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An Ecological, Socio-Economic and Silvicultural Assessment of the Sustainability of Reduced Impact Logging in Tropical Forests

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ABSTRACT

Reduced Impact Logging (RIL) is thought to be the most suitable, but also most politically discussed, method to exploit tropical forest ecosystems for timber. In this review we give an assessment of RIL from biodiversity, silvicultural and socio-economic perspectives. We first place RIL as a potential tool for retaining forest diversity and structure whilst moving towards a forest transition. We then discuss whether RIL is an advancement of traditional tropical logging methods using the three perspectives. We find that RIL offers benefits over conventional logging for biodiversity at species and population levels. However marginal or specialised habitats and species were most affected, suggesting RIL implementation would create species shifts in tropical forests. We discuss whether RIL can provide realistic management outcomes alone or alongside other silvicultural practices. We find that RIL risks high-grading and, sustainable yields may only be possible using additional silvicultural treatments alongside RIL. Finally we consider the socio-economic effects of RIL, how differing guidelines and implementation effect outcomes and how RIL costs compare with conventional logging. We find RIL is incompatible with retention of intact forest at the landscape scale and for many community forests

Keywords: *timber extraction; conventional logging; best practice;*

INTRODUCTION

Forest management is, at its most basic level, a balance between the regeneration ability of the wood and the degradation level deemed acceptable. Managing forests without considering the impacts of interventions on an ecosystem is as old as humankind[1]. Increasing human population, economic growth and growing demand for natural resources leads to increased pressure on forest ecosystems. This constant pressure exceeds the regeneration capacity of forest ecosystems resulting in deforestation and forest degradation by loss of habitat and biodiversity. The topic of forest sustainability for future use is traditionally dated back to Englishmen Arthur Standish and John Evelyn in 17th century, was put into practice by German mining administrator Hans Carl von Carlowitz in the 18th century and was formalized into education with another German named George Ludwig Hartig at the beginning of the 19th century [2,3]. The main aim at this time was to create plantations to ensure sustained supply of timber for industry. However a combination of changes in global economics, the realisation of plantation's shortfalls, and development in ecosystem understanding, diminished total forest cover as diagnostic to forest health. Forest institutions and the science community have the job of determining what biomarkers indicate that forest function is threatened and the severity of the threat. However, since the Brundtl and report in 1987 titled "Our Common Future", the discussion of forest health has gained widespread attention as it was attached to the narrative of future global development [3]. As forest resources become scarcer, it is essential to implement management regimes to look for long-term balance between human needs and conservation of nature resulting in a shift away from “one-way management”. Currently, forest interventions are moving towards sustainable management practices to fulfill human needs while maintaining ecosystem function.

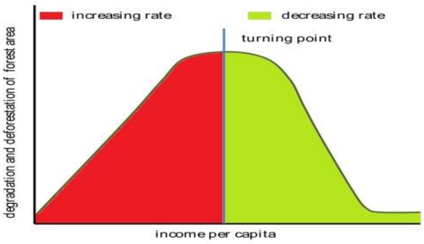

Figure1. *Modified Environmental Kuznets Curve for industrializing economies. The X-axis of income per capita reflects urbanization, growth of service sector activities and strong democratic state while Y-axis of deforestation and degradation is government investment, land tenure rationalization, increased education andmarket reform to limit loss of species diversity, soil degradation and long-term resource depletion.*

This pattern of social consciousness towards resource sustainability is seen as following an Environmental Kuznets Curve (Figure 1). The initial slope of the curve represents an industrializing economy’s “takeoff” stage where novel technologies and tools are being utilized for resource extraction [4]. An inflexion point occurs when environmental resources become less central to the economy as it diversifies into manufacturing and services, as people migrate away from rural areas, and as a stronger state develops. At this point is also when resources are not regenerating at the rate of extraction [5]. This is then followed by environmental awareness and higher rates of environmental investment: this is seen with the proliferation of public space and forests that have tailored dimensions for extraction efficiency and end-product use. Erhardt-Martinez et al. [4]demonstrated that internal issues were the key drivers for reduction in deforestation in developing countries. Alongside this has been the development of Forest Transition Theory and models of the pathways countries may take to achieve net forest gain [6].

Many of the countries that are still ascending or are near the peak of the Environmental Kuznets Curve are those near the equator where tropical forests dominate the landscape and purchasing power parity (PPP) is less than 5,500 [7]. Recent comparative studies have shown that the drivers are different for forest transition in different countries, or within countries [6,8-11]. Theoretically, all countries will achieve forest transition, eventually, although whether this will be permanent or not is subject to debate [12].

