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# Sustainable Management of Tropical Forests Can Reduce Carbon Emissions and Stabilize Timber Production

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## HIGHLIGHTS

- About 500 million hectares of tropical forests have been degraded due primarily to overexploitation
- Preventing premature re-entry into harvested areas can retain up to 34% of carbon stocks in the forests
- Adoption of reduced-impact logging and wood processing technologies (RIL+) along with financial incentives can reduce forest fires, forest degradation, maintain timber production, and retain carbon stocks
- About US$1.8 Mg $CO_2^{-1}$ or US$2 billion year$^{-1}$ is needed for the adoption of RIL+ for the whole tropical production forests.

The REDD+ scheme of the United Nations Framework Convention on Climate Change has provided opportunities to manage tropical forests for timber production and carbon emission reductions. To determine the appropriate logging techniques, we analyzed potential timber production and carbon emission reductions under two logging techniques over a 40-year period of selective logging. We found that use of reduced-impact logging (RIL) techniques alone in tropical production forests (PdF) could reduce carbon emissions equivalent to 29–50% of net emissions from tropical deforestation and land use change, while also supplying 45% of global round-wood demand. Adopting RIL plus other improvements (RIL+) in forest management (adopting forest certification and DNA timber tracking to prevent illegal logging) and wood conversion practices (adopting technology to increase recovery of sawn wood), would result in increasing long-term carbon storage in sawn-wood and reduce logging-induced fire-prone wood wastes by 14–184%. For this to happen, about US$2 billion or $1.86 per Mg $CO_2$ in financial incentives are needed annually for parties to adopt RIL+ and to prevent premature re-entry logging. Our findings suggest that future climate policies should explicitly include RIL+ to satisfy the "sustainable management of forests" proviso in the REDD+ scheme, and also count carbon in wood products as eligible credits for trading.

**Keywords: forest degradation, production forest, REDD, selective logging, timber production, carbon emissions**

## INTRODUCTION

Tropical forests are diverse in terms of flora and fauna species. Deforestation and forest degradation in the tropics have resulted in the annual loss of natural forests of 13 million ha, while degrading 500 million ha of primary and secondary forests (ITTO, 2002), and affecting up to 85% of the threatened and endangered species listed in the Red List of the International Union for Conservation of Nature (www.iucnredlist.org). In addition, tropical deforestation is responsible for net emissions of about 1 Pg C year$^{-1}$ (Pan et al., 2011; Baccini et al., 2012), or 10% of global anthropogenic emissions. Not included in these estimates are emissions from unnecessarily destructive logging, which also unduly reduces commercial timber stocks and, worse yet, render many forests prone to burning and clearing (Asner et al., 2006). Losses of commercial timber stocks and associated carbon emissions (referred to collectively as forest degradation) are difficult to evaluate with the available remote sensing technology (Bustamante et al., 2016; Palace et al., 2016) because trees are selectively logged from forests with dense canopies, but the extent of logging far exceeds that of deforestation (Bicknell et al., 2014). Although carbon emissions from forest degradation usually go unreported (Asner et al., 2005), some estimate the magnitude of these emissions to be equivalent to that from deforestation (Pearson et al., 2014). From 2000 to 2005, high-resolution global remotely sensed images showed that humid tropical forest logging had at least 20-times the geographic footprint of deforestation (Asner et al., 2009). Unplanned logging by untrained crews causes severe damage to residual forests and leaves behind huge amounts of logging waste. Unnecessarily large canopy openings coupled with the presence of flammable logging waste also render forests susceptible to destructive fires (Cochrane, 2003).

Sustainable forest management is defined by the International Tropical Timber Organization (ITTO) as the process of managing forest to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment (www.itto.int). In our study, the desired objectives are to achieve the flow of timber production and to retain carbon stocks in the forests by switching from conventional logging (CVL) to reduced-impact logging (RIL). Defined in this article as a logging practice with well-defined planning, well-trained logging crews, and supervised implementation of timber harvesting operations, RIL is capable of significantly reducing logging damages and wood wastes caused by harvesting operations compared to CVL (see Sasaki and Putz, 2009, for comparison of damages and wastes). Main activities under RIL include pre-harvest activities such as boundary demarcation, pre-felling inventory, tree hunting, training, and tree marking and mapping and harvest activities such as felling and bucking, skidding, and log deck operation (Medjibe and Putz, 2012).

Sustainable forest management for timber and maximization of carbon retention are currently jeopardized in much of the tropics by poor logging practices and premature re-entry into harvested areas (i.e., re-logging before the end of the designated cutting cycle). Our previous studies suggest that replacing CVL with RIL could substantially reduce carbon emissions (Kim Phat et al., 2004; Putz et al., 2012; Sasaki et al., 2012). RIL can contribute to biodiversity conservation ranging from trees (Bicknell et al., 2014) to mammals (Putz et al., 2012). Furthermore, Miller et al. (2011) demonstrated with eddy covariance and ecological measurements that RIL impacts on forest carbon stocks are minimal, ranging from 26.0 ± 1.5 to 32.6 ± 1.3 Mg C ha$^{-1}$ year$^{-1}$ in forest before logging and 31.1 ± 1.4 to 32.0 ± 1.1 Mg C ha$^{-1}$ year$^{-1}$ in forests after 1–3 years of logging. These findings provide further impetus for explicit inclusion of RIL as a way to reach climate change mitigation objectives. We assess the potential contributions of improved tropical forest management to climate change mitigation through the adoption of RIL, along with strict prohibition of premature logging re-entry and technological changes in forest industries. A combination of RIL and the use (PLUS) of improved logging technology and wood processing technology is referred to here as RIL+.

