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Financial and Economic Analysis of Reduced Impact Logging

Thomas P. Holmes*
Southern Research Station, USDA Forest Service, Asheville, USA
Research Triangle Park, North Carolina, USA

Abstract

Concern regarding extensive damage to tropical forests resulting from logging increased dramatically after World War II when mechanized logging systems developed in industrialized countries were deployed in the tropics. As a consequence, tropical foresters began developing logging procedures that were more environmentally benign, and by the 1990s, these practices began to be described as "reduced-impact logging" (RIL) systems. As scientific evidence accumulated demonstrating that RIL techniques could substantially reduce logging impacts on the residual forest relative to conventional logging (CL), attention turned to understanding the financial conditions under which logging firms would choose to implement RIL. While most studies conducted in Latin America show that RIL is financially competitive or superior to CL, research in Southeast Asia and Africa suggests that economic incentives will likely be required to induce logging firms to adopt RIL. One approach that appears promising to promote better logging practices in the tropics is to offer payments for the incremental carbon retained by RIL systems.

Keywords

Bioeconomic models; Carbon payments; Forest damage; Forest resilience; Sustainable tropical forest management

Introduction

The prevalence of destructive logging practices in the tropics exhibits a severe disregard for future forest productivity and a "dictatorship of the present" (Chichilnisky 1997) over future generations. Although a similar myopia was evidenced in the forest history of the United States and other industrialized countries, the loss of tropical forest biodiversity (Gibson et al. 2011) and increasing risk of crossing ecological tipping points (e.g., Barlow and Peres 2008; Malhi et al. 2009) during an era of rapid climate change suggest that the global consequences of tropical deforestation and degradation may be much more severe than prior human-mediated forest disturbances.

Global concern with the fate of tropical forests has led to an active debate regarding the degree to which tropical forests should be managed for a dominant use (such as parks or timber plantations) versus management for multiple uses (such as timber, non-timber forest products, and other ecosystem services). This debate has often led to polarized characterizations of alternative perspectives, pitting "conservationists" against "logging advocates" (Putz 2004). On the one hand, it has been argued that conservation funding should be targeted to the creation of parks and protected reserves, with the hope (not always realized, e.g., Gaveau et al. 2012) that protected areas will minimize the human footprint on tropical forest ecosystems (Bowles et al. 1998; Rice et al. 1997). Alternatively, it has been argued that logged forests can

*Email: tholmes@fs.fed.us

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provide surprisingly high conservation values (Chazdon 1998; Chazdon et al. 2009; Gibson et al. 2011; Putz et al. 2012; Zarin et al. 2004) and therefore incentives for the adoption of improved methods of selective logging are warranted (Putz et al. 2000). Of particular importance, an emerging literature suggests that careful logging in tropical forests can significantly reduce carbon losses from forest biomass and soil profiles (Fisher et al. 2014; Healey et al. 2000; Mazzei et al. 2010; Pinard and Putz 1996; Pinard et al. 2000; Putz et al. 2008; Sist et al. 2014).

Despite the extensive area assigned to protection forest (roughly 358 million hectares; Blaser et al. 2011), most tropical forests outside protected areas will be (or have been) selectively logged due to the substantial profits that can be obtained during the initial harvest entry. Recent evidence suggests that the human footprint imposed by harvesting tropical forests is dramatic: at least 20 % of all tropical forests were logged between 2000 and 2005 (Asner et al. 2009). Further evidence suggests that logging operations typically treat tropical forests as nonrenewable resources: in ITTO (International Timber Trade Organization) member countries, the area of the natural tropical production PFE estimated to be sustainably managed in 2011 was only about 4 % of the PFE (Blaser et al. 2011).

Conventional logging (CL) operations in tropical production forests are typically carried out by untrained, unsupervised crews that operate without detailed harvest plans that would help them find and extract harvest trees in an efficient and ecologically sound fashion. Consequently, collateral damage to the residual forest stand is high. Although a recent meta-analysis of more than 100 scientific publications revealed that selectively logged forests retain 85–100 % of plant and animal species after harvest, timber yields available for subsequent harvests were found to decrease by nearly 50 % after the first harvest (Putz et al. 2012). Diminished future timber yield is consequential because a loss in potential future economic profitability reduces the likelihood of sustained timber management (Asner et al. 2006; Barreto et al. 1998; Macpherson et al. 2010).

Concern with extensive damage to tropical forests resulting from logging increased dramatically after World War II when mechanized logging systems developed in industrialized countries were deployed in the tropics (Dykstra 2002; Fox 1968; Nicholson 1958; Wyatt-Smith and Foenander 1962). As a consequence, topical foresters began developing logging procedures that were more environmentally benign, and, by the 1990s, these practices began to be described as “reduced-impact logging” (RIL) systems (Putz and Pinard 1993). This term generally refers to “intensively planned and carefully controlled timber harvesting conducted by trained workers in ways that minimize the deleterious impacts of logging” (Putz et al. 2008, p. 1428). Over 200 studies have been published on RIL (FAO 2004) and conservation interest in this approach continues to expand due to its congruence with efforts to retain forest carbon (REDD+), certify sustainable timber management, devolve control of forests from governments to local communities, and reduce illegal logging.