However tropical forest quality is not synthesized by these theories, only overall forest cover. A brief view of European forestry shows the transition from:

- Low-level exploitation of forest, use of NTFP’s and some larger timber trees.
- Expansion of industry (salt, iron smelting, charcoal markets) and felling naturally seeded forests. Reduction of total forest cover, changes in forest composition towards favoured trees.
- Plantations to increase cover and ensure sustainable supply of wood. Increase of total forest cover but reduction in biodiversity. Mixing of regional and global intra-species varieties/pathogens.
- Uneconomic plantations considered as conservation areas, development of near-to-nature forest management[13].

In Europe much of the initial forest cover had been destroyed before any transition but global preference for retaining and preserving tropical forests’ structure, ecosystem services and biodiversity makes the retention of vast swathes of intact tropical forest a currently desirable cultural aim. In tropical countries plantations for timber are small scale currently, compared to the production drawn from primary and secondary forest. The challenge is, how can tropical timber production be made sustainable in the short to medium term whilst maintaining sufficient forest that is not degraded, or degraded only at low, recoverable levels?

Tropical forests are unique to production because of the diversity of goods and the production potential. However, two stipulations to the production power of tropical forests are the life cycle complexity and intensity of management to maximize per unit of land area. It is not only the growth that is impressive in tropical forest but the biodiversity. Forest inventories that consider all stems above 10 cm in diameter are known to record 250-300 tree species per hectare in the Central Amazonia with tree species approximated at 16,000 across the entire Amazon Basin, an area estimated at 6,684 million km^2[14,15]. Scaled to the entire tropical region the species list grows to an estimate of 40,000 [16]. Considering this diversity in a distribution to number of stems the Center for Tropical Forests found that of the 8,500 species found on their research plots half of the species make up less than 2% of total stems [17]. To put this diversity into perspective there are 1,575 total angiosperms, the predominant phylum of land plants in the tropics, of commercial value in the world market [18]. This dispersed population of timber species in the topics results in an annual increment of potentially harvestable wood of 1-2 m³/ha in natural forest [19]. In corroboration of this statistic, commercial timber volume in undisturbed tropical forests are five percent of total timber volume in the Americas and Africa, with Asian forests this percentage increases to 14% because of Dipterocarpaceae dominance [20]. Characteristics of high-value timber species are they are exceptionally long lived and slow growing, occur at low density when mature, have low recruitment hence sustain low regeneration at the stand level and rely on mutualistic association with animals for reproduction [21].

Since timber is diffuse in tropical forests the two methods of extraction are concentrating timber value through plantations and silviculture while the second is resource exploitation. Silviculture is the “art and science of controlling the establishment, growth, composition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society such as wildlife habitat, timber, water resources, restoration, and recreation on a sustainable basis” [22]. Silviculture in the tropical forests began with identifying that there was a finite timber resource for ship building material causing a minimum felling diameter moratorium in 1770 by colonizing countries and in the 1850’s forest institutions were created to introduce a legal framework for land allocation and management [23]. The first foresters are documented in Indonesia in 1849 and research station in 1913 [24]. Since then many silvicultural systems were developed to concentrate timber resources and value [25].Resource exploitation, often referred to as conventional logging (CL), also receives academic attention due to its common practice and role in changing land-use. The activities of CL are the most valuable trees are selectively harvested. When the prime timber is removed than the next-most-valuable trees are taken and loggers often return to a site 5 to 10 years later when trees have become commercially valuable after the first logging operation created canopy gaps key to catalyzing tree growth[26]. Once the forests have all the trees of value removed the land only regains its value when transitioned to agriculture or ranching [21]. This process causes deforestation that is cited at 0.58% transition from tropical forest cover to agriculture per year since the 1980’s [27]. It is also estimated that one third of all tropical forests are degraded due to selective logging practices which can be seen as the first step to deforestation [21]. The major drivers to deforestation are high timber and agricultural price, low rural wages and increases to deforestation when there are opportunities for long distance trade [28]. In aerial imagery this process is primary forest to a fish skeleton pattern of roads and patches to open ground where the soil is exposed.

Into this landscape comes the desire for sustainable forest management and one of its' main components, Reduced Impact Logging. Aimed at ensuring a sustainable supply of timber and minimising collateral damage, RIL is the preferred method for planning, felling and extraction. This paper will critically analyse reduced impact logging (RIL) and assess the evidence for and against it as a logging practice in tropical forests. In section 2 the ecological aspects are considered before moving on to silvicultural performance in section 3. Finally, section 4 presents the socio-economic factors surrounding RIL. We find that RIL has a variety of benefits compared to CL in terms of diversity maintenance at the genetic to population levels. We also consider how additional silvicultural practices can enhance RIL outcomes before assessing its' financial viability and applicability at the landscape scale.