## METHODS

### Tropical Production Forests and Current Logging Practices

Production forest refers to forest, where commercial logging for timber production is allowed once per cutting cycle of 25–60 years on average, depending on forest types and management intervention (Rutishauser et al., 2015). Timber is exploited through selective logging systems, under which merchantable trees with diameter at breast height (DBH) greater than the DBH limits imposed by logging regulations in tropical countries (see Sasaki and Putz, 2009, for a list DBH limits in selected countries) are felled after logging permit is issued by the country in question. As unsustainable logging, industrial agriculture and smallholder subsistence crop cultivation, and agricultural cultivation continue to destroy and degrade tropical forests and biodiversity, international efforts to protect the forests began to show promising results. The roles of Reducing Emissions from Deforestation and forest Degradation PLUS (REDD+), which includes conservation of forests, sustainable management, and enhancement of forest carbon stocks, were fully recognized in the Copenhagen Accord adopted at the 15th session of the Conference of the Parties (COP15) to the UNFCCC in December 2009 (Burgess et al., 2010). Under the Warsaw Framework for REDD+ at COP 19, the need to protect tropical forests for climate change mitigation was further encouraged by offering result-based financial incentives to developing countries for reducing carbon emissions under REDD+ (Norman et al., 2014). In addition to pledging to reduce emissions by major emitters of greenhouse gases, such as the United States and European Union, and setting an emission cap for China, 24 countries pledged about \$10 billion to Climate Finance at the COP20 in Lima in December 2014 (UNFCCC, 2014). REDD+ will inevitably be part of the future climate change regulations once Paris Agreement reached at the COP21 in December 2015 enters into force (UNFCCC, 2015). Sustainable forest management is an important element of REDD+ because of its multiple roles in commercial timber supply, job generation, biodiversity conservation, and reductions in carbon emissions from forest degradation. Sustainable forest management is a suitable goal for production forests (PdF)—the forests where logging for commercial timber is practiced. Logging in the tropics is practiced mainly under forest concessions in which governments grant logging licenses to companies to operate according to governmental regulations. Logging companies are usually required to submit a master plan outlining forest resource assessment methods, harvest planning, sequences of annual harvesting coupes, and socio-environmental impact assessments. Despite progress being made toward the writing of proper forest management plans, the called-for requirements are rarely met in practice and corruption is common. Therefore, sustainable forest management could play a positive role in supporting good governance, global timber supplies, and carbon retention if improved logging practices are adopted.

## Forest Areas Available for the RIL Practice

According to forest functions classified in FAO's Global Forest Resources Assessment 2010 (FAO, 2010), about 28.4% of the total area of tropical forests (1664 million ha in 2010) can be considered as PdF. RIL can be applied to manage these PdF for timber production and carbon retention. The area of PdF can be further classified to operable and inoperable areas. The former is the area suitable for logging operations, while the latter is the area of forests located in culturally, socially and environmentally sensitive areas such as around villages and culturally important sites, buffer zones along waterways, and on steep slopes, or other areas strictly protected by logging regulation. By subtracting inoperable areas from the total area of PdF, a net operable area of PdF can be obtained.

As reported in tropical forest resources assessment project (in the framework of the Global Environment Monitoring System of the FAO in 1984 (FAO, 1984), percentage of inoperable area ranges from 13% of PdF in central and Southern Sumatra to 30% in the whole of Sulawesi in Indonesia. In other tropical countries, inoperable area of PdF is about 30% of the total area of PdF (Kim Phat et al., 2004). For this study, we used 30% as the percentage of inoperable area and therefore the total net operable area of PdF is 330.8 million ha [=1664*0.284*(1−0.3)] for a 40-year cutting cycle or 8.27 million ha is subject to annual harvesting.

## Carbon Stocks for Each Logging Re-entry

Defined as re-logging before the end of the designated cutting cycle, premature re-entry logging has repeatedly caused the loss of carbon stocks until all marketable trees are harvested (Sasaki and Putz, 2009; Putz et al., 2012). To illustrate the impact of premature re-entry logging on carbon stocks on timber production and forest degradation, we assessed carbon stocks in natural PdF in the tropics under two logging methods—CVL and RIL. Under RIL, logging is implemented once at the beginning of a 40-year cutting cycle, while under CVL, two additional harvests are allowed in year 5 and year 20, well before the end of the 40-year cutting cycle. These two logging re-entries are referred to as premature re-entry logging. Equations (1)–(3) estimate forest carbon stocks for CVL and RIL. For the logging at the beginning, 30% of the aboveground biomass (including loss due to logging damages and wastes) are removed. Only merchantable trees (trees with DBH equal or greater than 50 cm) can be removed in the subsequently logging re-entries. Eq. 1 is carbon stocks affected by logging in the beginning of the cutting cycle under both logging methods, while the rest are subsequent premature re-entry logging under the CVL method:

$$\mathrm{CS_0(t = t_0)} = \frac{\mathrm{CS_{MAX} \times CS_0(t0) \times EXP(\alpha \times t)}}{\mathrm{CS_{MAX} + CS_0(t0) \times [EXP(\alpha \times t) - 1]}} \tag{1}$$

$$\begin{aligned}\mathrm{CS_1(t = t_{0-e1})} &= \mathrm{CS_0(t_{0-e1})} \\ &\quad + \frac{\mathrm{CS_{MAX} \times CS_1(t0) \times EXP(\alpha \times} t)}{\mathrm{CS_{MAX} + CS_1(t0) \times [EXP(\alpha \times t) - 1]}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{CS_2(t = t_{0-e2})} &= \mathrm{CS_1(t_{0-e2})} \\ &\quad + \frac{\mathrm{CS_{MAX} \times CS_2(t0) \times EXP(\alpha \times t)}}{\mathrm{CS_{MAX} + CS_2(t0) \times [EXP(}\alpha \mathrm{\times t) - 1]}}\end{aligned} \tag{3}$$

Where

$\mathrm{CS_0(t)}$, $\mathrm{CS_1(t)}$, and $\mathrm{CS_2(t)}$ are carbon stocks (Mg C $\mathrm{ha^{-1}}$) at time $t$ under the RIL, the first premature re-entry and second premature re-entry logging, respectively.

$\mathrm{CS_0(t0)}$, $\mathrm{CS_1(t0)}$, and $\mathrm{CS_2(t0)}$ are carbon stocks (Mg C $\mathrm{ha^{-1}}$) 1 year after RIL, first premature re-entry, and second premature re-entry logging, respectively.

$\mathrm{CS_0(t_{0-e1})}$ and $\mathrm{CS_1(t_{0-e2})}$ are carbon stocks affected by first re-entry (e1) and second re-entry (e2) until next harvest occurs

$\mathrm{CS_{MAX}}$ is the highest carbon stocks of the mature PdF. It is assumed to be 600 Mg C $\mathrm{ha^{-1}}$ for all logging methods. This maximum value is equivalent to the stabilized level of carbon stocks in the forest ecosystems (Krankina and Harmon, 1995).