In this chapter, we provide an overview of RIL techniques and explain how this approach to environmentally sensitive logging is a necessary (but not sufficient) step in developing sustainable tropical timber management systems (section “Reduced Impact Logging Systems”). We then focus attention on the financial analysis of RIL, as juxtaposed with CL (section “Financial Comparison of Conventional and Reduced Impact Logging”). As described in detail, comparative analyses have been conducted to evaluate the financial aspects of initial harvests as well as potential future harvest decisions based on mathematical models that forecast forest growth. Based on our literature review, we conclude that while RIL systems appear financially competitive in the cases observed in South America, this result does not hold for either Southeast Asia or Africa unless some form of economic incentive is provided

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(section "Conclusions and Recommendations"). One approach that appears promising, and deserving of future research, is linking carbon payments with improved logging methods. We also suggest that future research should develop a better understanding of how careful logging can increase the resilience of tropical forests to tipping points resulting from the interaction of climate, drought, and wildfires.

Reduced Impact Logging Systems

The RIL approach to selective timber harvesting does not provide a set prescription, but adapts best harvesting techniques, based upon the FAO model code for forest harvesting practice (Dykstra and Heinrich 1996), to management objectives, ecosystem characteristics, and market conditions. RIL systems generally include the following steps:

- Macro-planning of harvest areas for roads, bridges, and other permanent features
- Preharvest inventory and mapping of trees
- Preharvest planning of secondary roads and skid trails
- Preharvest 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
- Optimal size of landings
- Minimal ground disturbance
- Slash management
- Maintenance of primary and secondary roads used in the harvest area
- Closure of harvested areas, where possible

In one sense, RIL systems are not new, as they adopt logging technology that has been developed in temperate forests to tropical forest ecosystems. RIL is often considered to be one component of an overall silvicultural system designed to maintain future timber productivity and other conservation values. The fact that logging intensity and species diversity in the tropics are much different than in temperate forests greatly complicates the design of RIL operations. For example, average logging intensity in polycyclic tropical harvest systems is less than 30 $m^3\ ha^{-1}$, representing roughly 5–10 trees ha^{-1}, each of which may be a different species (Dykstra 2002). The variation in the harvest intensity of polycyclic logging systems around this average spans more than two orders of magnitude – from less than 1 $m^3\ ha^{-1}$ in Bolivia to more than 100 $m^3\ ha^{-1}$ in Indonesia and Malaysia (Putz et al. 2001). Designing the spatial layout of felling and log removal operations, as well as determining the level of harvest intensity that will promote future economic and ecological sustainability, poses substantial challenges for forest managers.

Despite the interest in promoting RIL operations to advance conservation goals in tropical forests subject to timber production, it is clear that RIL, by itself, does not guarantee long-run sustainable timber management (Putz et al. 2008; Sist and Ferreira 2007). Other silvicultural interventions, such as retaining seed trees in harvested stands, planting seedlings of commercial species, or liberating crop trees from competing vegetation, may be required to assure the ecologic and economic sustainability of logged areas (Peña-Claros et al. 2008; Putz et al. 2001; Wadsworth and Zweede 2006). In some cases where commercially valuable species are regenerated by large-scale disturbances such as hurricanes (e.g., *Swietenia macrophylla* and *Cedrela* species in the neotropics, *Entandrophragma* species in Africa, and

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Shorea leprosula in Asia), regeneration may require creating logging disturbances of sufficient size and intensity to mimic natural regeneration processes (Frederickson and Putz 2003; Sist and Brown 2004).

While not sufficient, RIL is generally considered a necessary prerequisite for sustaining profitable timber harvesting over several cutting cycles (Macpherson et al. 2010; Putz et al. 2008). RIL systems have been consistently shown to reduce damage to tropical forest ecosystems by limiting mortality of noncommercial and potential future crop trees by reducing soil disturbance by heavy equipment (e.g., Boxman et al. 1985; Johns et al. 1996; Pinard and Putz 1996; Uhl et al. 1997). In addition, RIL systems provide a method for maintaining the carbon sequestration functions (Mazzei et al. 2010; Putz and Pinard 1993; Sist et al. 2014) and structural diversity of tropical forests (Frumhoff and Losos 1998). Zweede et al. (2003) found that reentry logging is possible in well-planned and executed RIL systems in the neotropics with little marginal damage to the stand. Because logging has the largest impact of any silvicultural treatment on forest condition, the adoption of RIL systems can be the first step in developing sustainable forest management in tropical production forests.

To be effective in attaining both short-run and long-run goals for forest conservation, RIL operations need to be congruent with overall management objectives and ecosystem characteristics. For example, logging based solely on minimum diameter limits may be inimical to ecological sustainability, particularly in forests where diameter limits lead to high felling intensities (Sist et al. 2003). Recent evidence indicates that, to maintain high levels of aboveground live biomass consistent with carbon storage goals, logging operations need to exhibit special care in protecting large trees in the residual stand from harvesting damage (Sist et al. 2014).

