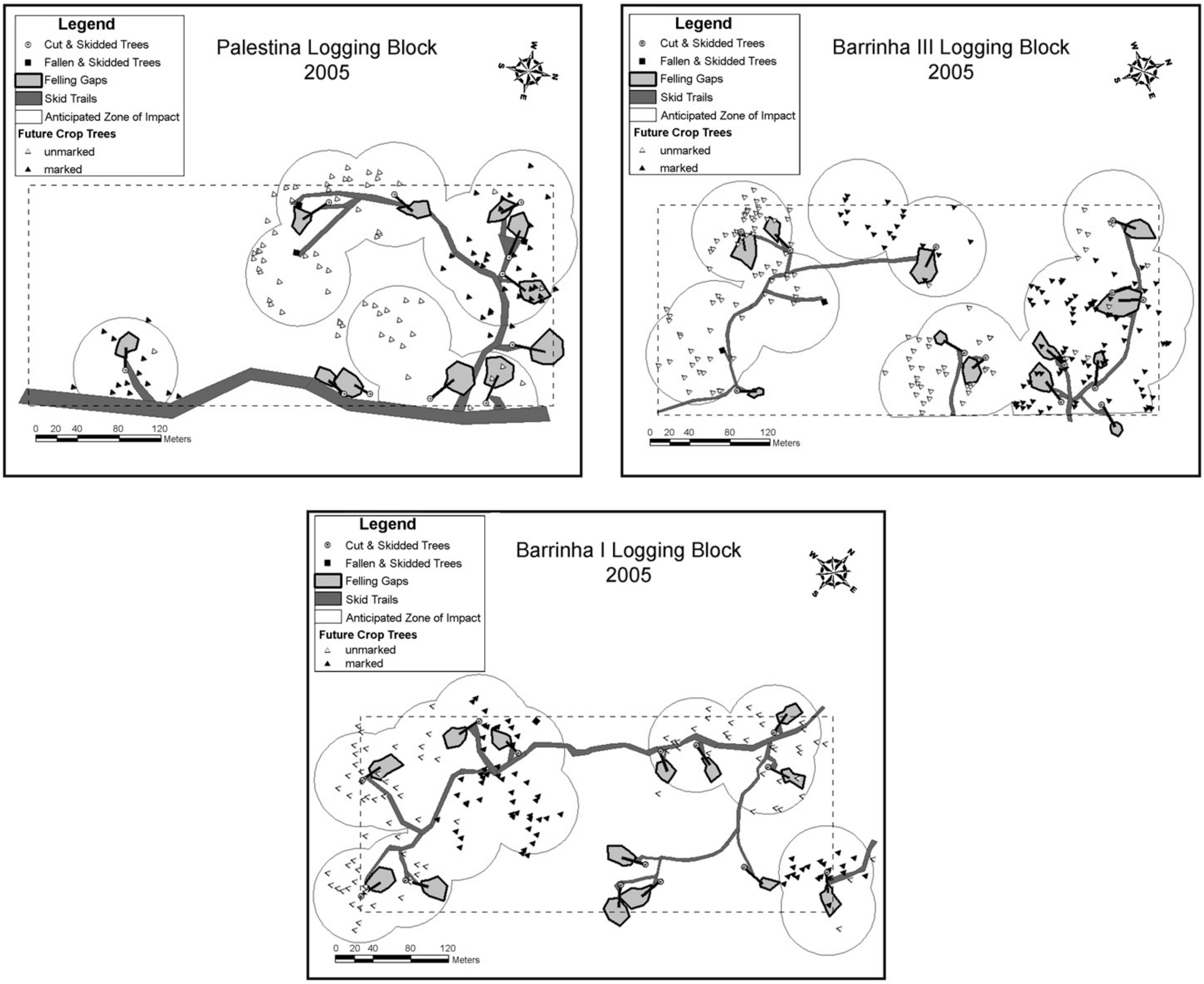

Fig. 1. An illustration of the three 10-ha logging blocks and 50 m zones of impact in which future crop tree (FCT) inventories were conducted. Marked (dark) and unmarked (light) FCTs are indicated by triangles. Logging impacts including felled and fallen harvested trees, and mapped harvesting gaps and skid trails, are shown as depicted in the legends.

activities in some way as to favor neighboring FCTs. This potential source of bias suggests that statistical independence of the FCT treatments would have been difficult to achieve with either experimental design choice.

