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Financial and ecological indicators of reduced impact logging performance in the eastern Amazon

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Abstract

Reduced impact logging (RIL) systems are currently being promoted in Brazil and other tropical countries in response to domestic and international concern over the ecological and economic sustainability of harvesting natural tropical forests. RIL systems are necessary, but not sufficient, for sustainable forest management because they reduce damage to the forest ecosystem during the initial forest entry. If conditions were identified where RIL costs were clearly less than conventional logging (CL) costs, then a strong incentive for RIL adoption would exist.

In this paper, a comparison of costs and revenues was made for typical RIL and CL operations in the eastern Amazon. An economic engineering approach was used to estimate standardized productivity and cost parameters. Detailed data on productivity, harvest volume, wasted wood and damage to the residual stand were collected from operational scale harvest blocks. Productivity and cost data were also collected using surveys of forest products firms.

The major conclusion of the study was that RIL was less costly, and more profitable, than CL under the conditions observed at the eastern Amazon study site. Full cost accounting methods were introduced to capture the direct and indirect costs associated with wasted wood. The impact of wasted wood on effective stumpage price provided the largest gain to RIL. Large gains attributable to RIL technology were also observed in skidding and log deck productivity. In addition, investment in RIL yielded an "environmental dividend" in terms of reduced damage to trees in the residual stand and reduction of the amount of ground area disturbed by heavy machinery. Developing institutions that can monetize the value of the environmental dividend remains a major challenge in the promotion of sustainable forest management in the tropics.

Keywords: Sustainable forest management; Logging costs; Wood waste; Logging damage; Full cost accounting; Environmental dividend

1. Introduction

Rain forest logging, as conventionally practiced in the tropics, depletes timber stocks and causes severe ecological impacts on residual forests that are not

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accounted for in economic terms (Repetto and Gillis, 1988; Johnson and Cabarle, 1993). Ecological degradation of logged forests induces economic costs due to loss of ecological services such as watershed protection, carbon sequestration, harvest of non-timber forest products and conservation of biological diversity (Dixon and Sherman, 1990; Chomitz and Kumar, 1998). Although the economic benefits of protecting and conserving tropical forests are probably large, quantification of these benefits is rarely undertaken (Albers et al., 1996; Kramer and Mercer, 1997). Economic cost-benefit analysis may ultimately justify the institution of financial incentives or imposing regulations on the forest products industry to adopt sustainable management practices. However, funding mechanisms for financial incentive programs are uncertain and existing forestry regulations are often not fully enforced. An alternative strategy to promoting good forestry practices in the tropics is to evaluate under what conditions the financial profitability of logging enterprises can be increased by adopting best forestry practices (Putz et al., 2000).

Reduced impact logging (RIL) systems are currently being promoted in Brazil and other tropical countries in response to domestic and international concern over the ecological and economic sustainability of harvesting natural tropical forests. RIL systems are necessary, but not sufficient, for sustainable forest management because they reduce damage to the forest ecosystem during the initial forest entry. RIL systems reduce ecosystem damage by planning forest operations to limit soil disturbance by heavy equipment and reduce damage to the residual stand.[1] In some areas, RIL systems also utilize environmental zoning constraints that prohibit logging in environmentally sensitive areas that would otherwise be harvested in conventional logging (CL) operations.

The environmental dividends provided by a shift from CL to RIL accrue to the forest owner, in terms of better condition of the residual forest, and to society, in terms of enhanced environmental protection and reduced fire risk. However, because of long cutting cycles, high interest rates, and tenure insecurity in many developing countries, the private benefits of RIL on subsequent timber harvests are very modest (Rice et al., 1997). Increased recognition of the environmental benefits of RIL by timber consumers suggests that opportunities exist for creating new markets through forest certification initiatives (Putz and Viana, 1996; de Camino and Alfaro, 1998) or through the development of carbon markets under the Clean Development Mechanism of the Kyoto Protocol (Putz and Pinard, 1993; Boscolo et al., 1997).

If, however, conditions were identified where RIL costs were clearly less than CL costs, then a strong incentive for RIL system adoption would exist.[2] Preliminary results from Sabah, Malaysia suggest that RIL is less profitable than CL in hill dipterocarp forests (with relatively high harvest intensities), due to increased RIL costs for careful felling and skidding and to volume reductions in RIL areas resulting from restrictions placed on harvesting steep slopes (Tay, 2000). In tropical forest regions where the topography is flat to moderately undulating, financial results are mixed and difficult to interpret due to differences in harvest design parameters. Development and application of the CELOS system in Suriname showed that planned logging could be cheaper than conventional logging due to reduced skidding costs (Hendrison, 1990). Recent research in the eastern Amazon state of Pará confirmed this result and showed that RIL increased profitability relative to conventional logging (Barreto et al., 1998). However, another study in Brazil, near Manaus in the state of Amazonas, found that environmentally sound forest harvesting was moderately more expensive than the traditional logging system (Winkler, 1997). In Guyana, research showed that the cost of RIL was nearly identical to the cost of "traditional" logging, although the "traditional" operation in that study involved planning, unlike CL in Brazil (Van der Hout, 1999). Finally, a recent study in Ecuador reported that the cost of RIL was moderately higher than the cost of CL

[1] The FAO model code of forest harvesting (Dykstra and Heinrich, 1996) provides the basis for RIL system design. It provides for the following fundamental activities: pre-harvest inventory and mapping of trees; prc-harvest planning of roads and akidtrails: pre-harvest vine cutting; directional felling: low stumps: efficient utilization of felled trunks: optimum width of roads and skid trails; winching of logs to planned skid trails; optima1 size of landings; minimal ground disturbance and slash management.

[2] Behavioral constraints such as lack of familiarity with new logging systems or lack of confidence that appropriate forest and market conditions exist will affect the rate of adoption of new logging technology.

(Montenegro, 1996). It should be noted that in several of the studies, logging intensity varied considerably across blocks being used for comparative purposes—from about 30% greater on the RIL block (Barreto et al., 1998) to about 154% greater on the CL block (Winkler, 1997). Lack of similar harvest intensity obscures comparisons of cost, waste and damage across harvest blocks.

The analysis presented here adds to the set of comparative financial studies through careful analysis of "standardized" operational data for typical, large-scale RIL systems relative to typical, large scale CL systems in the eastern Amazon. The study focuses on the financial, operational, and technical aspects of CL versus RIL systems. Although the study does not address biological or ecological questions directly, measurements were made of key parameters affecting future forest productivity and these parameters reveal future benefits of using RIL systems.

