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ANALYSIS

Financial returns under uncertainty for conventional and reduced-impact logging in permanent production forests of the Brazilian Amazon

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Abstract

Reduced-impact logging (RIL) techniques are designed to improve the efficiency of timber harvesting while mitigating its adverse effects on the forest ecosystem. Research on RIL in select tropical forest regions has demonstrated clear ecological benefits relative to conventional logging (CL) practices while the financial competitiveness of RIL is less conclusive. We conduct a comparative analysis of financial returns to one and two cutting-cycle logging entries for representative RIL and CL operations of the eastern Amazon. Observed variability in harvest efficiency and uncertainties of forest productivity are introduced in a stochastic simulation of future biological and financial returns to the alternative logging systems. Despite the perceived investment risks, RIL harvesting operations generate competitive or superior returns relative to CL for a wide range of discount rates due to gains in harvest efficiency and forest conservation.

Keywords: Amazon; Logging; Tropical forest; Sustainable management; Risk

1. Introduction

Reduced-impact logging (RIL) techniques are being designed and implemented throughout the tropics in order to improve resource use efficiency and conservation in the management of forested areas for timber production. Forestry enterprises across the tropics are targeting more sustainable, polycyclic timber harvesting in permanent production forests (Winkler, 1997; Hout, 1999; **Nittler** and Nash, 1999; Tay, 1999; Armstrong and

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Inglis, 2000). RIL, the harvesting element of a sustainable forest management program, is fundamental to achieving this goal. Research comparing RIL and conventional logging (CL) in Brazil, Ecuador, Guyana, Indonesia, Malaysia and Suriname has conclusively demonstrated that, at similar levels of extraction, RIL reduces residual tree mortality and better conserves the ecological integrity of managed forests (Hendrison, 1990; Johns et al., 1996; Pinard and Putz, 1996; Bertault and Sist, 1997; Winkler, 1997; Elias, 1999; Hout, 1999; Tay, 1999; Holmes et al., 2001). Results of economic studies of the alternative harvest systems are less conclusive, however. Harvest restrictions and operational efficiency, comprising labor productivity and timber recovery variables, commonly determine the comparative financial benefits of RIL and CL operations for initial logging entries (Hendrison, 1990; Barreto et al., 1998; Elias, 1999; Hout, 1999; Tay, 1999; Armstrong and Inglis, 2000; Holmes et al., 2001). When long-term timber harvesting is the landowner's objective, RIL is expected to generate higher future returns relative to CL due to gains in operational efficiency and increased timber productivity of the residual forest, given reduced damage and structural change in initial RIL entries (Barreto et al., 1998; Hout, 1999; Holmes et al., 2001).

Economic rationale posits that if RIL practices yield higher profits than conventional methods, they will be adopted by logging firms. Financial risk associated with the adoption of RIL may be high, however, given practitioner uncertainty concerning its production efficiency relative to familiar CL practices. Moreover, the economic benefits of long-term forest management employing RIL remain unclear due to uncertainties of tenure, market conditions, and forest productivity following disturbance in initial logging entries. Biological uncertainties concerning forest growing stock and merchantable yield constitute an important economic risk that impacts measures of profitability for long-term management (Montgomery, 1996; Erickson et al., 1999). Even with long-term tenure security, market uncertainties concerning future timber prices and land rents justify a precautionary preference among loggers and landowners for liquid assets rather than capital investment in long-term forest management (Tobin 1958; Dequech 2000).

The present study builds upon earlier work in tropical production forests of Paragominas, Brazil that showed RIL to be less costly than CL operations for initial harvest entries due to gains in operational efficiency and reduced timber waste (Barreto et al., 1998; Holmes et al., 2001). A contribution to research on the financial competitiveness of RIL relative to CL is made by explicitly considering observed and potential risk associated with polycyclic harvesting.[1] We consider the influence of fundamental operational, biological and market uncertainties on financial returns to logging over two cutting-cycles for representative RIL and CL operations of the eastern Amazon. For initial entries (year 0), we examine net returns to harvesting under observed variability in harvest efficiency. We then consider the conformity of logging outputs to merchantability criteria as a determinant of profitability. For future harvest entries we do not attempt to estimate the optimal cutting-cycle for polycyclic harvesting, but instead examine returns at constrained intervals determined by legal restrictions and profitability criteria. We compare financial returns to the alternative harvesting systems for two cutting-cycle entries under price, growth, and efficiency uncertainties and a wide range of discount rates. Monte Carlo simulation techniques are employed to generate distributions of expected financial returns that are subsequently compared using Student's *t* -tests. Lastly, we consider the sensitivity of financial returns to operational, biological and market uncertainties.