$\alpha = \mathrm{MAI/CS(t0)}$ is the growth rate for each logging method. This calculation is based on the fact that forests grow faster when more space is created by logging (Pinard, 2009). MAI is Mean Annual Increment (Mg C $\mathrm{ha^{-1}year^{-1}}$). Aboveground biomass increment (i.e., MAI) was reported to be about 1.30 Mg C $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$ in Amazon forests (Mazzei et al., 2010), and 1.63 Mg C $\mathrm{ha^{-1}}$ $\mathrm{year^{-1}}$ in the northern Borneo (Berry et al., 2010). In a tropical wet forest in Nicaragua, it was estimated to be 2.68 Mg C $ha^{-1}$ $year^{-1}$ (Mascaro et al., 2005). For this study, MAI is assumed to be 1.5 Mg C $ha^{-1}$ $year^{-1}$.

The literatures on carbon stocks in tropical PdF have become increasingly available (**Table 1**). The data suggest that the average carbon stocks in PdF are 174.0 ± 11.6 Mg C $ha^{-1}$ (± is for confidence interval of 90%). We took this average value for initial carbon stocks (aboveground carbon) in PdF prior to logging.

Merchantable trees account for 48.3% of total aboveground biomass in the Southwestern Brazilian Amazon (Cummings et al., 2002), 50.8% in Panama (Chave et al., 2005), and 56.2% in East Kalimantan, Indonesia (Sist et al., 1998). For this study, 50% is used for estimating aboveground biomass of merchantable trees. Biomass removal (biomass loss) at each harvest for both logging methods is assumed to be 30% of the total aboveground biomasses or 60% of the merchantable trees (including biomass in felled log, top log, stump, branches, and leaves). Subsequent first and second premature re-entry logging removes 30% of the total aboveground biomass until biomass of all merchantable trees is removed. When biomass of all merchantable trees is less than 30% of all biomass, that biomass is completely removed. However, no logging is assumed to occur when merchantable trees are completely logged.

## Carbon Fluxes in Sawnwood and All Wood Wastes

Important variables or factors relevant to RIL and CVL methods are once-time logging at the beginning of cutting cycle, first and second premature re-entry logging, logging damages (LD) to residual stands, logging wastes (LW) due to tree felling, skidding of felled trees, and transporting of logs to sawmill, sawnwood (SW), and wood wastes (WW) at the sawmill where logs are further processed to produce wood for end use. Longevity of wood utilization is affected by wood processing technology and therefore wood technology (see CIRAD, 2015, for currently developed methods to increase wood durability and lifespan) can increase carbon storage in end-use wood products when appropriate wood processing technology is employed under the RIL. Current wood processing technology used in tropical countries results in a sawnwood recovery rate of only about 40–50% (Enters, 2001). Carbon biomass allocation for each component after harvesting is illustrated in **Figure 1**, and each wood component and parameter under conventional and RIL can be derived from:

$$\mathrm{LD} = \mathrm{s} \times \mathrm{BL} \tag{4}$$

$$\mathrm{HB} = \mathrm{BL} - \mathrm{LD} \tag{5}$$

$$\mathrm{BR} = \frac{\mathrm{HB}}{\mathrm{BEF}} \tag{6}$$

$$\mathrm{SB} = \mathrm{HB} - \mathrm{BR} \tag{7}$$

$$\mathrm{LW} = \mathrm{a} \times \mathrm{SB} \tag{8}$$

$$\mathrm{RW} = \mathrm{SB} - \mathrm{LW} \tag{9}$$

**TABLE 1 | Summary of carbon stocks in production forests in the tropics (Mg C $ha^{-1}$).**

| Country | Pre-logging above-ground Carbon Stocks | References |
|---|---|---|
| Terra firme rain forest in the eastern Amazon (Brazil, Paragominas) | 188.8 | Sist et al., 2014 |
| Terra firme rain forest in the eastern Amazon (Brazil, Paragominas) | 205.0 | Mazzei et al., 2010 |
| Lowland moist forests in Central Africa | 126.0–216.0 | Nasi and Frost, 2009 |
| Managed forests in Campo-Ma'an area in South Western Cameroon | 137.0–204.0 | Djomo et al., 2011 |
| Sulawesi, Indonesia | 150.5–161.5 | Culmsee et al., 2010 |
| Primary forest in Seram, the Moluccas, Indonesia | 175.0 | Stas, 2014 |
| Unlogged forest in Sabah, Malaysia | 176.5 | Morel et al., 2011 |
| Brazil | 127.0 | Asner et al., 2005 |
| Brazil | 218.0 | Pearson et al., 2006 |
| Brazil | 218.0 | Keller et al., 2004 |
| Brazil | 186.0 | Miller et al., 2011 |
| Tapajos National Forest, Brazil | 168.0 | Figueira et al., 2008 |
| Brazil | 185.0 | Huang and Asner, 2010 |
| Cambodia | 116.6 | Kim Phat et al., 2000 |
| Monts de Cristal region of northwestern Gabon | 210.0 | Medjibe et al., 2011 |
| Gabon | 190.0–194.0 | Medjibe and Putz, 2012 |
| Guiana | 210.0 | Blanc et al., 2009 |
| Berau, East Kalimantan, Indonesia | 346.0 | Brown et al., 2011 |
| Indonesia (Berau district) | 199.3 | Sist and Saridan, 1999 |
| Malaysia | 138.0 | Berry et al., 2010 |
| Ulu Segama Forest Reserve, Malaysia | 164.0–166.0 | Pinard and Putz, 1996 |
| Malaysia (Tangkulap) | 126.0 | Imai et al., 2009 |
| Malaysia (Deramakot) | 178.0 | Imai et al., 2009 |
| Malaysia (Pasoh) | 137.0–155.0 | Okuda et al., 2004 |
| Papua New Guinea | 208.0 | Stanley, 2009 |
| Papua New Guinea | 96.0–126.0 | Bryan et al., 2010 |
| Papua New Guinea | 121.0 | Fox et al., 2010 |
| Philippines | 193.0 | Lasco et al., 2006 |
| Republic of Congo | 271.0 | Brown et al., 2005 |
| Average (use for this study) | 174.0 (range: 162.4–185.6)* | |
| 90% Confidence Interval | 11.6 (6.7% of the average)* | |

**According to the Approved afforestation and reforestation baseline and monitoring methodology (AR-AM0004) of the UNFCCC, the maximum allowable relative margin of error of the mean for carbon biomass estimate is ±10% at 90% confidence level.*

$$\mathrm{WW} = \mathrm{b} \times \mathrm{RW} \tag{10}$$

$$\mathrm{SW} = \mathrm{RW} \times \mathrm{WW} \tag{11}$$

where

**FIGURE 1 | Schematic illustration of carbon biomass allocation after logging and premature re-entry logging.** Background photos were taken by the first author in Kampong Thom and Koh Kong provinces in Cambodia.