3.6. Assessment of FCT damage

Inventory data were used to construct a spatial database in ArcGIS 9.0. For each FCT, distance to nearest felled tree, nearest gap edge and nearest skid trail were measured. Harvest intensity was estimated for each FCT (trees ha^{-1}) as the volume exploited in the surrounding 1 ha (circumscribed by a radius of 56.4 m). Local FCT density was estimated as all FCTs $\geq$20 cm dbh within a 25 m radius of a given FCT. This measurement was included to control for variation explained by local density when testing for other factors such as marking. Seven months after logging activities were completed, in June and July 2005, all previously inventoried FCTs were revisited and classified according to levels of damage or mortality (Table 2).

3.7. Statistical analyses

Two primary statistical analyses were completed for this study. An ANCOVA analysis was performed to determine the influence of crop tree dbh and crop tree species identity on felling gap area; and a logistic regression was performed to quantify FCT damage as a function of several tree- and forest-level variables. Differences were considered significant at $P < 0.05$.

In the logistic regression, the binary response variable (damaged/not damaged) was modeled as a function of liana presence, marking treatment, and presence/absence of bamboo.

Table 2
Classification of damage sustained by FCTs (future crop trees) during logging operations (modified from Jackson et al., 2002 and Krueger, 2004)

Damage type	Bole	Root	Crown
Severe	Snapped at base, bent or leaning	Uprooted	Loss $\geq$66% crown
Moderate	Exposed cambium	Exposed cambium tissue	Loss 33–66% crown
Minor	Bark scrape	Root scrape	Loss $\leq$33% of crown

A series of independent variables were also assigned as covariates to each FCT: local harvest intensity, distance to nearest felled crop tree, distance to nearest skid trail, distance to nearest gap, and neighborhood FCT density. There was some overlap between the original zones of impact, since in several instances, a 50 m radius naturally encompassed neighboring crop trees. Because the closest crop tree to each FCT was determined using ArcGIS 9.0, the overlap of zones did not pose a problem for analysis.

As the presence of logging damage was observed multiple times for each harvested tree, observations associated with each harvested tree are not necessarily independent. Correlated response data violate the assumption of independent observations necessary in regression analysis, which can inflate F-tests and lead to incorrect declarations of significant effects. Models can be modified, however, to account for this correlation by explicitly testing for and then incorporating a correlative relationship between observations into the error covariance matrix. Since data were spatially mapped, we first investigated the possibility of spatial autocorrelation by analyzing semivariograms of the damage data using the SAS procedure PROC VARIOGRAM (Version 8.2, SAS Institute, 2002). The semivariogram measures the variation between pairs of observations as the distance between them increases. Because model effects may sometimes mask spatial effects, semivariograms were calculated on both the raw data and residuals from a full model (incorporating all effects and interactions). These analyses showed no evidence of a spatial relationship. Instead, to account for the correlation associated with multiple measurements, the error covariance matrix was partitioned to include both experimental and sampling error using the SAS procedure PROC GLIMMIX (Version 9.1, SAS Institute, 2005). PROC GLIMMIX fits generalized linear mixed models, where the response variable is non-normal and/or correlated. Logging damage was modeled as a binary variable using a Logit link function. The error covariance structure was defined so that observations were grouped, treating the harvested trees as subjects. This ensured that the fixed effects in the model were tested using the appropriate error term and reduced degrees of freedom.