[1] Uncertainty and risk may be distinguished as suggested by Knight (1921), with uncertainty referring to situations in which the likelihood of outcomes is unknown and risk referring to situations in which the likelihood of possible outcomes is known. In the case of timber management in Brazilian tropical forests, both cases may exist, though knowledge of probabilities is likely to be exceptional. For the present study, we use the terms interchangeably.

2. Study area and logging system description

Lowland, closed-canopy *terra firme* forests of Brazil's eastern Amazon region of Paragominas, Pará (3° S, 50° W) are humid and evergreen with an aboveground biomass of some 300 t ha"[1], over 99% of which is constituted by tree species (Uhl et al., 1988). Industrial sawtimber production in Brazil's eastern Amazon is focused primarily on *terra firme* forest, given its accessibility for mechanized harvest (Eden, 1990). Currently, over forty species are harvested in the Paragominas region. CL operations commonly extract 20-50 m^3 of sawtimber per hectare (ha) (Verissimo et al., 1992).

Beginning in 1995, Fundação Floresta Tropical (FFT) established 500 ha of representative logging blocks in the Fazenda Cauaxi forestland, which is privately owned and managed. Blocks of 100 ha each were harvested under CL and RIL methods for industrial-scale operations in order to provide data for a comparative study of biophysical impacts and economic returns.

FFT's RIL harvest protocol comprises extensive pre-harvest inventory, infrastructure development, and vine cutting, as well as directional felling and skidding techniques intended to minimize damage to commercially important residual trees. The sampled conventional operation is typical of industrial forestry operations in Paragominas, which are conducted by vertically integrated firms like that managing the Cauaxi forestland. CL includes no pre-harvest planning, inventory, or infrastructure development, but instead follows two phases: (1) identification of merchantable stems by a *mateiro* or knowledgeable timber cruiser and felling by daily-contracted sawyers; and (2) expedient, unplanned road construction, log deck construction and skidding of felled stems. The RIL and CL operations employed Stihl AV 51 chainsaws for felling and bucking activities and Caterpillar D6 crawler tractors for road and log deck construction. For skidding of stems to log decks, the RIL operation used a rubber-tired skidder (Caterpillar 525) with winch and grapple, while the CL operation employed a Caterpillar D6 crawler tractor with winch.

Logging operations were conducted in flat or mildly undulating lowland *terra firme* forests, in which no harvest restrictions were necessary to protect steep slopes or riparian zones. Furthermore, RIL was not restricted to excluding seed trees, to observing standards for spatial distribution of extraction, or to establishing set-asides within the stand that would pose opportunity costs for the landowner or logger.

3. Methods

3.1. Costs and revenues

Financial returns to logging are calculated for initial and second cutting-cycle entries, using per unit area costs ($US ha ~') for pre-harvest activities and stumpage fees and per unit volume costs ($US m~~[3]) for harvest activities and gross revenues (Table 1). Costs in 1996 $US are estimated from hourly labor, capital, and machine costs reported in Holmes et al. (2001) and productivity measures from RIL and CL surveys in Paragominas, described below. Gross revenues are calculated for harvested sawtimber volume in 1996 $US log deck prices for three value classes: low ($10.74 m~[3]), medium ($21.61 m~[3]), and high ($58.57 m~[3]) (C.A.P. Ferreira, personal communication, 1997).

Costs of RIL pre-harvest planning and infrastructure activities are compounded forward at a nominal interest rate of 27.4% for 3-8 months, given implementation of these activities prior to logging.[2] RIL training costs are included in calculation of the hourly costs of RIL labor. Training costs are compounded at 27.4% for 5 years to approximate the opportunity cost to the forest manager of such expenditures. The remaining RIL costs and all CL costs are assumed to occur in year 0 for the first harvest entry and at the initial year of second cutting cycle operations. Costs and revenues from future logging entries are

[2]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 rates provides a conservative estimate of these costs.

discounted at 4, 8, and 20% to examine the impact of discounting on the profitability of long-term management.

RIL harvest efficiency measures are drawn from a larger sample of RIL blocks in Cauaxi, other FFT research sites, and from RIL studies by the *Instituto do Homem e do Meio Ambiente da Amazonia* (IMAZON) in Paragominas (Barreto et al., 1998). CL efficiency measures are drawn from IMAZON studies (Verissimo et al., 1992; Barreto et al., 1998) and FFT surveys of timber firms in Paragominas conducted in 1998 (Table 2). RIL and CL harvest impact measures are drawn, respectively, from surveys of harvest blocks 3 and 1 in the Fazenda Cauaxi forestland.