2. Study setting

In the Brazilian Amazon, between 8000 and 15 000 km^2 are annually logged, mostly using CL practices (Holdsworth and Uhl, 1997; Nepstad et al., 1999). In the eastern Amazon state of Pará, loggers harvest 4-8 trees per ha (Johns et al., 1996; Holdsworth and Uhl, 1997; Uhl et al., 1997), reduce canopy cover by 50% or more (Uhl and Vieira, 1989), severely disturb mineral soils (Johns et al., 1996) and kill or damage 10–40% of the living biomass (Verissimo et al., 1992). The resulting mosaic of gaps and forest patches is especially fire prone due to increased light penetration and fuel load (Holdsworth and Uhl, 1997; Cochrane and Schulze, 1999; Nepstad et al., 1999).

2.1. Site description

For the past several years, the Tropical Forest Foundation (TFF) and its Brazilian subsidiary Fundação Floresta Tropical (FFT) have developed and implemented operational RIL models at various locations throughout the Brazilian Amazon and trained forestry personnel in RIL methods. Between 1995 and 1997, FFT established cutting blocks covering 500 ha at Fazenda Cauaxi which is situated about 120 km southwest of the municipality of Paragominas (3°35′–3°45′S; 48°15′–48°25′W). The study site is located on moderately undulating terrain formed from the residual tertiary plateau, and the soils are oxisols with a distinct argillic horizon. Annual rainfall averages 1750 mm with a distinct dry season from June to November. Mean annual temperature is 28 °C. The forest is classified as tropical moist (Walsh, 1996), and is "terra firme" ("upland"). It is a mixed forest with more than 124 species (dbh > 10 cm), patches of emergent trees exceed 50 m in height (top of crown), and the forest is characterized by a dense vine load.

2.2. Market setting

The establishment of the Belem-Brasilia highway opened the forest frontier in Paragominas to harvesting and wood processing activities about 30 years ago. During the 1970s and 1980s, the industry grew rapidly, largely due to agricultural subsidies that induced conversion of forests to pasture (Verissimo et al., 1992). During the 1990s, new entry into the wood products industry slowed, exit of firms increased, better capitalized firms expanded processing capacity and some firms established export clearing houses (Stone, 1996). As the wood products industry matured, the most accessible timber stocks were depleted, log hauling distances increased, and firms began using larger trucks to help control transportation costs. Between 1990 and 1995, delivered log prices increased by 10–30% and stumpage prices doubled (Stone, 1996).

The Paragominas timbershed comprises roughly 5.6 million hectares. Most wood processed by mills in this timbershed is marketed domestically as sawn wood (about 80%), with lesser amounts of plywood (about 18%) and veneer (about 2%). Access to domestic markets permits 40-50 tree species to be harvested. At the time of this study, northeast Brazil was the primary product market (43% of volume), followed by the southeast (39%), the south (8%), and other areas in Brazil (2%). About 8% of the wood was processed for the export market (Ferreira, 1996).

CL operations in this timbershed can be categorized into three logging classes. The smallest operations (Class I) typically use a farm tractor and truck for logging and have little impact on the residual forest. The second class (Class II) is intensive, highly destructive and provides the initial step in converting forest to pasture. These operators typically own a small mill and some forest land, but rely on timber supplied from non-industrial private forests. They are the most common in terms of number of operators and volume of timber harvested. The third class (Class III) is comprised of large, industrial landowners, often with vertically integrated operations, who supply their mills predominately with timber harvested from their own land. These operations typically use the most modem equipment but, due to their harvesting techniques, have a large impact on the residual stand. This study focuses on Class III logging operations.

3. Methods

An assessment of the financial performance of RIL is complicated by the fact that tropical forests are heterogeneous. Variation in stocking of commercial timber species and differences in harvest design parameters affect estimates of productivity, cost, waste and damage. Although these sources of variation could ideally be accounted for using a factorial experimental design, and subsequent statistical analysis, this approach was not feasible because of budgetary limitations. Another approach is to use “engineering” functions based on technical efficiency criteria (Vaux, 1973; Hyde, 1980). Engineering functions capture shifts in logging costs associated with technical change using productivity parameters observed across multiple harvest blocks.

3.1. Data sources

In this study, observations from comparable RIL harvest blocks at Fazenda Cauaxi were used to estimate average or “typical” productivity parameters for each logging activity.” Six harvesting blocks were established on 500 ha (two blocks comprised 50 ha each, the remaining four blocks were 100 ha each). Block 1 was the conventional logging block, block 5 was the non-harvest control, and remaining blocks were used for RIL activities.[4] Pre-harvest tree inventories (100%) were conducted on all blocks and permanent plots representing 1% of the area in each of the blocks were established. Pre-harvest inventories included all commercial and potentially commercial trees greater than or equal to 35 cm dbh on blocks 1 (CL) and 3 (RIL). Post-harvest inventories were conducted on blocks 1 and 3 to allow computation of wood waste and damage. A standard harvest volume (q_{std} = 25.36 m^3/ha) was computed as the average harvest volume from blocks 1, 3 and 4.[5]

RIL standardized activity costs were computed by taking averages of daily parameter values reflecting productive activity of trained crews. Hourly labor costs were based on the standard monthly wage for each job category (including benefits) and the average number of effective work hours per month. Fixed equipment costs (depreciation, interest, insurance and taxes) were amortized on an hourly basis using standard formulas provided by equipment suppliers.

Productivity and cost of CL harvesting activities were estimated from survey data collected from CL operators in the Paragominas timbershed (FFT, 1998; Barreto, unpublished data).[6] CL data included information on timber harvesting productivity, labor cost, equipment used, crew composition and timber defects accepted by mills. Productivity and cost parameters were estimated by averaging across the surveyed firms.

The financial analysis is based on actual 1996 values for factor costs and output prices. Values are reported in 1996 US dollars.

3.2. Harvesting systems

RIL harvesting activities were planned up to 8 months in advance and crews were well trained in RIL methods. A full inventory of commercial and

‘Further study details are available in the report Holmes et al. (2000). The full report can be downloaded from the CIFOR (www.cifor.org) or the USDA Forest Service International Programs (www.fs.fed.us/global) websites.

[4] Not all RIL blocks were used in engineering function estimates for all activities. In particular, RIL activities associated with training activities did not represent “typical” productivity and were therefore not included.

[5] Merchantable volumes: block 1 = 26.09 m^3/ha, block 3 = 25.07 m^3/ha and block 4 = 24.90 m^3/ha.