Financial Comparison of Conventional and Reduced Impact Logging

Beginning in the late 1990s, as the ecological benefits of RIL operations were coming to be consistently documented across many tropical forest regions, researchers began focusing attention on the financial values that might motivate logging operations to adopt RIL principles. Although some logging analyses consider a subset of activities associated with RIL, such as the benefits of future crop tree flagging and skid trail planning (Krueger 2004), studies concerned with a comparative financial analysis of RIL relative to CL have analyzed entire logging systems. All RIL-CL comparative logging studies have reported key financial parameters associated with an initial logging entry, and a subset of studies have considered financial results from multiple logging entries. Because the costs of initial and multiple logging entries are incurred over time, both approaches must account for temporal costs using discounting (or compounding) so that all costs and receipts are adjusted to a common point in time. Further, studies including a second logging entry require the use of a growth and yield model for the residual stand, taking account of the differential damage from CL and RIL, so that meaningful comparisons of future harvests can be made.

Economic logic suggests that, if a set of ecological and market conditions were identified where the profits obtained from RIL were clearly (and substantially) greater than the profits from CL, then self-interest might provide the necessary incentives for RIL adoption. Further, if it was learned that RIL was more costly than CL, under specific ecological and market conditions, then such information could be used to assess the magnitude of economic incentives (such as carbon payments) that would be required to encourage adoption of RIL. This economic rationale, combined with the hope that the conditions dictating outcomes (e.g., availability of equipment, low staff turnover, limited environmentally sensitive areas) could be generalized beyond the individual case studies, set in motion a series of independent studies to compare the costs and revenues of RIL vis-à-vis CL.

Two general approaches have been adopted by researchers seeking to compare the financial aspects of RIL and CL: (1) side-by-side comparisons and (2) bioeconomic models (for a more complete description of

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this modeling approach, see the chapter on ► Bioeconomic Approaches to Sustainable Management of Natural Tropical Forests). Side-by-side comparisons provide what economists refer to as "positive" analysis, that is, analysis based on observations of actual behavior. In contrast, bioeconomic models are "normative," meaning that these models posit an assumed decision rule (e.g., maximizing profits or net present value) subject to a biological growth constraint. Both approaches recognize that, relative to many other production systems, tropical forest logging systems are complex to analyze because harvesting requires movement of people and equipment through a continuum of changing forest conditions due to factors such as hydrologic features, topography, weather, and spatial distances between target species. Further complicating matters is the often substantial price differentials between individual tropical timber species or species groups. Meaningful financial comparisons of alternative tropical logging systems must therefore address, in some fashion, the potentially confounding influence of heterogeneous forest and market conditions.

Side-by-side comparisons address the heterogeneity problem by establishing RIL and CL logging blocks in close spatial proximity so that forest and market conditions are as similar as possible when estimating productivity and financial parameters. Although most side-by-side comparisons use observations collected from an individual logging block or enterprise, some studies use data sampled from multiple logging blocks or enterprises to estimate average, or typical, productivity and financial parameters across a broader sample of observations (e.g., Holmes et al. 2002). When data are available from multiple logging blocks or enterprises, it is possible to use data on the entire distribution of productivity and financial parameters across cutting blocks or firms to simulate a distribution of outcomes rather than relying on a summary statistic, such as average (e.g., Boltz et al. 2001). One advantage of the second option is that it allows analysts to test hypotheses about statistically significant differences between RIL and CL operations.

Bioeconomic models address the heterogeneity problem by assuming that alternative logging operations use the same decision rule (e.g., maximizing profits) for organizing timber harvests. These models also are parameterized using economic and biological data that are drawn from, or are thought to approximate, conditions characterizing side-by-side studies. Each of these approaches is discussed in greater detail below.

Side-by-Side Comparisons of RIL and CL

The first step in conducting side-by-side analyses of alternative logging systems is to carefully identify every activity associated with each logging system. Next, estimates of the productivity associated with each activity are obtained using time and motion studies to observe the amount of time (e.g., hours) required for people (labor) and machinery/equipment (capital) required to accomplish each activity. The productivity of some activities associated with fixed costs will be area based, such as road and log deck construction. Having obtained information on the labor time (t_l) and capital time (t_k) required for each area-based activity and the hourly costs of labor (c_l) and capital (c_k) used in those activities, average fixed costs (f) for each activity can be computed using the formula

$$f = \frac{t_l(c_l) + t_k(c_k)}{q} \tag{1}$$

where q is the timber quantity (generally in m^3) harvested from the area under consideration. We note that capital costs associated with factors such as depreciation or interest on loans must be included in c_k. Likewise, all expenditures associated with labor, such as workman's compensation, must be included in c_l.