Table 1
Average costs for RIL and CL operations[a]

Activity	RIL cost	CL cost
	$/ha	$/ha
Stumpage fee	193.00	193.00
Block delineation	6.84	–
Inventory[c]	13.70	–
Vine cutting[c]	3.55	-
Data processing[b]	3.12	-
Map-making[c]	6.07	-
Tree marking	3.61	-
Road planning[b]	0.77	-
Road construction[c]	4.33	7.11
Log deck planning[b]	0.45	–
Log deck construction[c]	4.33	7.26
Skid trail layout	7.64	–
Sub-total	247.41	207.38
	$/m³	$/m³
Tree selection *(mateiro)*	-	0.14
Felling (two person)	0.67	0.49
Skidding	1.25	1.99
Log deck operations	1.29	2.01'
Support	0.32	0.41
Overhead	0.32	0.45
Sub-total	3.85	5.49

[a] Costs per activity are those reported in Holmes et al., (2001), with training costs included in unit cost estimates.
[b] RIL cost compounded 8 months at 27.4% per annum.
[c] RIL cost compounded 7 months at 27.4% per annum.
[d] RIL cost compounded 3 months at 27.4% per annum.

3.2. Logging system parameters

In order to correct for the heterogeneity of FFT's forest blocks in our comparisons, we selected observed parameters of felling intensity, timber recovery, and residual damage to simulate RIL and CL harvesting behavior for economic modeling and comparisons. Initial harvest comparisons required the simulation of CL practices on RIL block 3 and of RIL practices on CL block 1. Second CC harvest simulations are conducted for both stands utilizing observed logging parameters for each system. The use of characteristic parameters in modeling assumes that the observed operations suitably portray RIL and CL behavior in terms of success in identifying merchantable stems, extraction intensity per species and size class, and forest damage. Given that our sample was limited to one 100 ha harvesting block per logging system, we were constrained to making this assumption and attempting to account for inherent system variability by modeling operational, forest productivity and market uncertainties.

Felling intensity for each system is defined as the proportion of trees felled per size and value class. Timber recovery efficiency is defined as the proportion of sawtimber volume extracted to log decks relative to that felled. *Conformable* volume is measured as the percentage of recovered sawtimber volume meeting landowner species and size criteria for merchantability. Felled sawtimber volumes for the observed logging operations were 19.74 m^3 ha^{-1} for RIL in block 3 and 25.81 m^3 ha^{-1} for CL in block 1, assuming a taper of approximately 18% for the felled stems. RIL skidders recovered 93% (18.36 m^3 ha^{-1}) of felled sawtimber, all of which conformed to criteria for merchantability. For the CL operation, two cases are distinguished: (1) *conformable volume,* in which non-conform stems contribute nothing to gross revenues, weighted average net recovery was 68.4% of felled volume (17.66 m^3 ha^{-1}); and (2) *total volume,* in which non-conform stems contribute their full value per market class and volume to gross revenues, net recovery was 76.6% of felled volume (19.77 m^3 ha^{-1}).

Table 2
Assumed distributions for harvest efficiency, growth and future prices

Activity	Unit	RIL			CL		
		Minimum	Expected value	Maximum	Minimum	Expected value	Maximum
Delineation	ha h-'	0.89	1.19	1.20			
Inventory	hah-'	0.41	1.36	2.08			
Tree hunting[3]					0.96	1.03	1.11
Vine cutting	hah-'	0.41	1.36	2.08			
Tree marking	hah-'	1.72	2.81	3.40			
Road planning	ha h"[1]	7.90	15.66	15.67			
Road construction	hah-'	7.44	12.50	14.00	4.09	5.70	7.30
Log deck planning	ha h-.[1]	20.00	26.93	32.00			
Log deck construction	hah-'	10.31	12.50	15.00			
Skid trail layout	hah-'	0.93	1.34	1.78			
Felling (2 person)	m^3h-'	11.37	18.65 v 1	20.77	18.96	20.46	25.50
Skidding	m^3h-'	24.42	31.66	44.68	19.90	22.39	26.60
Log deck operations	m^3h-'	24.42	31.66	44.68	19.90	22.39	26.60
Growth[15]	cm per year	0.01	*G,*	2G,-0.01			
Timber price[c]	$m-[3]	0.5*i>	*P*	\.5*P*		same as RIL	
Stumpage fee[d]	$ ha~'	96.50	193.00	289.50			

[a] CL tree hunting involves identification of merchantable stems by a local tree cruiser or *mateiro,* while RIL inventory includes identification, measuring, and mapping.