ECOLOGICAL EVALUATION OF REDUCED IMPACT LOGGING

Conventional logging practices often severely destruct or degrade natural forest ecosystems. Negative influences on the ecosystem can be caused by the use of heavy machinery to extract the timber. The machinery compacts the forest soil and injures the vegetationor trees next to the skid-trails (figure 2). Further, if a high-volume of timber is harvested soil erosion can significantly increase and forest biodiversity and forest regenerative capacity can decrease. Under CL practices a high quantity of excess leaf litter and other organic debris is left in the forest which makes logged forests more vulnerable to disturbance, especially fire[29].To reduce ecological damage caused by harvesting, RIL has been advocated as a potential tool for conservation. RIL practices generally include:

1. Undertaking a full inventory of trees across the whole holding, from a minimum DBH upwards;
2. Cutting climbers and lianas before felling to minimise residual damage;
3. Directional tree felling to inflict the smallest impact on the surrounding trees, protect future crop trees (FCTs) and reduce the need for skid-trails;
4. Establishing stream buffer zones and watershed protection areas;
5. Using enhanced technologies to reduce impacts to soil caused by log extraction and skidding;
6. Cautiously planning road and skid-trail positions and limiting the slope of roads to avoid excess erosion;
7. Reducing wood waste for cut areas to increase wood utility rate.

These steps can limit damage to the surrounding forest, cut erosion of topsoil, enable faster recovery of the forest, and reduce the risk of fire [30,31]. RIL results in a sharp reduction of residual damage to the forest [19,32,33]. A study in Borneo, showed that 41% of the remaining trees that were not harvested were crushed by either falling lumber or tractors under CL regimes. This residual damage could be reduced to 17% by applying RIL practices[32]. The application of RIL in tropical regions has increased in recent years as it is a criterion for timber certification under the Forest Stewardship Council (FSC). Certified timber achieved top level timber prices, however currently accounts for only 5% of timber produced in global market[34].

Figure2. *Soil compaction and serious injury of the vegetation in the Central Amazon caused by heavy machinery (Picture source: Kunert N.).*

RIL also reduces residual damage to vegetation and soils, compared to CL. A study in Amazonia compared canopy cover reduction, surface soil moisture and nitrate to 8m depth between logged tropical forest gaps and intact primary forest, to test the long-term effects of RIL to forest soil [35]. Belowground nitrate storage to 8m depth and soil water depletion showed no obvious difference with a low harvest rate and disturbance intensity. This indicated that the impact of RIL on belowground inorganic N was limited. Although RIL can reduce the damage level to residual plants and soil, evidence suggests RIL procedures can still influence local soil property. Compared with primary forest, nitrate concentrations in forest openings were significantly higher at about 1m depth soil, suggesting RIL influences nutrient turnover and leads to partial N redistribution in logging gaps[35].RIL is more ecologically beneficial than CL, at least in short-term. Bicknell et al [36]conducted a complementary meta-analysis of assemblage responses to differing logging practices: conventional logging and reduced-impact logging. They found that biodiversity impacts are markedly less severe in forests that utilize RIL, compared to those using CL methods[36].In recent years, many studies have focused on the effects of RIL on species distribution and richness. In one study, the effects of RIL and CL practices on biodiversity was assessed by using soil fauna as indicators of disturbance. The study sites were the production forests of the Deramakot Forest Reserve and the Tangkulap Forest Reserve in Sabah, Malaysian Borneo. The study compared macro- and mesofauna in a pristine forest with no logging, a forest in Deramakot Forest Reserve where RIL had been used, and a CL forest in Tangkulap Forest Reserve. It was found that the impacts of logging on decomposers in the soil animal communities had been mitigated by the introduction of RIL in Deramakot Forest Reserve through the protection of tree vegetation [37].

A series of studies about the effects of logging behavior to fish and other aquatic faunas (Ordinate) in Eastern and Central Amazonia suggests stream physical characters, including temperature and amount of fallen trees in streams were lower in logged plots. However the effects of RIL on fish assemblages were generally minor and slighter than CL[38-42]. There was no evidence of species loss resulting from the logging concession practising RIL, but research by Dias et al [40] warned that the differences in log cover and ordination scores derived from relative abundance of fish species persisted even after 8 years. Noticeably negative effects were only exhibited in the richness of phytophagous species after logging[38], suggesting that vegetation near streams are vulnerable to disturbance triggered by RIL and highlights the importance of buffer zones surrounding riparian areas. Based on these results from Amazonian streams, RIL appears to be a viable alternative to clear-cut practices, which severely affect aquatic communities. Nevertheless, detailed studies are necessary to evaluate subtle long-term effects and in other tropical regions. An entomological study showed that RIL had little effect on insect communities in Eastern Amazonia[43]. Despite this the environmental conditions, especially of the riparian vegetation around streams, had been changed by RIL. One study chose Brazilian fruit-feeding butterfly as indicators and noticed that, despite the detectable effects of RIL on the composition of butterfly assemblages, the overall diversity was not affected. A similar pattern has been detected in many other groups, indicating that a noticeable part of the diversity of many taxa could be preserved in areas under RIL management. Two case studies, in Borneo and Guyana, used Dung Beetles (Coleoptera: Scarabaeoidea) as indicators[34,44].A higher diversity and species richness was recorded in the forest logged using reduced-impact techniques[44]. The CL site had both lower diversity and species richness, and lacked some primary forest specialists present in the reduced-impact forest samples. However, although RIL is considered better than CL, community analysis revealed that a logged forest supported a more uniform dung beetle assemblage compared to unlogged forest [34]. Differences in assemblage structure were driven by dissimilarity between closed canopy treatments, as plots in artificial and natural canopy gaps supported comparable assemblages.