‘Seven logging firms were surveyed by FFT in April 1998.

potentially commercial trees greater than 35 cm dbh occurred 7 months in advance of harvest and vines were cut at that time. A crawler tractor (Caterpillar D6 SR) was used for construction of roads and log decks. Roads, log decks and skid trails were planned in advance of the harvest operation to minimize the ground area disturbed by heavy equipment. A rubber tire skidder (Caterpillar 525) with winch and grapple was used for skidding operations. Secondary skid trails were laid out after tree felling and obstacles cleared in advance of skidding. Trees were directionally felled and bucked using a Stihl AV 51 chainsaw. Logs were trimmed, scaled and stacked on the log deck as they arrived from the skidding operation. A Caterpillar 938F Loader was used for log deck operations.

An industrial cooperator performed the timber harvest on the CL block following typical practices. The CL operator used a crawler tractor (Caterpillar D6 Logger) with winch for constructing roads and log decks and for skidding operations. A "tree hunter" (mateiro) worked with the sawyer in a "hit or miss" search for merchantable trees. Directional felling techniques were not used. Sawyers used a Stihl AV 5 1 chainsaw for felling and bucking operations. As is typical, timber fellers were paid on a piece rate that encouraged rapid felling with little regard for impacts on the residual stand. Skidding crews were not provided with precise information from felling crews regarding location of felled trees and, therefore, needed to search for logs by locating gaps in the dense forest canopy. This resulted in an inefficient skidding operation with significant damage to the residual stand, forest soils and skidding equipment. Log delivery to log decks was not synchronized with log deck operations, thus, complicating the maneuvering of the Caterpillar 938F Loader.

3.3. Gross revenue

Gross revenue per m^3 at the forest log deck was computed using log prices for three value classes: branco (low value) = US\$ 10.74/m^3, vermelho (medium value) = US\$ 21.61/m^3 and nobre (high value) = US\$ 58.57/m^3 (Ferreira, personal communication). A weighted average price (US\$ 25.50/m^3) was computed using the volumes recovered on Cauaxi blocks 1 and 3 in each value class.

3.4. Timber waste

The volume of merchantable timber wasted in CL and RIL blocks was computed using a post-harvest census of harvesting blocks 1 and 3.[7] Timber was wasted both in the forest and on the log deck. Three categories of timber wasted in the forest were measured: (1) timber wasted by cutting stumps too high, (2) timber wasted in the stem or crown (e.g. merchantable branches) of harvested trees due to improper bucking practices and (3) timber wasted because logs were not found by the skidder or bulldozer operator.

In the CL and RIL operations, logs were left on the log deck and never transported to the mill. Although it was not possible to unambiguously determine why specific logs were left, considerations included size, species and stem defects. On the RIL block, some logs were left, although they met the harvest criteria.

The formula used for computing the volume of wasted wood (waste-vol) for solid sections of the bole, based on a constant form factor was

$$\text{waste\_vol} = \tfrac{1}{4}\pi d^2 h \qquad (1)$$

where d is the diameter, h the height and $\pi/4$ the constant of proportionality. The formula for computing the volume of wasted wood due to improper bucking of sections containing hollows [waste_vol (hollow)] was

$$\text{waste\_vol (hollow)} = \tfrac{1}{4}\pi \left[d_{\log} - (d_{hb} + d_{ht})/2\right]^2 h \qquad (2)$$

where $d_{\log}$ is the diameter at the midpoint of the usable portion of the log, d_{hb} the diameter of the hollow at its base and d_{ht} the diameter of the hollow at its top.[8]

3.4.1. Harvesting cost

Engineering data were used to estimate productivity and cost parameters for each component activity of the timber harvesting system. Cost per m^3 was estimated as the sum of average fixed cost (f), average variable

[7] Merchantability was defined as timber sufficiently free from defects such that a typical mill in the region would accept it. Managers of seven sawmills in Paragominas were interviewed to determine the specifications for acceptable defects (FFT, 1998).

[8] For example, mills would accept hollows up to 50% of the log diameter for the highest value species.

cost (v), average waste cost (w), average stumpage cost (λ) and average training or "human capital" cost (h).

$$\text{costperm}'' = f + v + w + \lambda + h \quad (3)$$

3.4.2. Fixed cost

Fixed costs were partitioned into the following stages: (1) pre-harvest, (2) harvest planning and (3) infrastructure costs." Specific activities associated with each stage were

- pre-harvest: block layout, inventory, vine cutting, data processing and map making;
- harvest planning: tree marking, road planning, and log deck planning;
- infrastructure: road construction, log deck construction and skid trail layout.

Fixed cost per m^3 (f) associated with pre-harvest, harvest planning and infrastructure stages were computed for each activity using the formula

$$f = \frac{t_l(c_l + c_m) + t_e c_e}{q_{std}} \quad (4)$$

where t_l is the labor time, in hours, required per hectare; t_e the equipment time, in hours, required per hectare; c_l the labor cost per h, c_m the materials cost per hour, c_e the equipment cost per hour.

Time parameters for labor and equipment were based on "effective" time, that is, time in which labor and equipment were engaged in productive activity. Effective time per unit of fixed cost activity (e.g. effective hours per meter of road constructed) was distributed over the harvest block. This was accomplished by multiplying the ratio of the linear or area1 dimension (e.g. number of meters of road or square meters of log deck constructed) and the size of the harvest block by the effective time per unit of activity.

Pre-harvest and harvest planning activities typically occur three to 12 months prior to harvest. Planning costs were compounded forward at the rate of 21.4% per annum.[10] Block layout, road planning and log deck planning costs were compounded for 8 months. Inventory, vine cutting, road construction and log deck construction costs were compounded for 7 months. Data processing and map making expenses were compounded for 3 months.

In addition, the following fixed cost categories were included: (1) support (e.g. cook, food, camp, support vehicle) and (2) overhead (e.g. office, administration, communications). Support cost was computed by dividing support cost per harvest season by estimated volume harvested during a season. Support costs were prorated over the total volume harvested during 8 months for RIL operations and 7 months for CL operations." Overhead costs were computed as 10% of average variable cost.

3.4.3. Variable cost

Variable costs were computed for harvest activities associated with felling, bucking, skidding and log deck operations. Variable cost per m^3 associated with harvest stage activities were computed as

$$v = \frac{c_l + c_e + c_m}{p} \quad (5)$$

where p is the harvest productivity, in m^3 per effective hour of activity, and other variables are defined as above.

3.4.4. Waste adjustment cost

The volume of timber wasted is the difference between the potential volume recovered under "ideal" logging and the actual volume recovered. The potential volume was defined as the actual volume recovered on the standard block (25.36 m^3/ha) plus the volume lost in the following categories: (1) felled logs not found by skidding crew, (2) volume lost because poor felling caused logs to split and lose merchantability, (3) volume lost because logs were left unutilized on the log deck, (4) volume lost due to cutting stumps too high and (5) poor bucking of felled logs. Wasted wood incurs direct costs associated with felling, bucking, skidding and log deck activities (waste categories 1 through 3) and indirect costs by

'Fixed costs were defined as costs incurred in advance, and in support, of the harvest operation.