[b] 6, is the growth increment per size class estimated using our growth model. Maximum growth increment modeled was 1.39 cm dbh per year.

[c] Future timber price distributions are estimated relative to 1996 log deck prices (P) per value class: $10.74 m~[3] (low), $21.61m~[3] (medium), $58.57 m~[3] (high).

[d] Stumpage fees are estimated relative to 1995 prices for Paragominas, following Stone (1996).

Damage characteristics are defined as the observed damage inflicted upon the residual commercial inventory in each forest block. The measures are drawn from field surveys conducted by FFT in the Cauaxi blocks following logging. Only those damages judged fatal to residual commercial species with diameter at breast height (dbh) of 35 cm and greater were considered in harvest and growth simulations. Fatal damage to commercial and potentially commercial stems $\geq$ 35 cm dbh was measured at 10.4% for CL and 2.6% for RIL (Holmes et al., 2001).

3.3. Forest growth and yield model

We employ a diameter class growth model to project stand development following harvesting. The model was developed by deriving accounting equations for five components of stand growth (Eq. (1)) in order to project changes in the number of trees per size class over time (Davis and Johnson, 1987; Howard and Valerio, 1992).[3]

$$N_{i,t+1} = N_{i,t} + I_i - U_i - H_i - D_i - M_i \quad (1)$$

where, $N_{i<t+1}$, number of trees in size class *i* after one growth interval; N_{it}, number of trees in class / at the beginning of the growth period *(t); /,-,* number of trees growing into class *i* during the growth period; £/,-, number of trees growing out of class *i* during the period; H_t, number of trees felled in class *i* in the period, *D,,* number of trees

[3] Size classes comprise stems 35-155 cm dbh in 10 cm increments.

in class / fatally damaged during harvest operations; M_h number of trees in class / that die due to natural causes in the period.

Ingrowth and upgrowth are estimated by an annual diameter growth function (Eq. (2)). The growth function was derived by regression analysis of 19 size class growth measures from disturbed and undisturbed forests from IMAZON sites in Paragominas (3° S, 50° W) (Vidal and Viana, forthcoming) and in Brazil's Tapajós National Forest (2°45'S, 55° W) (Silva, 1989).

G, = - 0.0189 - 0.00747 + 0.0178$ - 0.00015S? + 0.02055 - 0.0354yS',.
(-0.673) (-0.123) (2.239) (-1.435) (1.698) (-0.814) **(2)**

where, G;, average annual growth increment per diameter class (cm); *y*, dummy variable^o reduce growth increment to that of an ifnfogged forest; S_h size class (cm dbh); #, stand basal area (m^2 ha~') following logging; i?^{2} = 0.69; *F*-statistic = 5.81 (5,13), P<0.01; ^-statistics for the parameters are shown in parentheses.

Growth increments are assumed higher for 3 years immediately following harvest, in which the forest canopy is open and tree growth is stimulated (Silva, 1989). A dummy variable *(y)* is included to estimate the growth increment per diameter class for the remainder of the growth period, which is assumed to be equivalent to that observed in an unlogged forest (Silva, 1989). In order to correct for potential misspecification of the growth function, we vary growth increment estimates in our risk analysis of future harvest yield and financial returns (Table 2).

3.4. Cutting-cycles

We do not attempt to estimate the optimal cutting-cycle for polycyclic harvesting. The value growth of the Cauaxi forest blocks never exceeds 2% per year beyond the first harvest entry. If one follows the criterion of postponing harvest as long as the marginal value growth rate exceeds opportunity cost (Duerr and Bond, 1952), the optimal solution would prescribe immediate liquidation of the merchantable growing stock. We apply alternative criteria, which may more accurately reflect the expected behavior of the landowner under constrained selection harvesting with a minimum 30-year cutting-cycle.[4] These criteria are: (1) this constrained legal minimum 30-year interval or if merchantable volume is inadequate to cover harvesting costs at this time; (2) the minimum, 'break-even' cutting-cycle interval necessary for profitable second cutting-cycle harvesting.

3.5. Risk analysis

To account for the uncertainty that influences the estimation of bioeconomic returns to long-term management, we consider observed and projected variability in four determinant variables, notably: operational efficiency, stand productivity following logging, future sawtimber prices, and future stumpage prices (Table 2). Ten thousand iterations are conducted per modeling scenario. Operational efficiency 'endpoints' (minima and maxima) used in the simulations are based on actual endpoints measured by FFT in Fazenda Cauaxi and by IMAZON in Paragominas (Verissimo et al., 1992; Barreto et al., 1998). It is assumed that the regression of forest growth data from production forests of the eastern Amazon (Eq. (2)) may not accurately project residual stand growth, thus we include a broader, triangular distribution for growth variability sampling than may be estimated utilizing standard errors of the regression. Timber and stumpage price distributions are also assumed to be triangular. Tests of the hypotheses that differences between net returns to harvesting, under uncertainty are significantly different follow Student's *t* -tests of the difference between mean values for samples of unequal variance.