Since many tropical birds are highly dependent on trees for habitat and food, bird communities are sensitive to forest logging practices. Species that require high forest cover rates and tree density have greater responses to logging [45], research in lowland Bolivia discovered that insectivorous or frugivorous avian species occurred in reduced abundances after logging [46]. Bicknell and Peres [47] demonstrated that large frugivores such as primates were less abundant in sites subject to RIL, whereas smaller frugivores, granivores, folivores and insectivores were more common in logged sites, but the reason for different responses of taxonomic groups is still not clear. Interestingly, the response of plants’ physiological traits to RIL show more plasticity and so are more difficult to predict. The influence of reproductive traits on liana abundance 10 years after CL and RIL in the Eastern Brazilian Amazon demonstrates the inter specific differences in liana responses to different types of logging; knowing species’ primary modes of reproduction is a valuable first step toward predicting those responses[48].

Beside species diversity, genetic variation can also be affected by RIL practices. Effects of RIL were found on genetic diversity and spatial genetic structure of a *Hymenaeacourbaril* population in the Brazilian Amazon Forest; RIL practices caused decreasing heterozygosis of the unlogged reproductive population, although results were not statistically significant. Logging also reduced the distance of the spatial genetic structure in the reproductive population, from about 800m to 200 m. This study showed that RIL can affect the gene pool and spatial genetic structure of the reproductive population[49].Overall then RIL shows reduced negative impacts to forest ecology when compared to CL. Whilst most studies in this area compare RIL to CL, the few that also include unlogged forest plots indicate that RIL can negatively affect species composition, reverie habitats and tree genetics.

In summary, the literature available definitively suggests that RIL is more ecologically friendly than CL. It causes fewer negative impacts than CL to soil properties and species distribution and richness with most studied species show no or only minor responses. However the response to RIL varies among species (habitat requirement, food source, abundant etc.) as rare and low-abundance species are more likely to be influenced by RIL than common species. Also, species with requirements for high forest canopy cover and/or forest density are more vulnerable to RIL practices. Besides species diversity, gene pool and spatial genetic distribution may change. So far the majority studies focused on the effects of RIL in short-term, long-term research is still needed. What information there is suggests that alterations caused by RIL to tree species regeneration patterns and seedling survival rates can affect the structure of tropical forest communities in the long term.

Figure3. *Even if the logging is conducted with care, it means a certain disturbance to the forest (Picture source: Kunert, N.)*

SILVICULTURAL EVALUATION OF REDUCED IMPACT LOGGING

While forestry in general is the practice of purposefully managing forests and their resources to benefit people, silviculture in particular is concerned with the methods used to achieve these goals. A fundamental aim underlying silviculture is to maintain the long-term continuity of ecosystem function and productivity [50].A definition used by the sustainable forest management (SFM) program, reflects the rising influence of the ecosystem management paradigm: Here, applying silvicultural is "a process for creating, maintaining, or restoring an appropriate balance of essential components, structures, and functions that ensure long-term ecosystem vitality stability, and resiliency" [50]. The theory of silviculture is implemented by the application of silvicultural regimes. Such a regime can be described as a "planned series of treatments for tending, harvesting and reestablishing a stand"[22].The cyclical sequence of regeneration, followed by tending and felling, and the equal weight of these practices is a core assumption of silviculture across the globe, especially in Europe and North America. The practice of RIL however, concerns only one dimension, the felling. RIL does not entail specific treatments to enhance the growth and survival rate of regenerating young trees of desired species in the tending phase. As mentioned earlier, the regeneration and vitality of young trees might be positively affected by RIL in comparison with CL. However, this is an indirect effect caused by generally minimizing damages to the remaining stand and not a result of active management to promote regeneration. The focus on felling with a disregard for regeneration and quality improvements through tending raises concerns over the long-term sustainability of the productivity of forests where RIL is employed. For this reason, we will look at some shortcomings but also about possible silvicultural solutions of RIL in the tropics.RIL is a selective logging system, where only a low certain number of stems per hectare are extracted. By focussing on the stems with best quality, the forest might become susceptible to degradation through high-grading, where the forest is depleted from the best genetic material of the desired species, one example being African mahogany [51]. Further, a study from the Amazon showed that especially those emergent trees are playing a crucial role in the hydrology of the forest [52].