The productivity of activities that vary with harvest intensity, such as felling, bucking, or skidding operations, requires volume-based measurement. The average variable cost associated with these activities can be computed as

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$$v = \frac{c_l + c_k}{p} \tag{2}$$

where p is the harvest productivity (generally in terms of $m^3\ h^{-1}$).

In addition to fixed and variable costs, some side-by-side studies include the cost of obtaining harvesting rights (stumpage fees or royalties). Including this cost category is important when the volume of wasted wood (e.g., felled logs not found by skidding crews) varies substantially between CL and RIL operations because wasted wood increases the effective stumpage price per unit volume recovered (Barreto et al. 1998; Holmes et al. 2002). It may also be important to compute the direct cost of wasted wood (e.g., the felling costs associated with trees that split or logs not found by skidding operators) in CL and RIL operations. Finally, we note that it is important to include the costs of training forest workers in RIL operations (Holmes et al. 2002).

All RIL-CL comparative financial studies that we reviewed provided data on the costs of each type of logging system, either on a unit volume recovered or an area basis. Some studies also included information on gross and net revenues (profits). In order to understand the nuances of the various comparative logging studies that appear in the published literature, as well as to develop an appreciation of the improvements and innovations in comparative financial analysis as the field evolved from 1989 to present, we review this literature in chronological order.

Perhaps the earliest side-by-side comparison of logging efficiency in the tropics was a study that assessed the CELOS silvicultural system as developed in Suriname (e.g., Jonkers 1987). This system was designed to use polycyclic, selection harvests in combination with silvicultural treatments to produce a sustained yield of timber. In developing this system, it quickly became apparent that logging operations that could reduce stand damage and leave the residual stand in good condition were prerequisite for long-run sustainability. Two experiments were conducted to evaluate residual stand damage in conventional (uncontrolled) and RIL (controlled) logging operations, and one experiment focused attention on the economic efficiency of felling and skidding operations. Conventional logging was performed by an ongoing enterprise using typical, haphazard logging methods that were common in the study area (no forest inventory, unplanned felling and skidding operations, untrained crews). Controlled logging (RIL) relied upon a preharvest forest inventory of commercially valuable trees which was used to guide the operation of felling and skidding crews. Notably, uncontrolled and controlled logging teams used identical equipment.

The results of this side-by-side study showed that a planned logging operation could be less expensive than a CL operation (Hendrison 1990). Felling productivity (man-days m^{-3}), and therefore felling cost, was approximately the same for CL (0.08) and RIL (0.07). As RIL felling crews were also responsible for inspecting and measuring felled trees, netting out these activities, total felling costs in the RIL operation were lower than in CL. Similar results were found for skidding efficiency. Skidding productivity in terms of labor (man-days m^{-3}) and capital (machine hours m^{-3}) was substantially different for RIL relative to CL (0.06 vs. 0.10 for labor; 0.23 vs. 0.39 for capital). Overall, the total costs for RIL (\$20.25/m^3), using the CELOS system, were substantially less than the costs for CL (\$24.10/m^3) (Hendrison 1990; Table 7.1, p. 161). Despite the apparent importance of these early results, they are sometimes overlooked as evidenced, for example, by their omission from a recent comparison of reduced-impact and conventional logging costs in the tropics (Medjibe and Putz 2012).

Publication of the FAO Model Code of Forest Harvesting in 1996 (Dykstra and Heinrich 1996) led to a test of its applicability to logging operations in the Brazilian Amazon which was undertaken with Mil Madeireira Itacoatiara Company, Ltd., on their privately held land near Manaus, in the state of Amazonas (Winkler 1997). This case study highlights one of the challenges in making meaningful side-by-side comparisons of the financial returns obtainable by different logging technologies as applied in the tropics.

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In particular, the harvesting intensity of the CL operation (16 stems ha^{-1}) was nearly three times the harvest intensity of the RIL operation (6 stems ha^{-1}) due to the fact that the CL operation harvested all commercial stems and the RIL operation only removed stems that exceeded a higher diameter limit. Variations in harvest intensity can influence the average cost of a logging operation. For example, in this study, it took RIL felling crews 2.13 min, on average, to locate harvest trees, whereas it only took 1.13 min, on average, for CL felling crews to locate (more closely spaced) harvest trees. On the other hand, the lack of directional felling in CL may undermine the ability of skidder operators to efficiently orient their machines in areas with high harvest intensity. We note that, in the tropics, the relationship between harvest intensity and the variable costs associated with different activities is not well documented.

In the Mil Madeireira study, Winkler (1997) did not report harvest revenues (which would presumably be much higher for CL due to the higher harvest intensity) and only reported costs in relative terms. Considering the costs of the CL operation to be 100, the costs of the RIL operation was reported to be 109. This 9 % incremental cost difference appears to be due, in part, to the system of pre-skidding (opening a single skid trail using a crawler tractor and winching logs to concentration points on the trail) prior to skidding logs (using a rubber tire skidder) to the log deck. Subsequent to the harvest, modifications to the RIL system were considered which were thought to likely lower the RIL relative cost to 102 (a 2 % incremental difference). Winkler (1997) mentions that a considerable amount of wood was wasted in the CL harvest due to commercial trees not found, high stumps, logs damaged during felling, and logs never located by the skidding crews. However, we note that the cost of wasted wood was not estimated in this study.