4. Results

4.1. Overview of the logging operation

A total of 22.3 ha were sampled in the three logging blocks (Fig. 1). Forty-five trees were harvested from all landholdings, with 38 actually cut and 7 that had blown down at least one

Table 3
Summary of harvesting impacts in 2004 for the three 10-ha logging blocks at PAE Porto Dias, Acre, Brazil

Impact variable	Barrinha I	Barrinha III	Palestina
Area sampled (ha)	8.0	8.4	5.8
Harvest density			
Number of harvested trees ha^{-1}	1.5	1.6	1.4
Percent of harvested trees $\geq$70 cm dbh	27	50	64
Volume harvested (m^3 ha^{-1})	7.6	8.5	7.7
Disturbance dimensions			
Number of logging gaps	14	13	11
Felling gap area (excluding bole) (m^2 ha^{-1})	545.6	433.4	476.6
Proportion of area damaged due to felling gap (excluding bole) (%)	5	4	5
Mean gap size $\pm$ SD, excluding bole (m^2)	389.7 $\pm$ 119	361.2 $\pm$ 249	433.3 $\pm$ 167
Skid trail area (m^2 ha^{-1})	519.4	318.6	347.0
Proportion of area damaged due to skid trail (%)	5	3	4
Total area damaged (ha)	1.15	0.83	0.89
FCT damage rate			
Total number of damaged FCTs	18	37	15
Basal area of damaged FCTs (m^2)	0.34	0.63	0.48
Proportion of FCTs damaged (%)	12	17	15
Frequency of damage categories (%)			
Minor or moderate crown, bole, or root damage	78	70	80
Severe crown damage	6	11	0
Severe bole damage	22	24	7
Severe root damage	6	3	27

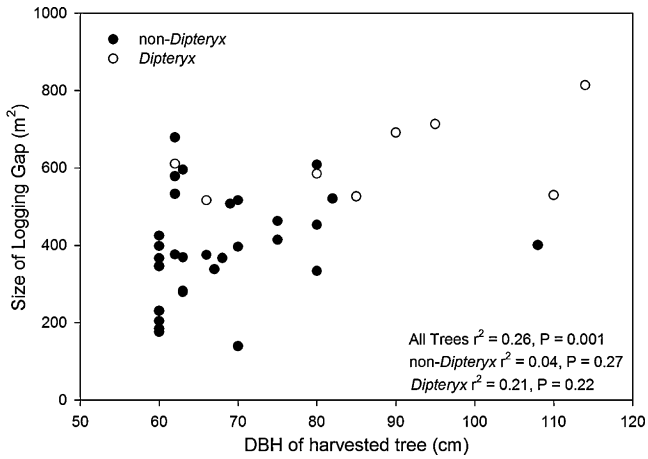

Fig. 2. Relationship between the size (dbh) of crop trees and the surface area of the corresponding logging gap created during felling. Crop trees of *Dipteryx* spp. were distinguished in the analysis because they comprised all but one harvested tree with dbh > 85 cm and because they tend to have large crown areas even at smaller stem diameters. The effect of crop tree size on logging gap surface area is not significant when the identity of *Dipteryx* trees is distinguished in the analysis.

Table 4
Results of a logistic regression for the probability of damage to future crop trees (FCTs) at Porto Dias, Acre, Brazil during 2004 logging operations

Effect	*F*-value	Pr > *F*
Liana presence	2.83	0.1025
Marking treatment	0.53	0.4827
Location in bamboo	0.01	0.9267
Liana*Marked	0.94	0.435
Liana*Bamboo	0.26	0.6461
Local felling intensity	0.68	0.6112
Neighborhood FCT density	0.5	0.4796
Distance nearest stump	1.7	0.1927
Distance nearest skid trail	**26.67**	**<.0001**
Distance nearest felling gap	**17.53**	**<.0001**

Shown are the estimates for five continuous covariates, including distance to nearest stump, felling gap, and skid trail, neighborhood FCT density (number of stems within a 25 m radius) and local felling intensity (number of trees felled in the surrounding hectare); and for three categorical independent variables, including liana presence, location in bamboo-dominated forest, and marking treatment. Interactions between liana presence and marking treatment, as well as between liana presence and location in bamboo-dominated forest, were also estimated. Statistically significant variables at $P < 0.05$ are shown in bold.

year prior to harvesting, for a total harvested volume of 237.7 m^3, or 7.9 $m^3\ ha^{-1}$. Felled trees ($n = 38$) ranged from 60 to 114 cm dbh, with a mean and standard deviation of 71.7 ± 14.7 cm dbh. Average harvested tree density was approximately equal between the three logging blocks (Table 3). Some trees originally selected were not cut for various reasons (usually they were found to be hollow prior to harvesting). Thus, previously-marked FCTS ($n = 18$) near these individuals were eliminated from the analyses. Similarly, damaged FCTs near crop trees that were selected at the last minute to substitute for lost volume of hollow trees were not included in the analyses, because no pre-logging data were gathered for them.