BL is total Biomass Loss or reduction during each logging entry. BL includes all harvested wood, branches, top logs, and destroyed trees. BL is same for both logging methods.

LD, HB, BR, SB, LW, RW, WW, and SW are Logging Damages, Harvested Biomass, BRanches of harvested wood, Stem Biomass of harvested wood, Logging Wastes, Round Wood, and Sawnwood under CVL and RIL, respectively.

*s* is logging damage to residual stands calculated as proportional to HB.

*a* is logging wastes such as top logs, broken trunks and high stumps created during tree felling, log skidding and transporting.

*b* is wood wastes created during processing of roundwood for sawnwood.

Values of BL, BEF and parameter *s*, *a*, and *b* are provided in **Table 2**.

Due to similarity of time to decay of wood products, cumulative carbon fluxes (carbon storage) in various harvested wood products can be grouped to two carbon pools. They are sawnwood (SW) and all logging and all wood waste (AW). AW is the sum of LD, BR, LW, and WW. Carbon fluxes in SW and AW ($\mathrm{SW}_f$ and $\mathrm{AW}_f$) can be derived using the first-order equations below:

$$\mathrm{SW}_f(t) = \mathrm{SW} \times \mathrm{e}_1^{-\mathrm{k}} \times t \tag{12}$$

$$\mathrm{AW}_f(t) = \mathrm{AW} \times \mathrm{e}_2^{-\mathrm{k}} \times t \tag{13}$$

Where t is elapsed times (years) corresponding to time evolving after logging.

$\mathrm{k}_1$, $\mathrm{k}_2$ are the decay rates, which are derived from $\mathrm{k} = \ln(2)/\tau$ ($\tau$ is time to decay half of its volume or half-life time in year). Subscript f refers to flux. $\tau$ and k are dependent on wood processing technology to be employed under CVL or RIL.

Coupled with its trained staff, RIL is assumed to employ the more efficient wood processing technology that can increase end-use wood recovery rate by 10% more than that under the CVL and prolong the half-life time of sawnwood from 30 years as suggested in IPCC 2006 Guidelines to 50 years (IPCC, 2006). The UN's Clean Development Mechanism has an additional goal of assisting non-Annex 1 Parties to achieve sustainable development by providing an incentive for Annex 1 Parties to transfer climate friendly technology to non-Annex 1 Parties—the developing countries mainly in the tropics. It is anticipated that adoption of REDD+ scheme in the future climate agreement will also

**TABLE 2 | Variables, parameters, and assumptions.**

| Description | CVL | RIL | Remarks |
|---|---|---|---|
| Initial Carbon Stocks (CS, Mg C ha$^{-1}$) | 174.0 | 174.0 | See **Table 3** |
| BL rate | 0.3 | 0.3 | 30% of CS. West et al. (2014) reported at about 17–26% |
| BEF | 1.74 | 1.74 | (Brown, 1997) |
| *s* | 0.3 | 0.15 | 30% of biomass loss (removed biomass) under CVL (Johns et al., 1996) and 15% under RIL (Sist et al., 1998; Kim Phat et al., 2000; Pinard et al., 2000) |
| *a* | 0.3 | 0.15 | 30% of harvested biomass under CVL (Sasaki and Putz, 2009) and 15% under RIL (Sasaki and Putz, 2009) |
| *b* | 0.5 | 0.4 | 50% of roundwood under CVL (Enters, 2001) and 40% under RIL (40% was based on Enters, 2001; Owusu et al., 2011) |

*Conventional logging (CVL) is a selective logging practice commonly used in production forests in the tropics. Usually, CVL does not have proper logging planning, enforcement or control, and trained crews to carry out logging operations (see Holmes et al., 2002; Medjibe and Putz, 2012) for detailed activities and associated costs for both CVL and RIL). Logging re-entry is a common practice of CVL causing rapid reduction of carbon stocks and biodiversity. CVL also creates huge logging damages to residual stands and wood wastes.*

*RIL is also a selective logging but it involves the use of proper planning of logging operations and trained crews. Refer to Medjibe and Putz (2012) and Holmes et al. (2002) for logging activities and associated costs. Logging damages and wood wastes created by CVL and RIL were reported by Sasaki and Putz (2009).*

*BL rate is the total reduction rate of aboveground biomass due to logging.*

*BEF is biomass expansion factor referring to proportion of total dry biomass of aboveground tree components such as leaves, branches, top logs, and twigs of the living trees to biomass in tree trunk.*

*s is logging damage caused by logging. Damage includes dead tree of residual stands killed by fallen trees.*

*a is logging wastes caused by logging operations such as tree skidding, trimming, and exporting.*

*b is wood wastes created during wood processing at the sawmill. It occurs outside forest area.*

result in the need for technology transfer to developing countries. Half-life time for AW is 5 years under both logging scenarios.

# RESULTS

## Sawnwood Production

Although same amount of biomass is removed under both CVL and RIL methods, removed biomass under RIL contains a smaller proportion of logging damages and other wood wastes, and therefore sawnwood production available for end use is much higher. Considering all tropical PdF, the RIL adoption could produce 287 million m$^3$ year$^{-1}$ of sawnwood production (about 478 million m$^3$ of roundwood) over a 40-year cutting cycle (**Table 3**) or 29% of global roundwood consumption in 2012 (FAO, 2012). We compared the results of our findings with the data produced by the ITTO because ITTO is the only intergovernmental organization that has maintained good statistical data on global tropical timber trade. ITTO's member countries represent about 80% of the world's tropical forests and 90% of the global tropical timber trade. ITTO's member countries produced 173.6 million m$^3$ of roundwood in 2011, or about an estimate of 204 million m$^3$ from all tropical forests. Given the fact that up to 87% of logging in the tropics is illegal (Hansen and Treue, 2008; Lawson and MacFaul, 2010; Lawson, 2014) and was usually unreported (Colfer and Resosudarmo, 2002; Asner et al., 2005), and by assuming an average illegal logging rate of 60% (Lawson and MacFaul, 2010), a conservative estimate of roundwood production using the figure reported by ITTO would be 510 million m$^3$ [= 204/(1−0.6)].