The next side-by-side study was conducted in one of the most important wood-processing centers in the Brazilian Amazon, located in Paragominas in the state of Pará (Barreto et al. 1998). Similar to the CELOS and Mil Madeireira case studies, CL operations in this region were unplanned (no forest inventory, unplanned felling and skidding operations, untrained crews), resulting in dramatic damage to the postharvest forest condition. The RIL system was designed by personnel affiliated with the nongovernmental organization IMAZON (Instituto do Homem e Meio Ambiente da Amazônia). In the IMAZON system, crop trees are identified in a preharvest inventory, skid trails are marked in advance of the skidding operation, and trees are directionally felled to best orient them for skidding (Amaral et al. 1998). The initial stocking of commercially valuable trees was similar between the side-by-side RIL and CL cutting blocks. However, the timber volume extracted from the RIL block (38.6 m^3 ha^{-1}) was about 30 % greater than the CL block (29.7 m^3 ha^{-1}). The difference in recovered volume is due to the greater amount of wasted wood in the CL operation during felling (not finding commercial trees, high stumps, split boles, and breakage during harvest) and skidding operations (not finding felled logs). The authors of this study realized that wasted wood is a cost that should be accounted for.

Similar to the CELOS study, Barreto et al. (1998) found that preharvest planning increased extraction efficiency. However, the greatest financial benefit of planned extraction (RIL) was associated with reducing timber waste, which was captured through the impact of waste on effective stumpage prices. Because logging rights (stumpage fees) were charged on an area basis, increased timber waste causes lower extracted timber volumes, *ceteris paribus*, thereby increasing unit costs. Overall, the net receipts from the RIL stand (\$14.32 m^{-3}) were substantially larger than the net receipts from the CL stand (\$10.64 m^{-3}).

A second innovation of the Barreto et al. (1998) study was the postharvest simulation of growth and mortality of the undamaged commercial trees in each stand until the time of a second harvest. A comparison of the net present value (NPV) of a second harvest, after a 20–30 year period, demonstrated that the NPV from the stand harvested using RIL would be 39–56 % greater than the NPV from the stand harvested using CL, depending on the interest rate used. These results demonstrated, for apparently the

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first time, that RIL can be financially superior to CL in both the initial and subsequent harvest entries under multiple cutting cycles.

One of the potential challenges confronted when conducting a comparative logging study is that the conditions characterizing a CL baseline can be ambiguous and vary greatly across studies. This situation is exemplified by a study conducted by the Tropenbos Foundation in Guyana (van der Hout 1999). As is made clear in that study, the conventional logging system used as a basis of comparison qualified as a "close to best practice operation" (van der Hout 1999, p. 4). In particular, roads were planned and constructed in advance of the CL operation, a preharvest inventory was conducted, and felling crews used an inventory map. This is clearly a different standard than the "hit or miss" approach of the previously described CL operations. Further, the ecological conditions guiding logging operations in Guyana are quite different than many other tropical countries. The primary commercial tree species in Guyana is Greenheart (*Chlorocardium rodiei*), which tends to grow in spatial clumps ranging in size from 4–6 mature trees to 20–30 mature trees. This spatial arrangement of commercial trees allowed the CL skidder operator to easily find areas with felled trees as he was guided by the relatively large canopy openings created during the felling operation.

The RIL operation in Guyana was largely based on the CELOS harvesting system (Hendrison 1990) and emphasized the planning of skid trails to reduce skidding damage. However, because previous Tropenbos research indicated that the large felling gaps associated with harvesting the spatial groupings of Greenheart were silviculturally and ecologically undesirable, harvest tree selection for the RIL treatment targeted even spacing of trees marked for felling. As might be expected, the felling and bucking costs for CL were less than for the RIL operation ($0.60 vs. $1.16 m^{-3}, respectively), presumably due to the closer spacing for harvest trees in the CL operation and the lack of directional felling practices, which take more time for RIL. However, skidding costs were found to be lower for the RIL operation relative to CL ($4.10 vs. $4.30 m^{-3}, respectively), likely due to the advance planning for RIL operations and the potential "log jams" created by CL felling operations. Taking all costs into consideration, the total costs of the two operations were virtually the same ($28.29 m^{-3} for CL vs. $28.23 m^{-3} for RIL; van der Hout 1999; Table 5.15, p. 196), although the author expressed some concern regarding the precision of overhead (support, logistics, etc.) cost estimates. Because these logging cost estimates are based on a logging intensity of 10 trees ha^{-1}, we can assume that the revenues, and therefore the profitability, of both operations would likewise be very similar if there are no significant differences in wasted wood due to high stumps, poor bucking decisions, and so forth in the logging operations.