4.2. Area disturbed

The percentage of total sampled area affected by harvesting was 28.9%, with the majority in felling gaps (16.8%). Average area per felling gap amongst all three logging blocks (mean ± S.D.) was estimated to be 393 ± 181 m^2. Although a general trend among cut trees showed an increase in the area of single treefall gaps with larger crop tree dbh, this result was confounded by the effect of the large-crowned *Dipteryx* spp. crop trees (Fig. 2). In fact, the ANCOVA analysis revealed that *Dipteryx* crop trees of all sizes tend to make larger gaps ($F_{1,35} = 8.1$, $P = 0.007$), and since they account for all but one harvested tree with dbh ≥ 85 cm, the true effect of crop tree dbh is not significant ($F_{1,35} = 2.6$, $P = 0.12$). Skidding damaged 11.8% of the total surface area (Table 3), or 263 m^2 per bole removed.

4.3. FCT damage

A total of 70 FCTs out of 468 (15%) were damaged during logging operations. The most common damage types were slightly broken crowns, followed by scraped boles and roots, classified as "minor" damage (Table 3). The proportion of trees damaged by felling and skidding was about the same.

Marking did not significantly reduce overall FCT damage in the Porto Dias operations (Table 4). Furthermore, the incidence of FCT damage levels was not higher in bamboo-dominated forest, nor was there a significant interaction between FCT presence in a bamboo-dominated stand and the marking treatment (interaction term in Table 4). Fifty-six percent of the inventoried FCTs carried lianas, but damage probability due to liana presence on the FCT was not highly significant ($P = 0.1025$) even though many damaged FCTs had at least one large liana attached to their crowns (67%).

The closer a FCT was to a skid trail or logging gap, the greater the likelihood of damage (Table 4). In contrast, distance to cut stump and local FCT neighborhood density had no significant effect nor did harvest intensity influence the probability of FCT damage.

5. Discussion

5.1. Area disturbed and FCT damage

Timber harvesting, as conducted by the Multiple-Use Community Forest Management Project in PAE Porto Dias, had minimal impact on FCTs ≥20 cm dbh, damaging only 15% compared with 26–75% injured during conventional logging operations (Johnson and Cabarle, 1993). Reported FCT damage in other neotropical RIL studies is variable: in his study in La Chonta, Bolivia, Krueger (2004) determined that RIL operations damaged 30% of the FCTs in the 30–50 cm dbh size class. Additionally, Webb (1997) found that 18% of FCTs (≥10 cm dbh) were damaged in his assessment of RIL operations in Costa Rica. Potential disturbance was also avoided by not constructing new log landings and log roads.

Even so, total operational disturbance was high in both skid trails and felling gaps. Values for felling gap area per tree cut were in some cases almost twice that of other reported neotropical studies (see Johns et al., 1996; Feldpausch et al., 2005). In many instances, large gap sizes were explained by the crown size of the trees that were felled. One of the most valuable taxa in Porto Dias, *Dipteryx* spp., tends to have larger crown areas even at relatively small diameters; accordingly, our analysis demonstrated that felling of these trees resulted in most of the larger gaps (Fig. 2). Forest managers might do well to consider the tradeoffs between creating a very large gap (thereby potentially increasing fire and windthrow risk) from large diameter and large-crowned trees and the substantial profit obtained for large wood volumes.