The basis for successful implementation of RIL or any other form of forest management is a solid information system, usually in the form of a forest inventory. Standard RIL procedure requires a pre-harvest assessment of the harvest area and further operational planning is based on this forest inventory. Due to the high number of tree species and structural diversity in tropical rainforests, normally only trees suitable for harvesting are mapped; regeneration is not directly inventoried. For better information about future crop trees (FCTs), Sist and Ferreira [31] argued to decrease the minimum diameter of the pre-harvest survey in the Amazon from 45cm to 35cm and to mark the trees to decrease damage during harvest operations. A key factor in determining the sustainability of RIL is the harvest intensity, which can be either expressed by the number of trees or the total harvest volume (m^3) per hectare in a given time period. The harvest intensity is a compromise between the economic returns and ecological integrity of the stand; a high harvest intensity operation with higher amounts of merchantable timber will increase revenues, but also increase the damage to the remaining vegetation and impair future harvest cycles. Throughout the tropics, a substantial decline of yields has been shown for forests managed with RIL; yields reached just 21 – 50% of the volume of the first harvest in lowland forests [30]. A meta-analysis showed that if only the same species are harvested, only 35% of the timber stock will be recovered under normal harvesting intervals [53]. By including other timber species, the stock could be increased to 45 %. The higher revenue of the first cycle of RIL was termed "primary forest premium" [54], while historically it was also dubbed "nature's bounty".

The decreasing timber yield between the first and the subsequent harvests has two severe implications:

1. Forest management must recognize and accept that the sustained yield is lower than the yield

of the first cycle and adjust their planning accordingly, and

2. There is a need to improve silvicultural regimes to maintain and ideally increase the long-term sustainable timber yield (STY) for the 2nd and consecutive cycles, in order to make selective logging a more economically competitive form of land use.

The most straightforward approach is to maintain STY is to lower harvest intensity by reducing harvest frequency and/or harvest volume. Extended rotation periods are problematic due to a discounting of the profits and thus reduced social acceptance, leaving the number of stems per hectare as the key parameter. The number of stems often has been derived from one criterion, the minimum cutting diameter limit (MCDL)[31]. As a result, the harvest intensity was often too high. More sophisticated methods to determine stems per hectare (SPH) do exist for some regions, i.e South East Asia [55], but not for all. Sist and Ferreira [56] deduced that the harvest would need to be reduced to 3.6 SPH on average to achieve sustainability.

Other approaches with the aim of increasing STY currently debated are the commercialization of new species and to increase the growth rate of FCTs through silvicultural treatments. An example would be liberation treatments, where lianas or long lived pioneer species (such as *Cecropia spec.*) which compete with the FCT are removed [57]. Intensive treatments, where non-commercial species overtopping FCT or with a DBH >40cm were removed by girdling, showed that that growth rates could be increased by 50-60% [58]. The largest increment increase was shown for shade-tolerant and partially shade-tolerant species. However, intensification of silvicultural management also results in a shift of species composition. Species composition can be viewed as a proxy for forest recovery of a disturbance such as harvesting. A recent study from Brazil showed that a reduction of the Basal area of 6.6 m^2 ha^{-1} through logging or thinning will result in a strong shift in species composition towards pioneer species, which might impair the sustainable production of goods and services in these forests[59]. However, light to silvicultural intervention could improve growth trees. To reconcile increased growth with low impact on species composition, treatments should be concentrated around FCTs [60]. Literature about the management aimed at securing regeneration of commercial species is scarce; one practice and legalised in Brazil is to leave 10% of growing stock in the forest to function as seed trees (De Avila, personal communication). Enrichment planting could be a costly, yet efficient way to establish additional regeneration across the tropics, for example in Brazil[61], Central America [62] and Laos [63]. Regeneration might also be aided by soil scarification in felling gaps to improve germination[58].RIL is an important step up in silvicultural management, but it alone is not sufficient to guarantee sustained productivity of commercially desired species. STY could be maintained and improved through light to moderate silvicultural management and an efficient combination of additional silvicultural practices. Implementation of these might be problematic due to socioeconomic restrictions.