"'This was the average nominal interest rate for Brazil in 1996 (Banco Central do Brasil, Relatório Annual 1997). Use of nominal. rather than real, interest rate provides a conservative estimate of the short term use of money.

[11] The harvest season is extended under RIL because roads are built the year before harvest. Under CL, the first month of the harvest season is spent building roads, so 1 month of harvest is lost.

increasing effective stumpage price (waste categories 1 through 5).[12]

Waste factors were computed to account for the total volume of wood felled, bucked and skidded for each unit of wood transported to the mill. The formulas used were

$$\alpha = \frac{q_{\text{split}}}{q_{\text{std}}}, \quad \beta = \frac{q_{\text{lost}}}{q_{\text{std}}}, \quad \delta = \frac{q_{\text{deck}}}{q_{\text{std}}} \tag{6}$$

where q_{split} is the per hectare timber volume wasted due to splitting, q_{lost} the per hectare timber volume wasted because merchantable felled logs were not found by the skidding crew and q_{deck} the per hectare timber volume wasted because logs were left unutilized on the log deck. Each ratio indicates the timber volume wasted at each harvesting step as a proportion of the standard volume of wood recovered and transported to the mill.

Direct waste cost per m^3 (w) was computed by multiplying each waste factor by the appropriate variable cost per m^3 recovered and then summing:

$$w = \alpha(v_{\text{fell}}) + \beta(v_{\text{fell}} + v_{\text{buck}}) + \delta(v_{\text{fell}} + v_{\text{buck}} + v_{\text{skid}} + v_{\text{deck}}) \tag{7}$$

where (v_{fell}) is the average variable cost of felling trees, (v_{buck}) the average variable cost of bucking logs, (v_{skid}) the average variable cost of skidding logs and (v_{deck}) the average variable cost of log deck operations.[13]

3.4.5. Stumpage cost

Stumpage costs were computed to account for indirect costs associated with wasted wood on RIL and CL operations. In the study area, stumpage was typically sold as "harvesting rights" on an area (per hectare) basis (λ_{ha}).[14] If RIL was more efficient than CL in recovering the volume potentially available for harvest on a standard cutting block, then effective stumpage cost per m^3 of wood recovered would be lower (higher) for the RIL (CL) operation.

Effective stumpage cost per m^3 on the typical RIL block (λ^{RIL}) was computed as stumpage cost per hectare divided by the standard volume.

$$\hat{\lambda}^{\text{RIL}} = \frac{\lambda_{\text{ha}}}{q_{\text{std}}} \tag{8}$$

Effective stumpage cost per m^3 on the typical CL block included a factor (Δ) for the difference in total volume of wood wasted (waste categories 1 through 5) between CL and RIL blocks:

$$\Delta = w^{\text{CL}} - w^{\text{RIL}} \tag{9}$$

where w^{CL} is the volume per hectare of timber wasted on the CL block and w^{RIL} the volume per hectare of timber wasted on the RIL block.[15] Effective stumpage cost per m^3 on the typical CL block was computed as

$$\hat{\lambda}^{\text{CL}} = \frac{\lambda_{\text{ha}}}{q_{\text{std}} - \Delta} \tag{10}$$

Eq. (10) implies that if CL and RIL were applied to the same block then the effective stumpage price for the initial harvest entry would be higher on the CL block because more wood is wasted due to poor logging practices.

3.4.6. Human capital (training) cost

RIL crews received specialized training to increase harvesting efficiency and decrease ecological impacts. CL crews received on-the-job training but did not receive specialized training. Therefore, if CL crews were to adopt RIL methods, investments would need to be made in "human capital". Estimated (direct) training costs for RIL were amortized over 5 years based on the assumption that crews would need retraining after that period. Amortized training costs were divided by estimated volume harvested over this period to arrive at an average training cost of US$ 0.21 per m^3.[16]

[12] Wasted wood on the CL block includes wood that was not conformable with mill specifications due to size, species or defect. All wasted wood on the RIL block was conformable with mill specifications. Conformable and non-conformable wasted wood incurs direct costs.

[13] It was assumed that RIL felling costs were 50% of felling plus bucking costs.

[14] Stone (1996) reported an average stumpage cost of $ 193 per ha for the study area.

[15] Volumes of wasted wood not conformable with mill specifications were not distinguished from conformable wasted wood. Thus, Δ is somewhat larger than if non-conformable wood were omitted from stumpage cost. However, we estimated that 170 conformable trees were not found on the CL block, but only 62 non-conformable trees were cut. Therefore, our estimates of A and λ^{CL} are conservative.

[16] Opportunity costs associated with training were not estimated. These costs would include foregone production during the training period and an increased likelihood that RIL trained personnel would demand higher wages or seek employment elsewhere.

3.5. Damage to residual stand

Damages avoided to the residual stand through implementation of RIL methods are benefits of RIL relative to CL systems. In this study, two key parameters indicating severity of damage to future forests were measured: damage to trees in the residual stand and the proportion of ground area disturbed. While it is recognized that reducing damage increases economic and ecological value of future forests, measurement of these values in economic terms was beyond the scope of this study.[17]

3.5.1. *Damage to trees*

Damage estimates were based on 100% census of Cauaxi blocks 1 and 3 of all commercial and potentially commercial tree species with good form and dbh > 35 cm. Only trees meeting these criteria were included because they will likely comprise harvests in the second cutting cycle.” The census was conducted about 20 months after harvest, so damage due to harvest-gap induced windthrow was included.

Identical protocols were used on RIL and CL blocks and the same data collection FFT technician supervised data collection. Trees were located using an inventory list with coordinates, common and scientific names, tree numbers, and diameters. Two assistants helped locate trees on the list, while two technicians assessed and recorded damage. Severity of damage to bole and crown, cause of damage, and health status of each tree in the census were assessed using a modification of the method reported by Johns et al. (1996) and is shown in Table 1.

3.5.2. *Ground area affected by heavy machines*

RIL systems are designed to reduce the impact of heavy machinery on the forest floor. Reduced ground disturbance is expected to yield greater future forest productivity because less advance regeneration is destroyed during harvest operations and less mineral soil is exposed.