5.2. Impact of marking treatment on FCT damage

Despite positive results of marking FCTs in at least one other study (Krueger, 2004), marking did not reduce FCT damage in the Porto Dias timber operation ($P = 0.4827$). That FCT marking had no effect on damage levels along skid trails was surprising, given that machine operators were from outside the community and therefore not as familiar with the forest. In our study, however, each local landowner was responsible for flagging skid trail paths (independent of the marking treatment) prior to extraction. Given their intimate knowledge of the forest, perhaps they tended to select trails that would cause the least FCT damage, explaining why the marking treatment itself had no detectable effect on FCT damage. As well, most logs were bucked to about 5 m prior to skidding, perhaps avoiding some of the damage that occurs when tree-length logs are skidded. Finally, two local experienced sawyers who have lived for many years in Porto Dias were also in charge of felling operations, adding to the operation's effectiveness.

5.3. FCT damage in bamboo-dominated forest

We expected higher FCT damage rates (due to low visibility) in bamboo-dominated forests, but results proved otherwise (Table 4). One possible explanation for this unanticipated outcome is that FCT damage was minimal simply because there were fewer FCTs to damage in the bamboo-dominated forests. In Madre de Dios, Peru, Griscom and Ashton (2003) reported over eight times lower average tree basal area (trees $\geq$10 cm dbh) in bamboo-dominated forest plots as compared with adjacent forest plots without bamboo. It was also uncertain as to how the synchronized mortality of *G. sarcocarpa* may have directly or indirectly affected felling operations since visibility may have improved in these stands when dead bamboo culms dried out and collapsed.

Even though location in bamboo-dominated stands did not significantly increase probability of FCT damage, the potential for other types of long-term residual stand damage in these forest types warrants future investigations. Increased light levels were observed (but not measured) in post-logging bamboo-dominated forest, likely due to loss of the biggest canopy trees in the block, of which there were few to begin with. Opening gaps in bamboo-dominated forest increases the chances of repeated small-scale disturbances, such as windthrow and fire (Webb, 1997). In turn, since *Guadua* benefits from disturbances, once a gap is opened, it tends to proliferate, competitively excluding the majority of tree stems (Griscom, 2003). One example of this phenomenon is the reduced value of Malayan forests invaded by arborescent bamboo after unplanned logging operations (Whitmore, 1984). Furthermore, bamboo-dominated stands are already generally characterized by a discontinuous canopy, which may amplify effects of openings created by logging activities. For future operations, in bamboo-dominated forest, managers may want to select crop trees based on the presence of large neighboring trees, ensuring that some sort of basic canopy structure is kept intact around the logging gap. Additionally, managers may want to experiment with post-logging release treatments around individuals of desired commercial species, since neighboring bamboo culms are likely to be a great source of below- and aboveground competition. Also, given that this forest type is characterized by reduced basal area in comparison with other systems, it may be advisable to avoid timber extraction as much as possible in these locales.

5.4. Impact of lianas on FCT damage

We expected lianas to increase FCT damage, but we did not observe significant effects ($P = 0.1025$). Other neotropical studies (see Johns et al., 1996; Vidal et al., 1997), have demonstrated increased damage during logging operations when lianas were not cut from trees to be harvested, principally due to a domino-like effect. In our case, we compared damage frequency between trees associated with lianas and those that were not, which is different than those previous studies that compared trees associated with cut and uncut lianas. The latter method establishes with more certainty the positive implications for cutting lianas, while our method merely draws a correlation between logging damage and tree/liana associations. Even so, we noticed parts of trees crowns pulled down by tractors as they moved through the forest. This observation suggests that even though results were not statistically significant, given results in other studies, it is probable that the magnitude of the outcome is biologically consequential. If lianas associated with FCTs had been cut at least one year prior to harvesting, other research suggests that some of this damage could have been avoided (Appanah and Putz, 1984).

Still, Porto Dias forest managers have expressed reluctance to cut lianas prior to the felling cycle (C. Rockwell, *pers. obs.*), citing their importance as a food source for wildlife species. Since benefits of cutting lianas prior to logging may be site-dependent (Parren and Bongers, 2001), local forest managers could experiment with this particular RIL guideline before making a final decision as to pre-harvest silvicultural prescriptions, particularly given the multiplicity of forest resources valued in the non-industrial forest setting.