SOCIO-ECONOMIC EVALUATION

Reduced Impact Logging is a socio-economic term. As succinctly pointed out by Dykstra [64], the term was coined by an entrepreneur interested in developing carbon offset practices for power generating companies in the USA and has gained credence due to its inherent acceptability to industrial and environmental minds alike. RIL was a product of its time, a chreode (after Sheldrake); in the burgeoning environmental awareness of the 1990's, deforestation and forest degradation were key concerns in the social consciousness. The rise of societal, and so regulatory, interest in reducing the impacts of human activities on the planet necessarily led to the development of logging techniques designed to reduce impacts on forest stands. In fact many of the techniques had been developed in the 1970's and 1980's with the aim of producing sustainable yields in tropical forests[64]. Indeed Dykstra himself, along with Rudolph Heinrich [see 65], were developing similar standardised techniques for the FAO around the same time as RIL was coined [64]. The difference? They used the term 'environmentally sound forest harvesting', a much less palatable term for environmental communities. So RIL gained legs and other terms did not; it has been implicit since the beginning that logging will have negative impacts on the forest being logged. So are the impacts of RIL sustainable, the best we can do, responsible and feasible now, 25 years later?

A look at the spread of RIL would certainly suggest so. It has been championed by CIFOR, FAO, WWF, IUCN, is part of achieving SFM for FSC and PEFC certification, and is recommended by many national forest regulations, for example Bolivia [58] and Indonesia's TPTI [66]. It is no surprise that RIL has become so pervasive. On the one hand the costs of managing a forest can be reduced, felled timber extraction is higher, access roads are fewer, collateral damage is reduced allowing, in principle, shorter extraction cycles[67]. On the other hand it has fewer negative impacts on the environment than conventional selective logging, and certified products carry a premium in the marketplace, e.g. a premium of 2-56% compared to non-certified timber in Malaysia [68].

The acceptance and development of RIL as part of most Forest Management Plans appears to be a good and progressive development, then. It has benefits for logging companies, environmental protection and sustainable forest management. However, beneath the veneer key differences exist in guidelines and implementation [69]. One example is the variation of guidelines for acceptable upper limit for ground based yarding. Most countries restrict ground skidding operations to slopes <17° to avoid detrimental effects to the surrounding stand[65]. The recommended maximum is 25° in Sabah, Malaysia, rising to 40° in peninsular Malaysia [30]. This variation in guidelines and practices has two main implications:

1. Skidding on steeper slopes will have greater environmental impacts to the surrounding ecosystem, for example introducing soil damage and creating permanent rivulets.
2. The expense of aerial yarding will render forests on steep slopes unavailable for logging practices and so increase the total forest area required to attain viable logging yields. For example in Sabah, Malaysia up to 40% of slopes can be excluded from logging under RIL [70].

Neither option is palatable and the highly selective nature of RIL, as part of SFM, compared to CL can actually to increased deforestation, for example in the Congo [71]. This study found that concessions run or funded by European companies that were highly compliant with SFM practices, as required by Congolese law, and certified by FSC, built more roads in search of their particular tree crops. The ingress of these roads into new logging territory caused greater deforestation than less compliant concessions logging more trees in a smaller area.

Another aspect is that RIL implementation is not always robust. Reports of over-harvesting, poor planning and creation of inaccurate inventories are not uncommon and these serve to further undermine its efficacy in the field. The strict guidelines and reduced harvesting rates lead to inappropriate use of RIL [72] and overharvesting can be as damaging to forest structure as CL [56]. For example, SFM compliance at three sites in Venezuelan Guyana ranged between 45-60% [73]and two certified entities in Brazil complied with just 66% and 80% of their SFM certification guidelines[74]. The robustness of implementation could feasibly be improved with increased monitoring and fines, yet the use of revenue-based instruments in Brazil in lieu of effective monitoring are likely to have little effect on compliance [75]. RIL and SFM then are implemented patchily and the example from the Congo basin suggests that even full compliance creates the risk of increased deforestation. Edwards et al.[76] compared species richness in Borneo under two forest management regimes: Land sharing where timber extraction is combined with biodiversity protection, and land sparing where some areas are more intensively logged whilst others are left as reserves. They found that land sparing would retain the highest species richness as land sharing leads to widespread degradation. Although a single area study of birds, beetles and ants this study highlights the fundamental weakness of the headlong rush to embrace RIL as 'environmentally friendly', namely that logging can never be good for intact tropical forests. Whilst RIL is preferable to CL it should not be used as a reason to begin logging in new areas. The risk is that certification of forest operations is viewed as validating the spread of concessions into new areas. As mentioned above, RIL is not capable of ensuring sustainable yield alone and so degraded concessions may have to be left in search of untouched areas with their ‘primary forest premium’.