The overall area of the RIL and CL blocks affected by roads, log decks and skid trails was measured. The same technician used a chain to measure the length and width of every road, skid trail and log deck in both harvest areas. Simultaneously, the relative direction was recorded to allow these areas to be added to the post-harvest map. In the office, surface area was estimated (length x width). Although compaction was not measured. disturbance severity was. Every 30 meters along all skid trails, an observation was made to evaluate whether mineral soil was exposed and if the litter layer or vegetation remained. The sampling unit was a single line across the width of the skid trail. Overall disturbance was the percentage of lines with exposed soil.

4. Results

4.1. *Overview of timber harvests on RIL and CL sites*

Pre-harvest inventories indicated that more trees were potentially viable for harvest on CL block 1 than on RIL block 3 (Table 2).[19] From the list of potentially viable trees, 343 trees (5 1.2% of trees meeting harvest criteria) on the RIL block were de-selected by the timber marking crew or the sawyer due to defect, lean or other factors jeopardizing harvest. For the CL block, only 15 trees (4.1% of trees meeting harvest criteria and found by sawyer) were de-selected. Failure to de-select trees by the CL sawyer likely induced greater volumes of wasted wood, particularly from split logs and bucking waste. Further, nearly half of the trees in the CL block that met harvest criteria were never found by the sawyer and the sawyer cut many trees that did not meet harvest criteria (14.6% of felled volume on the CL block).*” These results indicate that the “hit or miss” timber hunting procedure used by conventional loggers is inefficient in locating merchantable trees for harvest.

In addition to poor tree selection, harvest intensity was greater on the CL block, although this was at least partially due to the higher stocking. A total of 426 trees were felled on the CL block relative to 33 1 trees

“Economic impacts of RIL on net present value from two cutting cycles are reported by Boltz (1999).

[18] RIL has also been shown to reduce damage to trees smaller than 35 cm dhh (Johns et al., 1996), which will provide an advantage to cutting cycles beyond the second harvest.

“The landowner imposed criteria for merchantability according to mill capacity and market demand based on size, species and acceptable defect.

“‘Assuming that 49% of the trees on the CL block that met harvest criteria could have been felled, then 170 merchantable trees (347 x 0.49) were not found by the sawyer.

Table 1
Criteria used during post-harvest damage assessment at Fazenda Cauaxi, Pará, Brazil[a]

Severity class	Crown damage	Bole damage	Cause of damage	Health class
0	No damage, complete crown	No damage	No damage	No damage
1	Minor damage, i.e. <1/3 of crown damaged	Minor damage to <1500 cm^2 of bark	Felling	Clear signs of recover
2	Moderate damage, i.e. >1/3, but <2/3 of crown destroyed	Minor damage to >1500 cm^2 of bark	Skidding	No sign of recovery o
3	Severe damage, i.e. crown smashed	Moderate damage, i.e. deeper than bark, but <1500 cm’ in area	Road building	Clear signs of death o (e.g. insect of fungal
4	NA	Severe damage to area >1500 cm^2, e.g. a major tear or broken branch	Log deck construction	NA
5	NA	Irreversible damage (clearly dead or dying), e.g. smashed bole	Natural causes (unrelated to harvest activities)	NA

[a] NA: not applicable.

Table 2
General harvest characteristics on harvest blocks 1 (CL) and 3 (RIL), Fazenda Cauaxi, Pará, Brazil

Characteristic	Conventional logging (CL)	Reduced impact logging (RIL)
Trees meeting harvest criteria using inventory list	726	670
Trees rejected during marking	0	217
Trees marked for harvest	0	453
Trees meeting harvest criteria rejected after defect testing	15	126
Trees meeting harvest criteria not found by sawyer	347	0
Trees felled meeting harvest criteria	363	327
Trees felled not meeting harvest criteria	62	0
Trees with usable wood knocked down during felling	0	4
Total trees felled	425	331
Trees not skidded, not found by skidding team	16	1
Trees not skidded due to lack of usable wood	12	2
Total trees extracted to log deck	397	328

felled on the RIL block. On the CL block, 3.8% of felled trees were not found by the skidding team (16 trees) and 2.8% of felled trees were not skidded because of a lack of merchantable wood in the bole (12 trees). For the RIL operation, less than 1% of the trees felled were not skidded (three trees). The number of trees harvested (skidded to the log deck) on the CL block exceeded the number of trees harvested on the RIL block by 21.3% (70 trees).

4.2. Harvest impacts on forest structure

Based on pre-harvest inventory data, commercial and potentially commercial stems accounted for about 56.5% of all stems greater than 3.5 cm dbh. Changes in the structure of the commercial component of the forest will, therefore, have a large impact on overall forest structure.

The pre-harvest and post-harvest distributions of commercial and potentially commercial trees by harvesting system are shown in Table 3.[21] The pre-harvest distribution of trees by diameter class showed a negative exponential distribution consistent with the “de Liocourt curve” typical of uneven-aged, mixed forests. The negative binomial distribution was reasonably well maintained in the post-harvest distributions on both cutting blocks, although two differences in post-harvest diameter distributions were apparent. First, the residual RIL block contained a larger number of trees in the smaller diameter classes (<55 cm), but this was primarily due to the larger number of pre-harvest trees in these size classes. Second, the post-harvest distribution of large trees (90-130 cm) in the RIL block differed from the CL block. On the CL block, about 10% of the pre-harvest trees in these size classes remained after harvest, whereas about 21% of the pre-harvest trees in these size classes remained post-harvest on the RIL block. These data suggest that tree hunters on the CL block focused on the largest trees whereas the RIL system more closely maintained the initial forest structure.” In addition, the condition of trees remaining on the RIL block were superior to trees remaining on the CL block because planning resulted in fewer damages to the residual stand.

Although more than 50 species were harvested at Fazenda Cauaxi, 5 species accounted for about two-thirds of the harvest volume on cutting blocks 1 and 3 (Table 4). Maçaranduba (*Manilkara huberi Ducke*.), a medium value species, accounted for 26.5% of the initial volume of commercial species and accounted for 42.28% of the harvest volume on block 1. On block 3, this species accounted for 22.33% of the initial

[21] Trees in the post-harvest inventory were adjusted to account for standing trees that were considered to be dying in the post-harvest damage assessment.

‘“This result might be due to loggers on the RIL block “de-selecting” larger trees due to “hollows” and other defects. De-selected trees may provide benefits to wildlife and be an important seed source.