[4] Service order 001-89/IBAMA of the Brazilian Institute of the Environment.

Table 3
Expected net revenues ($US ha~') and coefficient of variation for initial harvest entries under variable harvest efficiency

	RIL	CL_C	/-stat	CLx	(-stat
Block 1	128.48 (0.08)	100.73 (0.07)	2.29 *P<0.05*	171.61 (0.04)	3.56 i>0.001
Block 3	131.34 (0.08)	73.80 (0.08)	4.80 *P*< 0.001	136.50 (0.05)	0.43 Not significant

4. Results and discussion

4.1. Initial logging entries

When species and size restrictions for merchantable sawtimber are strictly enforced, RIL consistently yields superior financial returns to CL for initial logging entries, under the obseffed uncertainties of harvest efficiency (Table 3, Fig. 1). RIL is expected to yield an incremental benefit of $27.75 ha"[1] in stand 1 and of $57.55 ha"[1] in stand 3 relative to conformable CL operations (cace CLc). Greater efficiency in recovering felled timber yields important financial benefits to RIL. The RIL operation recovered 25% more of the felled sawtimber volume than CL_C due to fewer lost stems, reduced felling and bucking waste, and full compliance with merchantability criteria. While 100% of RIL harvested sawtimber conformed to merchantability criteria, only 89% of the recovered sawtimber volume under CL was conformable and thus merchantable if such criteria are strictly applied.

It is assumed that the 11% of CL extracted volume that was non-conform is sold at full market value to the mill (case CLj-), however, CL net revenues are expected to be competitive with or significantly higher than those for RIL (Table 3, Fig. 1). The estimates of CLp profitability may be exaggerated, as we assume 100% of market value m~[3] for all non-conform stems, some of which are likely left on the log deck or are mill waste rather than merchantable output. Nonetheless, given the potential gains in profitability of milling non-conform timber, it may be expected that CL operations attempt to mill and market non-conform stems. CL appears to maximize profitability in the turnover of harvest blocks and in maintaining a flow of sawtimber from forest to mill, rather than extracting an optimal volume from the available merchantable stock. CL is less profitable than RIL if revenues are restricted to only conformable stems, and financially superior or competitive if non-conform timber is sold. More effective regulation of logging alone would provide financial incentives to adopt RIL practices.

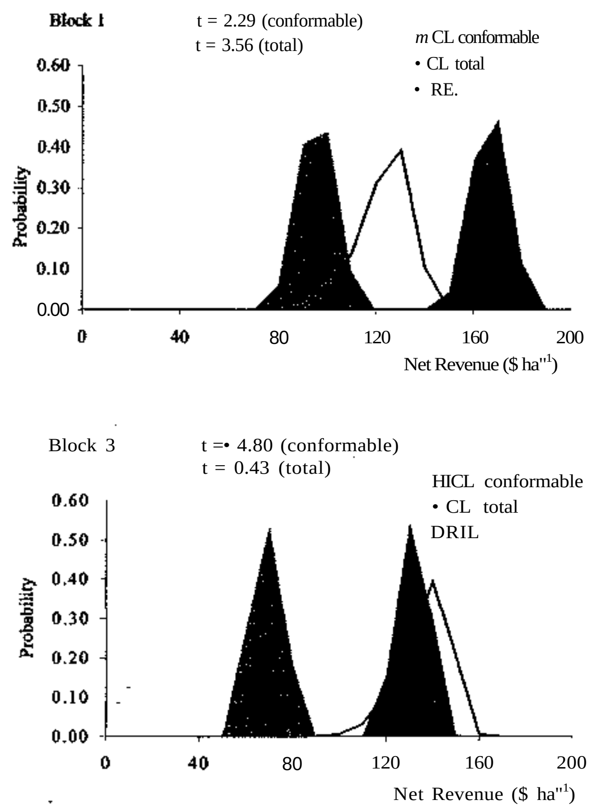

Fig. 1. Expected net revenues for initial RIL and CL entries with variable harvest efficiency.