A very basic prerequisite for the use of RIL is that it requires well trained staff and adequate monitoring /enforcement. Both of these can be addressed by capacity building. Well trained staff can improve RIL outcomes and increase the likelihood of increasing return on investment in the longer term. This manifests itself as:

1. Faster and more accurate inventories. For example the use of local knowledge in the Amazon basin, employing local people to carry out inventories. This can speed up inventory compiling, however there is not currently a full understanding of the nomenclature used across the region by locals, with about 10% of common names applied to more than one species [77],

making reporting and interpretation of inventories a difficult task;

2. Training in silvicultural treatments that go beyond RIL is required to help improve post-harvest growth rates of FCT's and move towards sustained yield [58];
3. Improving workers' labour conditions through training and education may help temporarily employed harvesting workers to decrease collateral damage and buy into RIL and SFM ethos and also improve the effectiveness of governmental monitoring [73];
4. Other benefits include reducing the costs associated with wasted wood, improve machinery use efficiency and reduce worker injuries[67].

RIL has financial consequences when compared to CL. The capital required to implement is front loaded due to requirements for inventories, road and skidding route planning and the cost of training competent practitioners to carry these activities out. This has led to a perception that RIL is more expensive than CL and some resistance to conversion[67]. However these costs can be offset by savings in the reduction of wasted wood, collateral damage, skidding savings and timber value which are realised later on in the process [78].

Different analyses of RIL implementation versus CL have produced different results with RIL costing less [79] or more[70]. Holmes et al. [67] examined a number of previous studies which showed no clear trend either way for profitability of RIL over CL, however comparison is not straightforward as CL accounting doesn't consider the value of wasted timber in the form of lost wood and excessive stumpage. Whilst RIL vs CL cost comparisons are inconclusive the ability of RIL to achieve sustained yield is limited and so longer felling cycles, reduced harvests, retention of seed trees should be considered. The financial consequences of implementing RIL in a manner that could allow SFM and a continuous crop of high-value timber species would "... substantially diminish harvestable timber volume whilst further increasing management and training costs"[21]. This raises the question of the long-term suitability of RIL as the preferred timber extraction method without supplementary financial incentives for concessionaires [80]. Such incentives do exist in the form of market-based premiums for timber from certified sources and the relatively new development of REDD$^+$ payments for RIL. However these both require the up-front investments, training and market forces to be viable options. For example a study of Southeast Asia found the cost of reducing one tonne of carbon using RIL was \$25 tC^{-1}[81]. Market-based payments under REDD+ would need to exceed this to encourage uptake of RIL which was only used in one third of sites in the study. Market forces alone may not be sufficient to ensure profits and forest sustainability; a strong governance system is also needed to increase the costs of illegal logging, for example[82].

Whilst RIL is applicable to industrial logging operations as an alternative to CL, is it fit for purpose at the smallholder scale? De-centralisation of forest ownership and governance is an ongoing process and local governance of forests as common-pool resources can reduce unauthorised access, illegal logging, and maintain local forest integrity [83]. In 2014 25% of tropical forests were under some form of local control with that figure expected to rise to above 30% in ensuing years [84]. There are real barriers to implementing RIL for these forest owners as they do not have the expertise or capital required to inventory their entire holding, often only making an inventory of the next harvesting block [83]. In the Amazon these blocks are typically only 10-50 ha. The resulting management decisions are based on insufficient sampling of the overall landholding and small scale clumping of tree species can lead to overestimation of stand density [83]. Coupled with the difficulties with nomenclature mentioned above, RIL planning at the smallholder scale will be based on weak foundations [77,83].

The cutting of lianas is often a pre-felling operation to reduce collateral damage caused by harvesting. However in smallholder forests where non-timber forest products (NTFP's) are a source of food and income this practice can impact on the livelihoods of local communities. RIL is focused on ecological functions of forests and not livelihood value and not well suited to smallholder forestry [83,85]. Local communities rely on the forest for more than just timber and the implementation of RIL can prioritise one aspect of forest goods and services over the others. Therefore the applicability of RIL, in its current form, to this substantial proportion of tropical forest is limited and possibly damaging. Care should be taken by governments and certification bodies to ensure smallholders are supported through RIL implementation. Assessing the capacity of smallholders and community forests to sustainably support the whole range of products and services should be part of the certifiers due diligence processes.

Logging in general, including RIL has important effects on availability of NTFP's for local inhabitants. This can impact in 4 main ways [85]:

1. Conflict of use: Species of tree with high timber and NTFP value, for example uxi, cumaru and amapá [86];
2. Competition: where an NTFP resource is valuable, logging workers may compete with locals for it;
3. Facilitation: Access into remote forest areas for outsiders provided by logging access roads to take NTFP's such as bushmeat;
4. Indirect effects: Functional changes to forest structure as a result of logging practices which may be positive or negative.

Conflict of use is considered the most damaging effect of logging on local communities that rely on NTFP's which suggests either NTFP's will have to become part of forest management plans or that timber bans are required for particular species. If RIL implementation cannot both maintain forest goods and services concurrently with maintaining profits for the concessionaires then it has limited value as a social or silvicultural method to ensure continuous forest cover. A combination of locally managed forests, logging concessions and government assessments of impacts on local peoples is needed in order to ensure all forest users are considered in multiple use management plans [73,83,85,86].