Table 3
Pm-harvest and post-harvest distribution of commercial and potentially commercial trees (form classes 1 and 2) by dbh class on blocks I and 3, Fazenda Cauaxi, Pará, Brazil

dbh class (cm)	Conventional logging			Reduced impact logging		
	Pre-harvest	Post-harvest	Percent remaining	Pre-harvest	Post-harvest	Percent remaining
40	683	594	0.87	784	757	0.97
50	546	472	0.86	581	556	0.96
60	333	264	0.79	367	286	0.78
70	237	159	0.67	213	123	0.58
80	164	91	0.55	148	64	0.43
90	104	32	0.31	87	46	0.53
100	82	28	0.34	55	35	0.64
110	40	7	0.18	28	14	0.50
120	28	8	0.29	14	10	0.71
130	5	2	0.40	10	7	0.70
140	7	4	0.57	8	5	0.63
150		1	0.50	4	2	0.50
160	3	1	0.33	3	3	1.00
1701	8	6	0.75	5	5	1.00
Total	2242	1669	0.74	2307	1913	0.83

volume and 32.03% of the harvest volume. Jatoba *(Hymenuea courburil* L.), a high value species, accounted for 4.95% (5.62%) of the initial commercial volume and 9.61% (12.30%) of the volume harvested on block 1 (block 3). Each of the five most common species harvested had less representation in the residual forest than in the forest prior to harvest. For example, although Maçaranduba accounted for 26.5% (22.33%) of the initial commercial volume on block 1 (block 3), it only accounted for 16.57% (17.50%) of the residual commercial volume. A greater reduction in the volume of the five most commonly harvested species occurred on the CL block (38.26% of initial inventory left standing) than on the

Table 4
Most common species harvested by importance in initial inventory, volume harvested, and post-harvest inventory on blacks 1 and 3, Fazenda Cauaxi, Pará, Brazil”

Brazilian name	Scientific name	Value class	Initial commercial inventory volume (m^3)	Harvest volume (m^3)	Post-harvest inventory volume (m^3)
Block 1 (CL)					
Maçaranduba	*Manilkara huheri Ducke*	Medium	1669.48 (26.50)	1028.75 (42.28)	640.73 (16.57)
Jatoba	*Hymenaea courbaril* L.	High	311.73 (4.95)	233.95 (9.61)	77.79 (2.01)
Muiracatiara	*Astronium lecointei Ducke*	Medium	19655 (3.12)	146.33 (6.01)	50.22 (1.30)
Maparajuba	*Manilkara amazonica*	Low	193.88 (3.08)	116.37 (4.78)	77.51 (2.00)
Louro vermelho	*Nectandra rubra*	Low	253.37 (4.02)	95.32 (3.92)	158.06 (4.09)
Block 3 (RIL)					
Maparanduba	*Manilkara huheri Ducke*	Medium	1326.47 (22.33)	632.47 (32.03)	694.00 (17.50)
Jatobá	*Hymenaea courbaril* L.	High	333.89 (5.62)	242.76 (12.30)	91.12 (2.30)
Muiracatiara	*Astronium lecointei Ducke*	Medium	321.51 (5.41)	182.29 (9.18)	140.22 (3.54)
Maparajuba	*Manilkara amazonica*	Low	181.48 (3.05)	116.30 (5.89)	65.18 (1.64)
Breu sucuruba	*Trattinickia burserifolia SW*	Low	292.32 (4.92)	82.75 (4.19)	209.57 (5.28)

[a] Values shown in parenthesis are in percentage.

Table 5
Ground area disturbed per tree harvested and total hectares disturbed on blocks 1 and 3, Fazenda Cauaxi, Pará, Brazil

Activity	Conventional logging		Reduced impact logging	
	Disturbed/tree harvested (m^2)	Total ha disturbed	Disturbed/tree harvested (m’)	Total ha disturbed
Secondary roads	34	1.35	20	0.65
Log decks	26	1.05	19	0.63
Skid trails	193	7.66	120	3.90
Total	253	10.05	159	5.18

Table 6
Potential future crop trees (commercial and potentially commercial species; form classes 1 and 2) damaged per tree harvested by felling and other activities (total number of trees shown in parentheses), blocks 1 and 3, Fazenda Cauaxi, Pará, Brazil

Health class	Conventional logging		Reduced impact logging	
	Felling damage	Damage from other activities	Felling damage	Damage from other activities
Recovering	0.14 (54)	0.11 (43)	0.24 (80)	0.17 (57)
No change	0.16 (63)	0.05 (21)	0.18 (58)	0.05 (17)
Dying	0.34 (136)	0.04 (16)	0.16 (52)	0.01 (2)
Total impacted	0.64 (253)	0.20 (80)	0.58 (190)	0.23 (76)

RIL block (48.87% of initial inventory left standing). Thus, species selection was more narrowly targeted on the CL block.

4.3. Ground area disturbed

Due to planning the location of roads and skid trails on the RIL block, the amount of ground area disturbed by the operation of heavy machinery was much lower than on the CL block (Table 5). Overall, heavy equipment disturbed 10.05% of the ground area in the CL block versus 5.18% of the ground area in the RIL block.” Although this result was partially due to the higher harvesting intensity on the CL block, the ground area disturbed per tree harvested was 59.1% greater on the CL block relative to the RIL block. In addition, 100% of the CL skid trails were cleared to mineral soil due to skidding technique and equipment used, whereas less than 10% of the RIL skid trails had exposed mineral soil.

“This 2 to 1 ground disturbance ratio is similar to results reported by Hendrison (1990) comparing conventional and controlled logging in Suriname.

4.4. Damage to next harvest trees

Due to directional felling technique and planned layout of roads, log decks and skid trails, the number of fatally damaged future crop trees in the residual stand was greatly reduced (Table 6). This fact suggests that economic and ecological benefits provided by the residual stand will be greater on the RIL block. For every 100 trees felled on the CL block (RIL block), 34 trees (16 trees) in the residual stand that were commercial or potentially commercial, greater than 35 cm dbh and with good form, were fatally damaged. As can be seen, felling is the most important cause of tree mortality.[24]

4.5. Fixed cost

For the standard RIL block, it was estimated that pre-harvest and harvest planning costs US$ 1.34 per m^3 (Table 7). Planning the location of roads and log decks reduced construction costs by reducing ground

“Natural causes accounted for an additional 61 trees on the CL block and 50 trees on the RIL block that were dead or dying.

Table 7
Typical pre-harvest, harvest planning and infrastructure costs in Paragominas, Pará, Brazil

Activity	Conventional logging cost	Reduced impact logging cost
	(US$ per m^3)	(US$ per m^3)
Pre-harvest planning		
Block layout	–	0.26
Inventory		0.48
Vine cutting		0.14
Data processing		0.10
Map making		0.20
Harvest planning		
Tree hunting	0.14	–
Tree marking	–	0.13
Road planning		0.02
Log deck planning	–	0.01
Infrastructure		
Road construction	0.28	0.16
Log deck construction	0.29	0.16
Skidtrail layout	–	0.27
Total	0.71	1.93

area disturbed. However, total infrastructure costs were slightly higher (US$ 0.02 per m^3) in the typical RIL system due to skidtrail layout.” Overall, planning and infrastructure costs were US$ 1.22 per m^3 greater for RIL. Although concern regarding fixed harvest costs may hinder adoption of RIL systems, significant gains in both efficiency and the environmental dividend were attributable to these investments.