Although the financial indicators of RIL performance in South America appear very favorable relative to CL operations, a much different situation is revealed when examining the comparative financial costs and benefits of logging operations in Malaysia. The one side-by-side project that we identified in the literature was a project located in the Sabah Foundation forest concession in Sabah, Malaysia (Tay 2000; Tay et al. 2002). The project area has hilly topography characterized by broken ridges with altitudes ranging from near sea level up to 1,200 m. The forest in this region is dominated by trees in the *Dipterocarpaceae* family, and a heavy cover of lianas is typically present. Prior to harvest, timber fellers and bulldozer operators in CL operations typically cruise the harvest area using maps to help them determine the location of trees, roads, and skid trails. Substantial damage to the residual forest is created by CL operations due to a high felling intensity of 8–15 trees ha^{-1} exceeding 60 cm DBH and the damage caused by lianas pulling down neighboring trees. Bulldozer teams also create extensive damage in skidding operations. In contrast, the RIL system reduces damages by a variety of methods including cutting large lianas prior to timber harvest; planning all roads, landings, and skid trails; winching logs to skidders; creating streamside buffers; and rehabilitating logged sites. Notably, RIL operations avoided steep slopes, only logging 56 % of the total area, and had a lesser harvest intensity than the CL operation (106 m^3 ha^{-1} vs. 136 m^3 ha^{-1}, respectively).

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Analysis of the productivity and cost of these logging systems showed that felling efficiency was higher for the CL operation, largely because RIL fellers only cut two or three trees at a time in one area to minimize damage to previously felled trees that had not yet been extracted. Skidding efficiency was also higher for the CL operation because bulldozer operators drove to felled trees regardless of topography, whereas RIL operators would winch logs uphill to designated skidding trails. The combination of these factors, along with the lesser harvest intensity, caused RIL operations to be about 18 % more costly than CL operations when evaluated on a per cubic meter basis. We note that the cost comparison does not include any adjustment for wasted wood, although it is unclear how this factor (which was important in the South American comparative analyses) affects comparative costs in this region. Furthermore, when evaluated on a per-representative-hectare basis, RIL operations yielded about 52 % lower net revenue than CL operations, primarily due to the fact that RIL operations avoided logging on steep slopes and in riparian areas. Therefore, this sort of comparison is not one of similar harvests from different logging systems but rather provides a comparison of different harvest levels and forest treatments.

The popularity of side-by-side financial comparisons of RIL versus CL apparently diminished after the publication of the Tay et al. (2002) study. One explanation for this lacuna is that side-by-side studies are expensive to conduct and the practical logistics of conducting such studies are difficult to organize. A second explanation is increasing recognition that factors other than financial profitability are key determinants of the (lack of) adoption of RIL practices (such as resistance to change and satisfaction with current profitability of CL). A third possible explanation is that it had become evident that RIL would not be universally adopted, because of the large financial penalty in forest management units with steep slopes or other environmentally sensitive areas. In these cases, compliance with RIL reduces potential revenues to the degree that the acronym became pejoratively associated with the phrase “reduced income logging” (Putz et al. 2000).

Despite these apparent obstacles, a side-by-side cost comparison study was recently reported for Gabon, Africa (Medjibe and Putz 2012). Relative to the studies described above, the harvest intensities in this study area were very low (0.82 trees ha^{-1} for RIL, 0.97 trees ha^{-1} for CL). Although it is unclear how effective RIL might be in reducing impacts on the residual stand at such a low harvest intensity (this was not reported in the manuscript), harvest planning and directional felling under RIL might be expected to have a positive impact on future harvest potential.

As we note in the Medjibe and Putz (2012) study, the costs of felling/bucking and log deck operations associated with RIL were higher than the costs of those operations under CL ($1.65 vs. $0.68 for felling/bucking and $2.19 vs. $1.75 for log deck operations, respectively). We speculate that these differences may be due to extra effort applied in RIL operations to enhance worker safety through the use of directional felling techniques combined with time spent clearing feller escape routes. We also note that the increased cost for the log deck operations under RIL was due to the inclusion of a supervisor not present for the CL operation. While the average cost of the CL operation was less than the cost of the RIL operation (\$17.66 m^{-3} vs. \$20.90 m^{-3}), this study highlights the importance of documenting not only the ecological benefits of RIL but also being cognizant of the potential benefits to worker safety under a RIL system.

In contrast to the previous side-by-side studies that use data from single enterprises or cutting block, another approach is to use data sampled from multiple enterprises or logging blocks to estimate average values across the sample. When data are sufficient for statistical analysis, regression methods can be used to estimate economic relationships, where the regression line identifies average firm behavior. For example, Bauch et al. (2007) collected information on timber harvesting, transport, and milling operations in the Brazilian Amazon and were able to estimate economies of scale for typical (CL) logging operations.