The variability of financial returns to initial logging entries is most sensitive to the efficiency of skidding activities (mean correlation coefficient (/?): RIL $p = 0.63$, CL $p = 0.98$). Skidding is more efficiently implemented under RIL and thus less costly relative to CL. The lower efficiency of CL operations is primarily attributable to the lack of harvest planning and infrastructure development, which forces logging teams to waste time searching for merchantable stems, orienting felled timber for extraction, and skidding through dense forest to unplanned log decks. The efficiency of log deck operations is highly significant for RIL ($p = 0.65$), as it depends upon skidding efficiency.

Felling efficiency also has an important impact on the variability of expected profits (RIL p — 0.19, CL $p = 0.15$). RIL felling activities aremore time consuming and thus more costly thail'those observed for CL due to RIL investment m directional felling practices. Cost reductions gained in improved RIL skidding efficiency largely compensate for the additional costs of directional felling, however.

4.2. Two cutting-cycle entries

Harvesting is expected to be profitable for both RIL and CL following the 30-year minimum cutting-cycle interval in the well-stocked forest (block 1). Neither RIL nor CL harvesting is profitable in block 3, however, due largely to an existing scarcity of commercial growing stock in this forest plot. Stocking of commercial species in the 40 cm dbh class was 47% lower in block 3. The minimum cutting-cycle lengths necessary to generate positive net revenues for second entries in block 3 are estimated at 33 years for RIL and 46 years for CL.

Under deterministic estimation for harvest intervals of 30 years (block 1) and 33 years (block 3), financial returns to two cutting-cycle entries are consistently greater for RIL operations (Table 4). The incremental financial benefits of RIL derived from its greater harvesting efficiency are increased in second cutting-cycle entries due to 'its superior' conservation of merchantable growing stock. Timber volume increments following RIL are 13.3% (5.0 m^3 ha"~') greater in block 1 and 7.2% (2.53 m^3 ha~') greater in block 3 relative to CL residuals, over respective 30 and 33-year cutting-cycles. Estimated future values of standing sawtimber at second harvest entry are 15.8% ($114.39 ha-') higher in stand 1 and 9.5% ($64.01 ha"^{1}) higher in stand 3 following RIL. Reduced fatal damage to future crop trees accounts for most of the incremental growing stock gain under RIL.

Table 4
Deterministic estimation of NPV for initial and second cutting-cycle returns

	RIL	CL_C	CL_T
r = 0.04			
Block 1	160.55	100.27	115.35
Block 3	144.59	58.64	68.17
r = 0.08			
Block 1	145.50	98.41	103.27
Block 3	142.36	67.35	70.09
r = 0.20			
Block 1	138.79	97.57	97.77
Block 3	141.60	70.76	70.85

r, discount rate.

RIL is expected to allow for more profitable reentry at harvest intervals of 30-40 years due to gains in the conservation of the timber growing stock. Important changes to forest structure are caused during initial logging entries for both harvesting systems, however, resulting in a greater dependence on smaller stems for second harvest entries at the harvest intervals examined (Fig. 2). Extracting comparable timber volumes (20-30 m^3 ha~') without silvicultural guidance for sustained timber yield would likely result in a decrease in standing volumes for subsequent harvests and an important increase in cutting-cycle length.

Net returns to RIL and CL for the second harvest entry comprise a very small part of the profits captured over the two cutting-cycle horizon. Assuming pre-harvest costs are compounded at 8%, the future value of returns to RIL for a second cutting-cycle entry at 30 years in block 1 is estimated at $70.36 ha~' or 51% of initial profits. CL is expected to yield positive but lower profits relative to RIL and only 34% of its initial profits from block 1 (CL_C \$8.89 ha"[1]; CLj- \$57.80 ha"[1])- The existing deficiency of commercial timber stocking in block 3 and depletion of the merchantable timber during initial harvests yields low profit expectations for second cutting-cycle entries at 33 years. The future value of RIL profits for the second cutting-cycle entry is a mere \$9.81 ha-[1] or 7% of initial net returns in block 3. CL incurs a net *cost* for harvesting in block 3 at 33 years due to its greater impact on residual stand stocking and productivity.

Under stochastic estimation with uncertain efficiency, biological productivity, and market prices, RIL is expected to generate competitive or superior financial returns relative to CL for two cutting-cycle entries for a wide range of discount rates (Table 5). The simulated results under economic risk generate more accurate estimates of expected NPV than the deterministic model and the comparative analysis is more rigorous as a broader distribution of potential returns to each harvesting system is examined (Fig. 3). Relative to the deterministic results, expected financial returns under uncertainty are lower for both harvesting systems. This may largely be explained by the skewness of the distributions for harvest efficiency variables utilized in stochastic analysis. These fundamental production uncertainties indicate that financial benefits of RIL may be lower than postulated in earlier studies (Barreto et al., 1998; Holmes et al., 2001); however, the comparative financial advantage of RIL relative to conventional practices in the Eastern Amazon is conclusively demonstrated (Table 5).