Our model suggests that sawnwood production under RIL is 124.7 m$^3$ (207.8 m$^3$ of roundwood) or 77.0% higher than that under the CVL if premature re-entry logging is prevented (**Table 3**). As first premature re-entry logging is allowed in the 5th year, the CVL method can produce total sawnwood similar to that of RIL. The CVL method with two logging re-entries produces by 345.9 million m$^3$ of sawnwood (692 million m$^3$ of roundwood) or 20.6% higher than that from RIL when sawnwood from the second premature re-entry logging in the 20th year is also included in the calculation (**Table 3**). However, when future commercial wood availability is compared (88.0 m$^3$ ha$^{-1}$ remaining at the year 40 under RIL compared to only 27.3 m$^3$ under the CVL as shown in **Figure 2X**), the RIL adoption results in a 222% [222 = (88.0–27.3)/27.3] higher availability of merchantable timber than under CVL. Although total wood production from all premature re-entry logging is higher, CVL is likely to destroy all merchantable trees, and therefore putting tropical PdF at risk of being cleared for industrial agricultures as logging option is no longer feasible economically.

## Carbon Stock Changes, Emission Reductions, and Removals

Average carbon stocks decline from 174.0 Mg C ha$^{-1}$ to 121.8 Mg C 1 year after RIL logging, but recovers to the pre-logging level or higher by year 40th if premature re-entry logging is prevented (**Table 4** and point A in **Figure 2X**), depending upon forest growth rate and harvest intensity. Our model results agree with those of Keller et al. (2004). Similarly in Amazonian Brazil, where premature early-entry logging was prevented, it took only 16 years for forests to recover 100% of their biomass under RIL while during the same period only 77% was recovered under CVL (West et al., 2014). In contrast, under CVL with two premature re-entries, carbon stocks continue to decline until all merchantable trees are harvested (point D in **Figure 2X**). If premature re-entry logging is allowed, carbon stocks decline by 19.5 and 34.3% for first and second premature logging, respectively. Considering all PdF, and by taking carbon stocks under RIL for meeting the "sustainable management of forests" provision of REDD+ as carbon stocks retained through project activities, and using carbon stocks under CVL as the baseline, preventing first and second premature re-entry logging could reduce emissions of 279.9 and 493.7 Tg C year$^{-1}$ (1026.4–1810.4 Tg CO$_2$ year$^{-1}$) respectively, in addition to removing (sequestering) −8.2 Tg C year$^{-1}$ (−30.1 Tg CO$_2$ year$^{-1}$) from the atmosphere (**Table 4** and **Figure 2Y**). These emission

**TABLE 3 | Adopting RIL to increase sawnwood production while decreasing fire-promoted wood waste.**

| Logging Practices | Harvest (TgC) | Sawnwood | | | | All Waste | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CVL | RIL | RIL-CVL | | CVL | RIL | RIL-CVL | |
| | | | | TgC | (%) | | | TgC | (%) |
| **ANNUAL PRODUCTION IN ALL PRODUCTION FORESTS IN THE TROPICS FOR A 40-YEAR CUTTING CYCLE IN TgC, EXCEPT OTHERWISE STATED** | | | | | | | | | |
| No Re-entry | 431.7 | 60.8 | 107.6 | 46.8 | 77.0% | 370.9 | 324.1 | −46.8 | −14.4% |
| 1st Re-entry | 327.9 | 46.2 | N/A | | | 281.8 | N/A | | |
| 2nd Re-entry | 290.4 | 22.7 | N/A | | | 267.7 | N/A | | |
| Total for first re-entry logging (*1) | 759.6 | 107.0 | 107.6 | 0.6 | 0.6% | 652.7 | 324.1 | −328.5 | −101.3% |
| Total for second re-entry logging (*2) | 1050.0 | 129.7 | 107.6 | −22.2 | −20.6% | 920.3 | 324.1 | −596.2 | −183.9% |
| **ANNUAL PRODUCTION IN ALL PRODUCTION FORESTS IN THE TROPICS FOR A 40-YEAR CUTTING CYCLE IN MILLION $m^3$ (*3)** | | | | | | | | | |
| No Re-entry | | 162.1 | 286.8 | 124.7 | 77.0% | | | | |
| 1st Re-entry | | 123.1 | N/A | | | | | | |
| 2nd Re-entry | | 60.7 | N/A | | | | | | |
| Total for one re-entry logging | | 285.2 | 286.8 | 1.6 | 0.6% | | | | |
| Total for second re-entry logging | | 345.9 | 286.8 | −59.1 | −20.6% | | | | |

*(*1): Total production for first premature re-entry logging practice is the sum of production from "No Re-entry" practice and actual harvest at the first re-entry.*

*(*2): Total production for second premature re-entry logging practice is the sum of production from "No Re-entry" practice, actual harvest at the first and second re-entry.*

*(*3): Sanwood volume in $m^3$ was derived by CarbonVolume/(sawnwood density, 0.75 times carbon density, 0.5). Sawnwood density (0.75) was based on Simpson (1999) and carbon density (0.5) was based on IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003).*

reductions and removals are equivalent to about 28.8–50.2% of carbon emissions from tropical deforestation between 2000 and 2010 (Baccini et al., 2012) or 93–162% of emission reductions committed by European Union for the second period of the Kyoto Protocol (European Commission, 2013). Furthermore, using logging emission factors of wood extraction and logging damages of 0.82 Mg C $m^{-3}$ harvested wood in Indonesia (Pearson et al., 2014), total emissions from harvesting 324–692 ($324 = 162.1/0.5$ and $692 = 345.9/0.5$ in **Table 3**) million $m^3$ of roundwood are 266–567 TgC $year^{-1}$, respectively. However, in practice, such logging-related emissions were usually unreported (Pearson et al., 2014).

Minus (−) in **Table 4** refers to carbon sequestration (sinks or removals). Emissions from tropical deforestation was based on Baccini et al. (2012). Emission reductions committed by EU were based on European Commission (2013).

## Reducing Fire-Prone Wood Waste by Adopting RIL and Preventing Premature Re-entry Logging

In recent years, increasing fires in selectively logged forests were observed and pose threats to forest management. Humans are the direct cause of most fires in tropical forests and indirectly exacerbate the problem through anthropogenic climate change induced droughts and destructive logging (Cochrane, 2003). The presence of flammable logging wastes coupled with openings of tropical forest canopies render forests very susceptible to destructive fires (Siegert et al., 2001; Gerwing, 2002; Cochrane, 2003). Although CVL could produce more sawnwood when all premature re-entry logging is considered, it creates huge wood waste (371–920 TgC) or up to 183.9% higher if compared to waste created by RIL (**Table 3**). This wood waste is prone to destructive fires but can be reduced with the adoption of RIL combined with improved logging technology such as use of Logfisher, skyline, yarder, and/or helicopter (Abdul Rahim et al., 2009) and wood processing technology such as use of wood-Mizer milling technology rather than freehand chainsaw or chainsaw with frame attachments (Owusu et al., 2011). Forests become prone to destructive fires when the canopy is opened by selective logging and huge amounts of wood waste are left after timber felling. According to Matricardi et al. (2013), the total forest area affected by fires, selective logging, and a combination of logging and fires in the Amazon tripled from 5,889, 5,588, and 392 $km^2$ in 1992 to 9038, 24,188, and 2471 $km^2$ in 1999, respectively.