When the sample of observations on firm behavior is limited, such as the case for comparisons of a new technology (RIL) with a standard technology (CL), opportunities for regression analysis are more limited (although, see van der Hout 1999). In this case, a sample of observations can be used to estimate average

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(or typical) production and economic parameters. For example, Holmes et al. (2002) used a sample of production and cost parameters obtained by the Fundação Floresta Tropical (Tropical Forest Foundation, FFT) from seven logging firms, all operating in the same region of the eastern Amazon as the RIL operation, as the basis for characterizing a typical CL operation. Similarly, the authors used production and economic parameters obtained from several cutting blocks harvested using RIL techniques to characterize a typical RIL operation. (It is important to note that measures of timber waste and damage to the residual stand in this study were based on observations recorded during visits to a single CL block that was harvested by an industrial cooperator following typical practices.)

Similar to the Barreto et al. (1998) study, conducted in the same eastern Amazon region, the Holmes et al. (2002) study found that planning harvest operations resulted in substantial gains in production efficiency, particularly regarding the skidding and log deck operations. However, the greatest financial benefit of RIL relative to CL was the impact of wasted wood on costs. In this study, wasted wood incurred direct costs (but no revenues) associated with felling, bucking, skidding, and log deck activities, as well as incurring indirect costs by increasing the effective stumpage price. The direct plus indirect cost of wasted wood increased the average cost of CL operations by \$1.79 m^{-3} (about 11 % of the total cost of the CL operation). Overall, the average net revenue of the typical RIL operation (\$11.66 m^{-3}) was about 18 % greater than the net revenue of the typical CL operation (\$9.84 m^{-3}) in this region.

A second method for analyzing CL and RIL operations when observations on multiple firms or cutting blocks is available is to consider the entire distribution of the sample of observations obtained on production and economic parameters. This approach recognizes underlying uncertainty (stochasticity) in logging operations and that the distribution of forest production parameters may not follow the standard Bell curve (normal distribution). Consequently, averages may be misleading and other parameters characterizing forest production parameters (such as the median) may be more appropriate for describing outcomes that are most likely to occur.

A procedure for incorporating observed variability in timber harvest productivity and uncertainty regarding future timber prices was conducted for an initial and second cutting cycle harvest (Boltz et al. 2001) using the FFT data supporting the Holmes et al. (2002) analysis as well as including a matrix model for timber growth and yield. Productivity parameters used in the simulations were assumed to follow triangular distributions and were based on observations of minimum, maximum, and median values as recorded in the FFT data. Future timber and stumpage price distributions were also assumed to be triangular. To estimate commercial timber availability for the second cutting cycle under RIL and CL, timber growth and yield functions were estimated using field data from disturbed and undisturbed forests in the study area.

Boltz et al. (2001) reported that "…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 observed uncertainties of harvest efficiency" (p. 393). This result is entirely consistent with the results reported by Holmes et al. (2002). Further, Boltz et al. (2001) concluded that for second cutting cycle harvests, RIL harvesting operations generate competitive or superior economic returns for a wide range of discount rates and that this result is due to gains both in production efficiency and forest conservation under RIL operations.

Bioeconomic Models

In addition to the positive models of firm behavior described above, forest economists have developed normative models to simulate logging behavior over multiple cutting cycles. Similar to the Boltz et al. (2001) model, this approach requires the analyst to collect demographic information on timber growth, mortality, and (perhaps) regeneration (depending on the forecast period), so that a forecast of

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future timber stocks can be made. The presumed behavior of logging firms that maximize net present value of multiple harvests can then be analyzed under alternative management or policy innovations.

The first study using this approach to study the behavior of CL and RIL operations was conducted in Ghana using cost data collected from a single large timber company and growth and yield data from the Subri River Forest Reserve (Bach 1999). It was assumed that reducing damage to the residual forest would require increased effort, due to advanced planning of skid trails and roads, and that the cost of this effort would raise fixed costs from $72 ha^{-1} to $122 ha^{-1}. It was further assumed that CL operations damage 30 % of the residual stand and that adopting RIL would reduce the damage by one-third (i.e., 20 % of the residual stand would be damaged). The model simulates the behavior of a forest concession that maximizes the net present value of current and future harvests subject to the constraints imposed by timber growth and harvesting damage. Although the rate used to discount future revenues to the present is relatively modest (5 % yr^{-1}) in this study, the enhancement of the yield of future timber trees due to reduced damage from RIL were inadequate to motivate loggers to switch from CL, due to the slow growth rate of timber trees. However, providing an area-based subsidy that is very close to, but less than, the incremental fixed cost associated with RIL induces loggers to switch to a more environmentally benign logging system.