4.4. Variable cost

The additional time necessary to directionally fell trees and buck logs to maximize wood utilization led to a relative decrease in RIL productivity (Table 8). Felling and bucking cost under RIL were about US$ 0.13 per m^3 (26.5%) greater than CL. Investment in these stages of the harvest operation resulted in less wasted wood and an increase in the environmental dividend.

Planning the extraction path for felled logs and marking skid trails in advance led to a large increase in RIL skidding productivity and concomitant decrease in skidding cost (Table 8). This is because relatively inexpensive labor costs are substituted for relatively large fixed and variable equipment costs. It is also noted that the hourly operating cost for the CAT 525 skidder used in the RIL calculation (US$ 32.31 per hour) is lower than the hourly operating cost for the CAT D6 tractor used in the CL calculation (US$ 34.05 per hour). Given these considerations, RIL skidding costs were US$ 0.75 per m^3 (37.7%) lower than CL skidding costs.

Productivity of log deck operations is limited by skidding productivity, as logs cannot be trimmed, scaled and stacked faster than they arrive at the log deck. Synchronization of skidding and log deck operations is also necessary for gains in log deck efficiency. Under CL, skidding and log deck operations often lack coordination resulting in haphazard piles of logs on the decks. For these reasons, log deck productivity was assumed to be directly linked to skidding productivity. Overall, the cost of log deck operations was, thus, reduced by US$ 0.73 per m^3 (36.3%) for RIL (Table 8).

4.7. Harvesting waste

RIL activities were effective in reducing the amount of wood wasted relative to the CL operation (Table 9). Wood wasted under CL (RIL) represented 23.9% (7.6%) of the standard harvest volume. Clearly, RIL activities resulted in a large gain in timber utilization efficiency. Further, costs associated with wasted wood are generally not accounted for in CL cost accounts as they require post-harvest monitoring of the harvest block to compute volumes wasted. As shown below, failure to account for wasted wood results in a severe underestimate of the full cost of CL logging operations.

Most of the wood wasted in the forest was due to improper bucking of logs (CL = 1.97 m^3/ha versus RIL = 0.85 m”). On the CL block, the second most important source of wasted wood was logs not found by skidding operation (0.96 m^3/ha). On the RIL block, only 1 log, representing 0.06 m^3/ha, was not found by the skidding crew. Logs split due to improper felling accounted for 0.87 m^3/ha on the CL block and 0.31 m^3/ha on the RIL block. Cutting stumps too high wasted 0.28 m^3/ha on the CL block and 0.10 m^3/ha on the RIL block. Finally, wood left unutilized on

[25] Skidtrails are not laid out in advance in CL operations.

Table 8
Typical productivity and cost parameters for felling, skidding and log deck operations, Paragominas, Pará, Brazil

Activity	Conventional logging		Reduced impact logging	
	Productivity (m^3/h)	Cost (US$ per m^3)	Productivity (m^3/h)	Cost (US$ per m^3)
Felling and bucking	20.46	0.49	18.65	0.62
Skidding	22.39	1.99	31.66	1.24
Log deck operations	22.39	2.01	31.66	1.28
Total		4.49		3.14

Table 9
Merchantable wood wasted in the forest and on log decks, blocks 1 and 3, Fazenda Cauaxi, Pará, Brazil[a]

Source	Conventional logging waste (volume per ha)	Reduced impact logging waste (volume per ha)
High stumps (m^3)	0.28	0.10
Split logs (m’)	0.87	0.31
Bucking waste (m^3)	1.97	0.85
Logs lost (m^3)	0.96	0.06
Total forest (m^3)	4.08	1.32
Log deck (m^3)	1.97	0.60
Total (m^3)	6.05	1.92

the log deck amounted to 1.97 m^3/ha on the CL block and 0.60 m^3/ha on the RIL block.

Waste factors shown in Eq. (6) were computed using data in Table 9. For the CL (RIL) operation, a = 0.034 (0.012), β = 0.039 (0.002) and δ = 0.078 (0.024). The sum $\alpha + \beta + \delta$ indicates the volume of wood wasted per unit recovered that incurred a direct cost. Entering these values into Eq. (7) resulted in a waste adjustment cost of US$ 0.40 per m^3 for typical CL operations and US$ 0.09 per m^3 for typical RIL operations.

As described above, stumpage costs were computed to account for the difference in wasted wood volume between RIL and CL blocks (Eq. (8) through (10)). Stumpage cost on the RIL block was US$ 7.61 per m^3.[26] Adjusting this value for the CL waste increment (Δ = 4.13 m^3/ha), stumpage cost on the CL block was US$ 9.09 per ha. Thus, under CL, effective stumpage price is increased by US$ 1.48 per m^3 due to poorer recovery of the merchantable volume. Further, as stumpage prices in this market increase over time due to increasing timber scarcity, the impact of effective stumpage price on CL’s full cost will likewise increase.

4.8. Costs and returns from RIL versus CL operations

A comparison of the cost and revenue for typical, large scale RIL and CL operations in the Paragominas timbershed is shown in Table 10. The bottom line is important. Given the forest, industrial and market conditions under which this analysis was conducted, total cost was less, and net revenue was greater for RIL. Direct and indirect costs associated with wasted wood contributed to, but did not dictate, the competitive financial position of RIL. Excluding the waste adjustment and the difference in effective stumpage price, RIL and CL average costs were virtually the same. This result obtained because investment in training forest personnel in RIL methods led to large gains in skidding and log deck productivity. As can be seen in the table, the competitive financial position of RIL was further enhanced by accounting for direct and indirect costs associated with wasted wood.

Net profit margin for logging operations in this timbershed, computed as the ratio of net revenue to gross revenue, were substantial. Net margins for CL were 38.6% and for RIL were 45.7%.[27] For “typical” large scale operations in this timbershed, first harvest entries into the primary forest appear very lucrative. Although it is not possible to state with certainty the nature of the typical logging firms’ objectives, the

[26] Computed as ($ 193 per ha)/(25.36 m^3/ha).

[27] Compare with an estimated net profit margin of 33% for logging and sawmill companies in Pará (Jenkins and Smith, 1999).