## Carbon Storage in Harvested Wood Products

As short-life wood waste is reduced and long-life sawnwood is increased, more carbon storage in harvested wood products can be achieved under RIL+. Using equations (12, 13), adopting RIL+ could result in carbon storage in sawnwood of 82.6 TgC $year^{-1}$, while it is only 39.7 TgC under the CVL if compared to one harvest under the "RIL+" (**Figure 3**). Carbon storage in all wood waste is 370.9 TgC and 324.1 TgC at the start of harvesting but reduces to 1.5 TgC and 1.3 TgC at the year 40th, representing the annual average storage of 69.6 TgC and 60.9 TgC under CVL and RIL+, respectively over a 40-year cutting cycle (**Figure 3**). Since carbon storage in all waste under RIL is 8.7 TgC (69.6–60.9) smaller than that under CVL, adopting RIL+ for managing all PdF could reduce emissions by 34.1 TgC $year^{-1}$ (125 $TgCO_2$) or about 21% of emission reductions committed by the United Kingdom for the first commitment period of the Kyoto Protocol

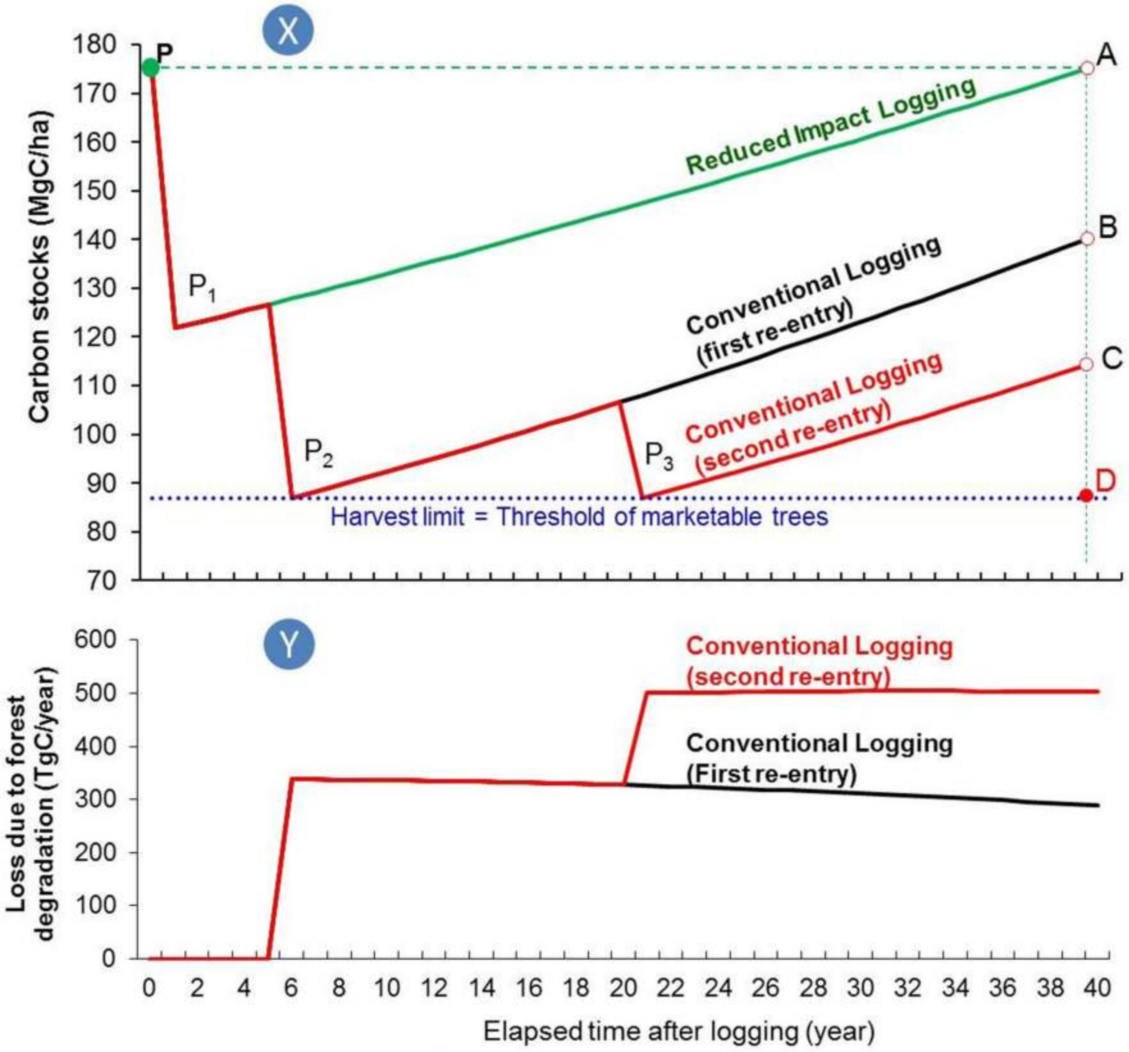

**FIGURE 2 | Forest carbon stocks, storage, and loss in a typical hectare of lowland tropical forest affected by harvest methods and re-entry logging.** Under reduced-impact logging **(X)**, carbon stocks dropped 30% to P1 after logging but carbon stocks recovered to the pre-logging level (A) after 40 years. If premature re-entry logging is allowed at the 5th and 20th years and CVL practices are employed, carbon stocks continue to drop to point P2 (losing all marketable trees) and P3, respectively. Commercial harvests for timber are unlikely when stocks are below D, but wood extraction for charcoal might continue. Over a 40-year time span, carbon stocks can recover back to point B and C (reaching 81–66% of pre-logging) if the area is not cleared. Reduced emissions from forest degradation are about 35–61 Mg C $ha^{-1}$ over a 40-year period if the first and second episodes of premature re-entry logging are prevented, respectively. At the global level, carbon loss **(Y)** was derived by subtracting the carbon stocks under RIL from the baseline (i.e., carbon stocks under the first and second episodes of premature re-entry logging).

between 2008 and 2012. If sawnwood and all waste obtained under the CVL from all premature re-entry loggings are compared, carbon storage in wood products (sawnwood plus waste) under CVL is higher but its declines faster because of a greater proportion and rapid decay of short-life wood waste.