A similar bioeconomic model was constructed to analyze CL and RIL operations in Peninsular Malaysia (Boscolo and Vincent 2000). Timber growth and yield data were obtained from virgin forest inventories conducted in the Pasoh Forest Reserve. Logging damage was calibrated using previously published research (from eastern Malaysia) indicating that CL felling of all commercial trees greater than 60 cm DBH would kill half of the trees in the 10–20 cm class and that RIL would reduce damage to that size class by two-thirds. It was further assumed that the incremental fixed cost of RIL was $135 ha^{-1} and the simulation evaluated the net present value of timber harvesting revenues under CL and RIL. Similar to Bach (1999), the results showed that, using a 5 % discount rate, it was uneconomical to adopt RIL, although at a 1 % discount rate, the profit maximizing solution would reduce the harvest intensity of the CL operation. The results also showed that imposing a performance bond, and making reimbursement conditional on adopting RIL, would cause loggers to switch from CL to RIL only if the level of the bond was marginally larger than the incremental cost of RIL. We note that the initial gain in carbon storage at the time of harvest resulting from adopting RIL (at a cost of $135 ha^{-1}) was about 55 t ha^{-1}.

A more recent study of incentives for carbon sequestration in forests logged using RIL versus CL was reported using data from East Kalimantan, Indonesia (Indrajaya et al. 2014). The basal area and amount of carbon stored in the climax forest were similar to the values reported in Boscolo and Vincent (2000). Detailed data from East Kalimantan showed that RIL had higher fixed costs ($390 ha^{-1}) but lower variable costs ($44.8 m^{-3}) than CL ($297 ha^{-1} and $46.4 m^{-3}, respectively). Damages to the residual stand were specified to depend on harvest intensity, logging technique, and diameter class. It was assumed that RIL reduced damages to the residual stand by 17 % on average and by 25 % for trees 50 cm DBH and larger. The assumed objective function was to maximize land expectation value over an infinite horizon, and future logging profits were discounted using a rate of 4 %. In the model, it was assumed that the logging firm can receive carbon credits under REDD^{+} only when using RIL techniques. Similar to Bach (1999) and Boscolo and Vincent (2000), this study found that, in the absence of carbon credits, loggers would prefer using CL techniques. In contrast, RIL is the preferred logging practice at carbon prices up to $2 t^{-1}. If carbon prices exceeded $2 t^{-1}, CL would be the preferred practice in the initial harvest, followed by leaving the forest untouched. However, as the authors note, CL cannot be used when applying for carbon credits under REDD^{+}.

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Conclusions and Recommendations

The published literature comparing RIL and CL in financial terms provides evidence that RIL can be competitive under certain forest conditions and logging intensities (Boltz et al. 2003). Of the six comparative studies conducted in South America, four studies (Barreto et al. 1998; Hendrison 1990; Holmes et al. 2002; Boltz et al. 2001) provide compelling evidence that RIL is financially competitive or superior to CL during the first harvest entry. Two studies (Barreto et al. 1998; Boltz et al. 2001) examined future financial profitability, and both concluded that RIL operations increased the future financial profitability of RIL relative to CL. One study (van der Hout 1999) concluded that the costs of RIL and CL were virtually the same in Guyana where, notably, the CL basis of comparison was a system representing a "close to best practice operation" (van der Hout 1999, p. 4). Consequently, the only evidence that RIL is not competitive with, or superior to, CL in South America is provided in the study by Winkler (1997). However, as noted in our description above, the harvesting intensity evidenced in the CL operation in this study was nearly three times the harvesting intensity for the RIL operation. Because a higher harvest intensity can induce economies of scale in logging operations, and because the RIL system employed a two-stage skidding operation not subsequently utilized in other RIL operations, we consider this study to be an outlier and not very informative about the financial benefits or costs of operational RIL systems.

Although it appears that there is substantial evidence regarding the financial competitiveness or superiority of RIL in South American forests where harvesting intensity is moderate, the evidence suggests a different conclusion is warranted for the forests of Southeast Asia. In Sabah, Malaysia (Tay 2000), the higher harvesting intensity described for CL operations, as well as the exclusion of extensive environmentally sensitive areas from RIL harvesting plans, contributed to the financial superiority of CL in the initial harvest entry. The relatively slow growth of the residual stand after harvest also leads to the superiority of CL when evaluated over two or more cutting cycles (Boscolo and Vincent 2000; Indrajaya et al. 2014). However, both Boscolo and Vincent (2000) and Indrajaya et al. (2014) demonstrated that RIL could be financially superior to CL if carbon payments were available at relatively modest carbon prices, due to the ability of RIL techniques to limit disturbance to the residual stand. We suggest that more research on the potential effect of carbon payments on the financial attractiveness of RIL is warranted under a variety of tropical forest conditions.

Finally, we note that scientists have recently expressed concern that climate change during the twenty-first century may cause a large-scale dieback of tropical rainforest, largely due to increases in drought and wildfires (Barlow and Peres 2008; Malhi et al. 2009). Suggested strategies for increasing the resilience of tropical forests to avoid ecological tipping points include policy interventions that maintain intact forest area and limit the spread of wildfire (Malhi et al. 2009). Because poor logging practices can increase forest vulnerability to future burning (Nepstad et al. 1999; Cochrane et al. 2004; Stolle et al. 2003), research is urgently needed to evaluate the contribution that alternative logging techniques can add to the resiliency of tropical forests subject to the risk of catastrophic wildfire.

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