5.5. Impact of harvest intensity on FCT damage

Harvest intensity seemingly had no effect on residual stand damage (trees ≥20 cm dbh), even when the maximum harvest intensity (4 trees ha^{-1}) was reached. This type of low intensity selective logging is attractive for conservationists espousing implementation of sustainable forest management as a way to limit canopy cover loss and protect ecosystem function and biodiversity (Whitman et al., 1997). Gullison and Hardner (1993) note that as the number of trees removed increases, fewer new skid trails are required (although the damaged area per tree due to logging gaps remains constant). In a recent study, it was determined that RIL causes much less ground disturbance than conventional logging, but only at higher volumes of timber extraction (Feldpausch et al., 2005). In our case, however, while highest harvest intensities caused no additional damage to FCTs, average area damaged per tree harvested due to skid trail construction (relative to the number of trees harvested per hectare) was high compared with other neotropical studies. Johns et al. (1996) found that unplanned logging operations using a tractor to skid trees damaged 119 m^2 per bole (versus 263 m^2 in our study), with an average harvest intensity of 5.6 trees ha^{-1}. The higher levels of area damaged per tree harvested in our study suggest that there might be a tradeoff associated with harvesting isolated trees across even a relatively small area of 10 ha, both in terms of cost and as a function of area and trees damaged.

One way to offset damaging a larger area when implementing low intensity harvests would be to increase localized harvest intensity at a fixed volume (in Brazil, smallholders with ≤500 ha are allowed to extract 5 trees ha^{-1}) (Hirakuri, 2003). By concentrating harvested trees in smaller areas, one would expect reduced mortality of smaller size classes as well as fewer skid trails (Panfil and Gullison, 1998). Still, increasing localized harvest intensities would likely create larger gaps, allowing more solar radiation to reach the forest floor, drying remnant organic matter and increasing the amounts of fuel in post-logging sites (Johns et al., 1996). Furthermore, release thresholds of pioneer species, lianas and bamboo in larger gaps are unknown (although conditions might be ideal for regeneration of gap-loving species such as *Swietenia macrophylla* (Meliaceae; mahogany) (Panfil and Gullison, 1998). As such, the implementation of increased localized harvest intensity is risky, especially for a landowner limited to a management unit of 300 ha.

5.6. Impact on other livelihood activities

In our study, locally important non-timber forest product (NTFP) taxa such as Brazil nut and rubber were not tallied during the original inventories, since we focused solely on future merchantable timber species. During the post-logging survey, however, damage to several NTFP trees was observed. For future studies, it would be prudent to address the impact of timber extraction on other livelihood activities and forest services, such as NTFP collection, particularly in such regions as the Brazilian Amazon where many communities are attempting to integrate a suite of income-generating activities. NTFP species such as Brazil nuts, rubber, *Copaifera* spp. (Fabaceae; copaiba) and *Carapa* spp. (Meliaceae; andiroba) could be adversely affected by the increasingly important timber harvests, begging the question: can timber harvesting and other livelihood strategies be made more compatible and if so, what are the tradeoffs (see Salick et al., 1995; Romero, 1999; Menton, 2003)?

6. Conclusions

Reducing damage is one of the most important components of a sustainable forest management program (Johns et al., 1996). Our study looked at logging damage in a community-based system in bamboo-dominated forest. Direct damage to FCTs was shown to be slight, a finding consistent with the well-held assumption that small-scale timber extraction is more environmentally-friendly than its industrial counterpart (Salafsky et al., 1998). Even so, as shown in our study, the gap mosaic of the forest will change dramatically even when low intensity guidelines are followed (Webb, 1997). Accordingly, community forest managers must establish their own management regime while building on the RIL model.

Historically, most neotropical research and forest legislation has focused on large-scale operations (Oliveira, 2000). Smallholders operations necessarily differ from industrial enterprises, given their low harvest volumes, management regimes that favor a suite of forest products and services beyond timber, and their inability to completely avoid bamboo-dominated forests (Rockwell et al., 2007). As more communities incorporate formalized timber management into their traditionally NTFP-based livelihood strategies, it becomes increasingly important to test, monitor and document these systems.

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