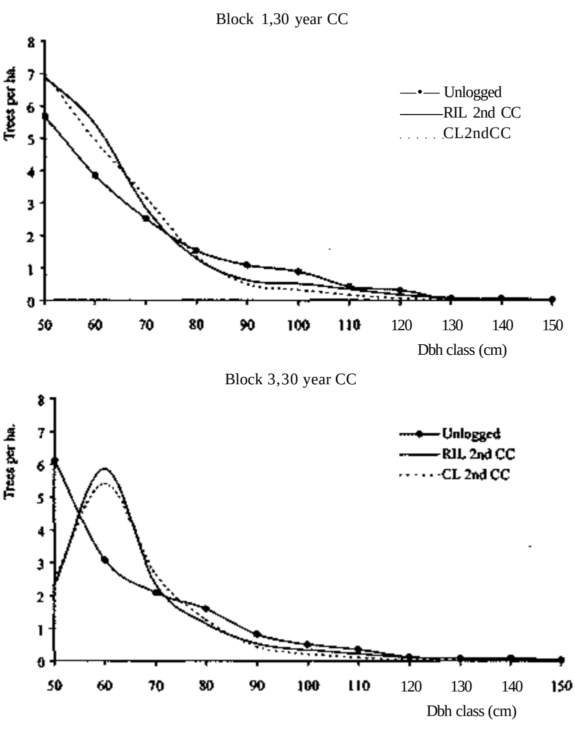

Fig. 2. Forest structure under RIL and CL following the legal minimum harvest interval, relative to unlogged conditions.

At the lowest simulated discount rate of 4%, returns to the two harvesting systems are most competitive, given the important influence of timber and stumpage price uncertainties on future returns to harvesting (Table 5). At 4% discounting, the variability of NPV estimates is most sensitive to the prices of medium value species and stumpage fees (Table 6). The significant effect of these market uncertainties at low discount rates may be expected, given the important volume contribution of medium-value species in harvest returns (64% and 70% of initial harvest volumes for RIL and CL, respectively) and importance of stumpage fees as a proportion of total costs (mean 58% for all samples).

Operational efficiency becomes increasingly decisive for the profitability of management with increases in the discount rate. When future returns are discounted at 8%, RIL returns are significantly greater than those for CL due primarily to gains in skidding efficiency and timber recovery (Table 6). At the highest simulated discount rate (20%), operational efficiency determines the profitability of second cutting-cycle harvests and gains in skidding efficiency largely account for the superior financial performance of RIL. NPV variability for both harvest systems is most sensitive to skidding and felling efficiency at a 20% discount rate, while market and biological uncertainties become relatively insignificant (Table 6).

Simulation results indicate that RIL is both biologically and economically advantageous relative to conventional logging practices of the eastern Amazon. At cutting-cycles of 30 and 33 years examined for our comparative analysis, CL is constrained to extracting lower merchantable vol-

Table 5
Expected NPV (1996 $US ha^{-1}) and coefficient of variation under efficiency, price, and growth uncertainties

	RIL	CL_C	r-stat	CL_T	i-stat
r = 0.04					
Block 1	150.93	105.83	1.32	121.24	0.84
	(0.17)	(0.21)	Not significant	(0.20)	Not significant
Block 3	135.40	64.66	2.43	74.75	2.03
	(0.17)	(0.28)	$P<0.05$	(0.26)	$P<0.05$
r = 0.08					
Block 1	135.56	102.42	2.02	107.38	1.69
	(0.10)	(0.09)	$P<0.05$	(0.09)	$P<0.10$
Block 3	132.35	71.15	4.15	74.06	3.92
	(0.11)	(0.09)	$P<0.001$	(0.11)	$P<0.001$
r = 0.20					
Block 1	128.72	100.86	2.30	101.07	2.30
	(0.08)	(0.07)	$P<0.05$	(0.07)	$P<0.05$
Block 3	131.28	73.70	4.73	73.79	4.73
	(0.08)	(0.08)	$P<0.001$	(0.08)	$P<0.001$

r, discount rate.

umes, given inadequate recovery and growth of residual stands. This implies not only sub-optimal forest resource use from a silvicultural perspective, but also unsustainable economic returns to long-term management. High levels of sawtimber extraction, targeted depletion of large stems of high and medium value, and high levels of residual stem damage in initial CL entries results in an important decrease in the cost efficiency of second cutting-cycle harvests and to expectations of low or negative returns to CL at short cutting-cycle intervals (30—35 years). RIL, in contrast, yields positive expected returns and remains cost efficient for second cutting-cycle entries following 30 and 33-year growth intervals in the sampled forest blocks.