Table 10
Typical costs and returns of conventional logging versus reduced impact logging, Paragominas, Pará, Brazil

Activity	Conventional logging (US$ per m^3)	Reduced impact logging (US$ per m")	Difference: RIL - CL
Pre-harvest	0.00	1.18	1.18
Harvest planning	0.14	0.16	0.00
Infrastructure	0.57	0.59	0.02
Felling and bucking	0.49	0.62	0.13
Skidding	1.99	1.24	-0.75
Log deck operations	2.01	1.28	-0.73
Waste adjustment	0.40	0.09	-0.31
Stumpage cost	9.09	7.61	-1.48
Training		0.21	0.21
Overhead/support	0.97	0.86	-0.11
Total cost	15.66	13.84	-1.82
Gross returns	25.50	25.50	0.00
Net revenues	9.84	11.66	1.82

existence of substantial net profit margins combined with the complex calculations required to account for the full cost (including waste and effective stumpage costs) of logging operations, suggest that firms may simply seek an acceptable level of profit.[28] Alternatively, logging firms may seek to maximize revenue subject to a satisfactory profit margin.*" Understanding the decision making behavior of logging firms in tropical production forests could provide insight into the opportunities and constraints regarding the adoption of RIL technology, and should be considered a topic for future research.

5. Conclusions and discussion

The overall conclusion of this study is that RIL was less costly, and more profitable, than CL under the conditions reported here for the eastern Amazon. This conclusion generally confirmed the experimental results reported by Barreto et al. (1998) for a different location in this timbershed. In that study, RIL increased profitability of the first harvest by 35%, or nearly twice the gain in profitability reported here (18.5%). However, the difference in profitability across studies may reflect heterogeneity in forest structure across sites and the fact that in this study, productivity parameters were averaged across operations to obtain "typical" values. Taken together, however, the two studies suggest that adoption of RIL would be financially feasible in this timbershed.

Extreme caution must be exercised in generalizing this conclusion. Many factors, including forest type, industrial scale and market conditions may have contributed to the enhanced profitability of RIL in this timbershed. At present, knowledge of the marginal effects of these and other possible factors, in isolation or in combination, on RIL profitability are unknown. Thus, the following discussion considers some of the conditions that may have been salient in affecting the results reported here, and are considered topics for future research.

Relative to other tropical forest regions, such as the dipterocarp forests of Malaysia and Indonesia, harvest intensities in the eastern Amazon are moderate. It is likely that planning enhances skidding productivity under conditions of moderate harvest intensity because felled trees would otherwise be difficult to locate due to density of the remaining foliage and stems. Under conditions of high harvest intensity, however, less foliage and fewer stems remain post-harvest to impede the search for, and recovery of, logs

"Herbert Simon (1956) suggested that firms attempt to "satisfice" (seek satisfactory outcomes) rather than maximize profits, particularly when faced with complex calculations and poor data.

[29] The "revenue maximization" hypothesis was suggested by Baumol (1959).

by skidder operators. Skidding productivity under high harvest intensity may in fact be greater for CL if skidding operators disregard damage caused to trees in the residual stand and travel at greater rates of speed than RIL considerations would dictate.

Topography in the eastern Amazon is, in general, mildly undulating and logging operators don’t operate on steep slopes as is done in hill dipterocarp forests. Environmental constraints, in terms of setting aside environmentally fragile areas, are thus, not as binding. Volumes harvested per harvesting block are likely more similar under RIL and CL in the eastern Amazon than other areas facing more severe environmental constraints, and this condition tends to equalize the financial comparison of RIL and CL. Of course, it should be noted that both a reduction in harvest intensity and the necessity for imposing environmental constraints may occur when RIL is a component of a sustainable forest management system that includes silvicultural, wildlife habitat and other objectives.

Wasted wood incurs financial costs that are not typically accounted for, because accounting depends on a post-harvest inventory to identify wasted wood volume. Thus, typical CL cost accounts are biased downwards. In this study, full cost accounting methods were introduced to capture the direct and indirect costs associated with wasted wood. Full cost accounting enhanced the relative profitability of RIL and would be anticipated to increase the relative profitability of RIL at other sites as well. However, volumes of wasted wood are a function of forest characteristics and logging technology. For example, at the study site, large trees of certain species contain hollow areas inside of boles that are not apparent before testing, either with a hammer or by inserting a saw blade. Failure to “de-select” large trees containing hollows increased the volume of wood wasted, both through splitting during the felling process and poor bucking to cut out non-merchantable sections of logs. Further, good access to domestic markets allowed 40-50 commercial species to be harvested. While this market condition permitted moderate harvesting intensity, it may have hampered correct selection of marketable species by untrained logging personnel. Thus, the volume of timber wasted would be expected to be less in forests where large trees had fewer internal defects and where moderate to high harvest intensities were possible from relatively few tree species.

At the study site, investment in training forest personnel provided a large “environmental dividend” due to less soil disturbance and less damage to the residual stand. At present, the environmental dividend cannot be monetized. However, the Clean Development Mechanism of the Kyoto Protocol may provide an incentive for companies to adopt RJL through payments made for incremental additions in carbon storage. Incremental additions computed from the reduction in damage, and thus, increased biomass of the residual stand, have been estimated for dipterocarp forests in Sabah, Malaysia.[30] There, RIL resulted in a 50% decrease in mortality and a 60% decrease in ground disturbance compared to CL, and these reductions were associated with an increase of 36 Mg C per ha over 60 years. In the current study, damage to a subset of residual stems with dbh > 35 cm was measured. However, the overall damage and ground disturbance results matched those from Sabah. It seems reasonable to predict, therefore, that the carbon storage gains associated with RIL in Sabah may also be realized in the eastern Amazon.[31] It is essential that future research be undertaken to estimate both the biophysical amount and the monetary value of the environmental dividend resulting from the application of RIL technology in tropical production forests.

Finally, this study indicated that under CL, tree hunters focused harvesting pressure on larger trees and fewer species. Also, tree hunters did not locate nearly one-half of the trees that were on the harvest list and could potentially have been harvested. In addition to being inefficient from the perspective of the initial harvest, these trees implicitly contribute to the volume available for re-entry logging during the cutting cycle which ultimately increases the level of ecological damage. Under RIL, the initial structure of the forest, in terms of size and species distributions, was more closely maintained after harvest. Combined with less damage to the residual stand and soils, RIL methods set the standard for timber certification

[30] See (Putz and Pinard, 1993; Pinard and Putz, 1996, and Pinard and Cropper, 2000).

[31] For estimates of above ground biomass based on all size classes for a forest in the middle Amazon (see Keller et al., 2001 in review).

initiatives. Research concerning market development for certified wood products from tropical forests would help advance the cause of sustainable forest management in forest regions otherwise subject to ecological degradation.

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