## DISCUSSION

One of the major problems in managing tropical production forest is premature re-entry logging of stands that have not been allowed to recuperate for the entire length of the cutting cycle determined to be needed to sustain timber yields (Putz et al., 2012). Premature re-entry logging is driven by timber scarcity and prices, often coupled with governance failures; when market demands or timber prices increase, forests are often harvested prematurely. Low harvest costs due to the availability of previously constructed logging roads further encourage premature re-entry logging (Ravenel, 2004). The same phenomenon is also associated with changes in governmental and corporate leadership when concession maps are commonly redrawn and previous harvest plans are disregarded. Furthermore, in anticipation of unfavorable treatment by newly installed governments, logging companies

**TABLE 4 | Achieving emission reductions and removals by preventing premature re-entry logging in tropical production forests.**

| Logging practices | Carbon Stocks | | | | | | |
|---|---|---|---|---|---|---|---|
| | Per hectare | | | All production forests | | | |
| | Year0 | Year40 | Change | Year 0 | Year40 | Annual Change (reductions or removals) | |
| | (Mg C) | | | (Tg C) | | (Tg C) | (Tg $CO_2$) |
| No re-entry | 174.0 | 175.0 | −1.0 | 57,559.8 | 57,888.5 | −8.2 | −30.1 |
| 1st re-entry | 174.0 | 140.2 | 33.8 | 57,559.8 | 46,363.0 | 279.9 | 1026.4 |
| 2nd re-entry | 174.0 | 114.3 | 59.7 | 57,559.8 | 37,810.3 | 493.7 | 1810.4 |
| Total reductions | | | | | | | 1056.5–1840.5 |
| Proportion to tropical deforestation (%) | | | | | | | 28.8–50.2 |
| Proportion to emission reductions committed by the EU (%) | | | | | | | 93.0–162.0 |

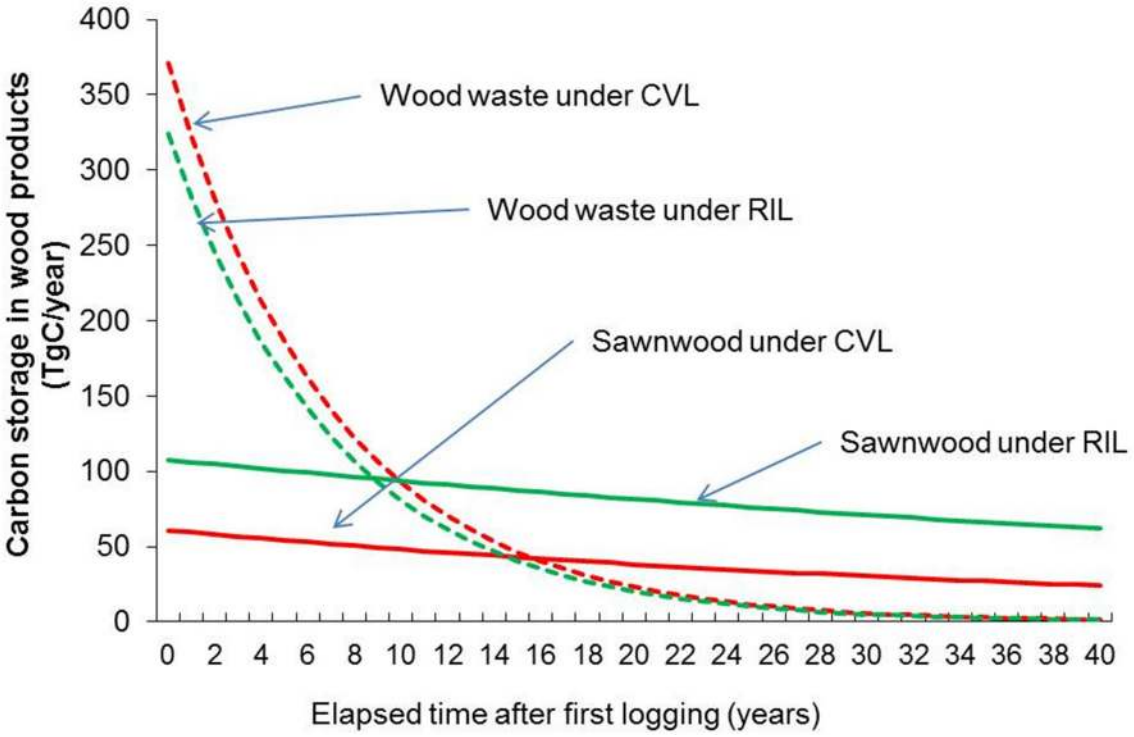

**FIGURE 3 | Carbon storage in harvested wood products (sawnwood and wood waste).**

often harvest as much timber as possible prior to or during elections (Burgess et al., 2012). Future climate agreements should include binding agreements that validated projects adopting RIL shall not be interrupted before the end of a harvest cycle.

In the wood processing sector, rapid technological developments provide new hope for increasing the use and lengthening the longevity of wood products (Fleming et al., 2014). Since RIL increases the amount of wood product from the same amount of harvested timber, RIL adoption can increase carbon storage in long-lived wood products and reduce short-lived wood waste. Furthermore, technological advancements in the logging industry can create more jobs (Clark, 2004) and facilitate low-carbon based economies. To encourage the use of advanced technologies for higher carbon retention in wood products, future climate agreement should also include carbon credits for long-lived wood products as eligible credits for trading.

As up to 87% of the timber harvests can be illegal in a given (Lawson, 2014), about \$30–100 billion year$^{-1}$ is lost globally due to this illegal logging (UNEP INTERPOL, 2013). Forest certification schemes have played an important role in certifying the timber products from sustainably managed forests (Durst et al., 2006; Cerutti et al., 2011; Putz et al., 2012), thereby reducing illegal and unsustainable logging practices to some extent (Cerutti et al., 2011; Kishor and Lescuyer, 2012). Nevertheless, as forest certification is based commonly on paper, and logging in the tropics is being practiced with corruption and falsification of logging permits (Nellemann, 2012), forest certification alone is still vulnerable to document falsification. A combination of forest certification and newly developed timber tracking technologies (Dormontt et al., 2015) to monitor and control wood products is critical for reducing illegal logging and for the prevention of premature re-entry logging. According to a recently established working group of the United Nations Office on Drugs and Crime, a range of technologies are available to verify timber source claims (e.g., anatomy, stable isotopes), but DNA timber tracking technology seems like the best source of information about the tree species, country, forest concession and even individual tree from which wood was derived (Dormontt et al., 2015). Further development, integration, and support for this verification technologies is now required.