5. Conclusions

RIL generates competitive and, in most cases, superior financial returns relative to industrial-scale CL operations typical of the eastern Amazon for both initial and second cutting-cycle harvest entries. This conclusion holds true under conditions of uncertainty for operational, biological and market conditions that largely determine expected financial returns to logging in the region.

The incremental costs of implementing RIL, including sunk investments in pre-harvest planning and training, are more than compensated by gains in operational efficiency and timber recovery. RIL improvements in the planning and execution of skidding activities should be readily adopted by the logging industry, given the sensitivity of financial returns to skidding efficiency and the clear financial benefits of RIL methods.

RIL profitability is consistently superior to CL for initial harvest entries when non-conform sawtimber is excluded from CL revenues. More effective regulation of logging for compliance with species and size merchantability criteria would provide clear financial incentives to adopt RIL.

RIL demonstrates clear forest productivity benefits by reducing harvest impacts on residual stems and more effectively maintaining forest structure. Relative to conventional practices, RIL may be expected to yield greater profitability for second cutting-cycle entries as it enables more rapid reentry and yields a more valuable sawtimber stock from logged stands. Implementing RIL without appropriate silvicultural guidelines is an insufficient prescription for sustainable forest management, however.

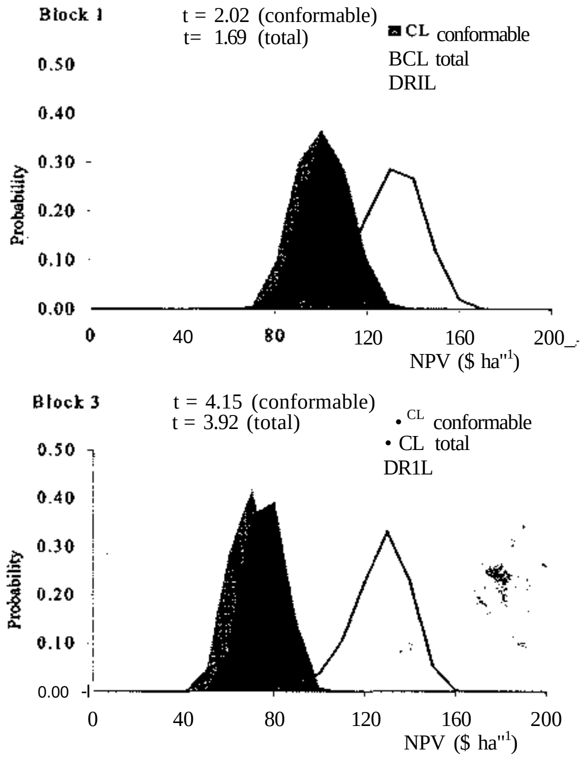

Fig. 3. Expected NPV under efficiency, price and growth uncertainties at 8% discount rate.

Uncertainties concerning the marginal efficiency gains and cost reductions of RIL systems relative to familiar, highly profitable practices may create a resistance to change among logging firms. However, such resistance is unwarranted, given the clear financial benefits of RIL for both one and two cutting-cycle horizons under substantial economic risk.

Table 6
Sensitivity of expected NPV variability to source of uncertainty

	Source of uncertainty (correlation coefficient)	
	RIL	CL
r = 0.04	Medium value spp. (0.54)	Medium value spp. (0.61)
	Stumpage (-0.46)	Stumpage (-0.55)
	Log deck operations (0.33)	Skidding (0.37)
	Skidding (0.32)	High value spp. (0.20)
	Growth 30 cm dbh (0.25)	Growth 30 cm dbh (0.12)
r = 0.08	Log deck operations (0.55)	Skidding (0.74)
	Skidding (0.54)	Medium value spp. (0.42)
	Medium value spp. (0.33)	Stumpage (—0.38)
	Stumpage (-0.26)	High value spp. (0.14)
	Felling (0.16)	Growth 30 cm. dbh (0.07)
r = 0.20	Log deck operations (0.65)	Skidding (0.98)
	Skidding (0.64)	Felling (0.14)
	Felling (0.19)	Road construction (0.13)
	Inventory (0.14)	Growth 80 cm dbh (-0.02)
	Skid trail layout (0.11)	Medium value spp. (0.02)

r, discount rate.

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