Development of logging roads has long been recognized as a key driver for ingress of new settlers, poachers, illegal loggers and, eventually, conversion to non-forested land [21,28,87]. Land use change is the main factor behind deforestation. The current reliance on RIL may create the perfect storm of circumstances to enable further land conversion [69]. Access to new forest areas, subsequent degradation and devaluation of the remaining timber stock and the need to log less intensively but more widely are direct consequences of RIL. Coupled with ineffective monitoring, weak central governance and de facto access to forest products for opportunists and the future looks bleak for RIL as part of any sustainable plan for the future. But what other options are there? Tropical plantations currently cover 55 million ha and so are not sufficient to sustain the estimated 349.3m m^3 of tropical logs, sawn wood, veneer and plywood produced in 2013 [88]. Of the 1.77 billion ha of tropical forest remaining [89], 9% suffered from partial canopy cover loss between 2000 and 2012 according to FAO [90]. Given the most optimistic harvesting cycles of circa 40 years required for sustained yield [31], RIL would involve harvesting in over 30% of global tropical forests cyclically. This would be in a world with no illegal logging, no land use change, no steep slopes, and creation of new markets for timber retention such as REDD+. Killmann et al [79] found that average harvesting rates under RIL were 37m^3. At this rate, in order to maintain 2013's global tropical timber production of 349.3 million m^3 [84] we would see 1.059 billion ha of tropical forest used if RIL were implemented fully in all timber production. This is clearly an unsustainable practice due to the massive demand for tropical wood products so a line in the sand must be drawn. 25 years on from the coining of the term RIL it has become ingrained in our governance and certification systems with no thought of the end game. It is time to reassess tropical timber production.

CONCLUSIONS

Overall, we conclude that RIL has ecological advantages over CL, collateral damage is lower, biodiversity at the genetic, species and community levels is less impacted and soil structure is less disturbed. Evidence shows that the benefits over CL extend into the lithosphere, hydrosphere and biosphere. However, the current harvest intensities are too high and so the benefits are not necessarily realised, especially when coupled with weak implementation. Capacity building, better governance and incentive schemes can improve RIL implementation and both the quality and predictability of outcomes.

RIL cannot guarantee sustainable timber yield alone so regeneration and tending strategies need to be developed. Negative effects could be mitigated by implementing a more detailed inventory, avoiding high-grading, reducing harvest intensity. Consideration also needs to be given to a suite of post felling operations, applicable on a site to site basis, in order to increase regret of target species. However options such as enrichment planting are expensive, making SFM a desirable but unachievable aim for many.

RIL is very much here to stay and largely achieves its aim of reducing negative impacts from the species level up to the size of a forest concession or holding. However there are inherent problems when considered at the landscape scale with more widespread degradation and concentration of felling on low gradient areas resulting from increased RIL implementation. Land sparing may be a way of mitigating impacts on the larger scale, especially if multiple concessions were to work together to plan felling cycles, intensity, road construction etc. together. In this way resources could be pooled and further cost savings made.

RIL is not currently sufficient for ensuring NTFP continuity and work needs to be directed towards understanding and mitigation of resource conflicts. The applicability of RIL to smallholder forestry, over a quarter of the total land available, is limited.

Due to the reduced logging intensity of RIL and the global demand for timber, the approach is not applicable at the ecosystem level. Hence we speculate that if RIL were to be implemented by just 25% of all tropical forestry production then RIL would become the biggest threat to our tropical ecosystems in terms of primary forest degradation leading to land use change. We suggest that a mixture of land zonation and different logging intensities be used in order to balance the need for sustainable production areas and durable, functioning, intact ecosystems. This must be done on multiple scales to ensure both that the local conditions are considered and also the ecosystem. Timber certification organizations must include ecosystem impacts as a consideration for any concession. Funding must be directed towards this aim as the current fragmented regime of certification, financial incentives and capability capacity is not sufficient to stop widespread degradation through RIL conversion and subsequent facilitation. Ultimately if demand for timber doesn't fall then tropical forests will become remnants if RIL is the primary ethos employed there. Logging intensity must be reduced to enable a move towards sustainable yields but we must not let it merely proliferate the area of degraded forest. Instead new parcels of land must be found to be reforested in order to protect more ecologically valuable forest.

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AUTHOR CONTRIBUTIONS

G.M. took lead in the preparation of the manuscript. A.L.R, A.S., M.S. wrote the introduction of the paper. A.E.K., G.M. and Z.S. did the literature research and were writing section 2 to 4. N.K. distributed the subsection to the different authors, evaluated, revised and edited the final manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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