Costs are currently the major concern for adopting the RIL or RIL+. RIL has higher costs for pre-harvest and harvest planning activities, and infrastructure development (depending on locations, it may also include costs for helicopter or cable system for logging on steep terrain or wet soil) and for adopting chainsaws to increase wood recovery rate (Holmes et al., 2002; Medjibe and Putz, 2012) but lower costs for harvest operations (Sasaki and Putz, 2009). In Malaysia, although average costs for helicopter logging are \$50–60 compared to US\$10 $m^{-3}$ for CVL, logging damage to surrounded trees were 3.8 times lower than damage created by CVL (Abdul Rahim et al., 2009). Our previous study (Medjibe and Putz, 2012) found that the costs for RIL techniques are lower in four of the ten case studies than costs of using CVL for logging in PdF in Brazil, Gabon, Guyana, and Malaysia. On average, costs for adopting RIL are US\$1.43 ± 1.57 (90% of CI) higher than that under CVL (**Table 5**). For the whole tropical PdF, total additional costs for adopting RIL are about US\$821 million $year^{-1}$ in order to harvest 574 million $m^3$ of roundwood. The cost for certifying forests where RIL has been adopted are estimated to be US\$2.55 to \$10.06 $m^{-3}$ for every 5 years in Brazil and Indonesia, respectively (White, 2011) or \$0.51 to \$2.00 $m^{-3}$ $year^{-1}$. Assuming \$2.00 $m^{-3}$ for certifying forests implementing RIL, it would cost US\$1969 million $year^{-1}$ to certify all 574 million $m^3$ of roundwood.

As adopting RIL can result in emission reductions of 288–502 TgC (1056–1840 $TgCO_2$), the costs for adopting RIL techniques with certified timber products are US\$0.60–1.86 per Mg $CO_2$. This is well below the carbon price for reducing deforestation project traded in the voluntary carbon markets in 2013 and 2012, which was US\$ 4.20 and 7.40, respectively. As Paris Agreement was reached at the COP21 by the parties to the UNFCCC to limit the greenhouse gas emission emissions, new demand for carbon is likely to increase, especially after this agreement enters into effect after 55 countries responsible for 55% of global carbon emissions ratify the agreement (UNFCCC, 2015). Thus, carbon price is also likely to increase. Furthermore, costs for DNA timber tracking (to enforce legislation as well as to reduce export/import of illegally sources timber) is less than 0.01% of the timber values but these costs can be covered from the premium price of the certified timber. Although using DNA technology to track the tropical timber trade is still in its infancy stage, a study on 38,000 log transactions from sustainable forestry in the Japanese market found that certified timber has a price premium of 1.4–4.0% depending on timber species (Yamamoto et al., 2014). Furthermore, as some governments such as European Union, Australia, the United States of America began to enforce the legality of timber import from tropical countries, DNA timber tracking is the only natural identification technology that cannot be falsified (Lowe and Cross, 2011). Financial incentives are therefore still required to get tropical forest industries to reform their harvesting practices such as appropriate logging planning; use of trained crews for forest inventory, tree marking, tree directional felling, log skidding and trimming; and supervision of logging, to adopt less destructive technologies whenever possible such as the use of directional felling, cable system, or helicopter logging system or a combination, and to increase efficiencies (i.e., through the use of trained crews and advanced chainsaws at wood processing mills) from harvest to the final product.

**TABLE 5 | Cost differences between conventional logging and RIL.**

| Cost Difference (US\$ $m^{-3}$) | Remarks | Locations | References |
|---|---|---|---|
| −1.82 | RIL cost is cheaper | Fazenda Cauaxi, Brazil | Holmes et al., 2002 |
| 2.84 | RIL cost is higher | Para, Brazil | Boltz et al., 2001 |
| −0.05 | RIL cost is cheaper | Pibiri, Guyana | Van der Hout, 1999 |
| 1.53 | RIL cost is higher | Fazenda Agrosete, Brazil | Barreto et al., 1998 |
| 6.50 | RIL cost is higher | Sabah, Malaysia | Healey et al., 2000 |
| 0.35 | RIL cost is higher | East Kalimantan, Indonesia | Dwiprabowo et al., 2002 |
| 4.04 | RIL cost is higher | Sarawak, Malaysia | Dagang et al., 2002 |
| 3.24 | RIL cost is higher | Monts de Cristal, Gabon | Medjibe and Putz, 2012 |
| −0.54 | RIL cost is cheaper | Terengganu, Malaysia | Saharudin et al., 1999 |
| −1.83 | RIL cost is cheaper | Sarawak, Malaysia | Schwab et al., 2001 |
| 1.43 | Average (RIL cost is higher) | | |
| ±1.57 | 90% Confidence Interval | | |

## CONCLUSION

Improved tropical forest management is an important element of the UNFCCC's REDD+ scheme that also supports the long-term supply of commercial timber products and safeguards local social welfare and biodiversity. Our study suggests that about 28% of the total area of tropical forests (i.e., all the officially designated tropical PdF) can be targeted for RIL+

and RIL+ can produce 287 million $m^3$ $year^{-1}$ of sawnwood, reduce emissions of up to 494 Tg C $year^{-1}$ or 50% of carbon emissions from tropical deforestation, and increase carbon storage of 8.2 Tg C $year^{-1}$ in sawnwood, while preventing logging-promoted and enhanced forest fires. RIL+ also requires technological development because it requires proper planning at every stage of logging and wood processing operations. Our study also suggests that technological development throughout the logging industry can further reduce carbon emissions through the use of improved machinery used in logging operations, transport, wood processing and source verification. Recent advances in DNA timber tracking technology along with forest certification scheme will further enforce the legality of tropical timber import. To achieve long-term production of tropical sawnwood and logging-induced emission reductions, financial incentives of US$ 1–2 billion per year or up to $2 Mg $CO_2$ will be needed at least initially for the management of all tropical PdF.

## AUTHOR CONTRIBUTIONS

NS designed research and performed data analysis. NS, GA, YP, WK, PD, HM, IA, AL, LK, and FP equally wrote the article.

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