

Sustainable Forest Management and Carbon Balance in Tropical Forests

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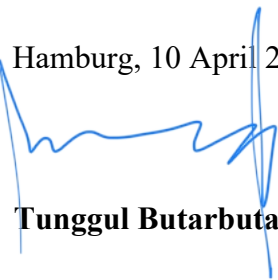
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Declaration

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I, Tunggul Butarbutar, have written the present dissertation on my own and have not used other than the acknowledged resources and aids.

Hamburg, 10 April 2025



Tunggul Butarbutar

Personal Contribution of The Peer-Reviewed Articles

The articles presented in this cumulative dissertation, along with the comprehensive summary, represent a significant portion of my contributions. Their selection was based on the criterion of substantial personal involvement. Furthermore, none of the scientific papers included have been or are currently part of any other cumulative dissertation.

1. Butarbutar, T., Soedirman, S., Neupane, P.R., Köhl, M. (2019): Carbon recovery following selective logging in tropical rainforest in Kalimantan, Indonesia.

the author contribution of the first peer-reviewed article for the cumulative dissertation were as follows:

Conceptualization: Tunggul Butarbutar (TB), Michael Köhl (MK) and Prem Neupane (PN). Data Collection and Preparation: TB and Soeyitno Soedirman (SS). Data Analysis: TB and MK. Draft Preparation: TB, MK, PN, SS. Review and Editing: TB, MK, PN, SS. All authors read and approved the final manuscript.

The article was published in the peer-reviewed journal “Forest Ecosystem” on 2 September 2019. <https://doi.org/10.1186/s40663-019-0195-x>

2. Butarbutar, T., Michael Köhl, and Prem Raj Neupane (2016): Harvested wood products and REDD+: looking beyond the forest border

the author contribution of the second peer-reviewed article for the cumulative dissertation were as follows:

Conceptualization: TB and MK. Data collection: TB. Modelling/scenario analysis and prepared the manuscript: TB, MK and PRN. All authors have read and approved the final manuscript. The article was published in the peer-reviewed journal “Carbon Balance and Management” on 21 May 2016. DOI 10.1186/s13021-016-0046-9

3. Butarbutar and Michael Köhl (2023): The Substitution effect of harvested wood products from timber producer countries (in submission)

the author contribution of the third peer-reviewed article for the cumulative dissertation were as follows:

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4. P.R. Neupane., C.B. Wiati., E.M. Angi, M. Köhl, T. Butarbutar, Reonaldus and A. Gauli (2020): How REDD+ and FLEG-VPA processes are contributing toward SFM in Indonesia- the specialist's viewpoint

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Summary

This cumulative dissertation consolidates the findings of studies exploring the interactions between sustainable forest management (SFM), harvested wood products (HWPs), and policy tools like REDD+ and FLEGT-VPA in Indonesia. The thesis emphasizes the importance of strengthening these linkages to ensure that efforts to reduce greenhouse emissions and address climate change align with the overarching aim of promoting the sustainable use of forest resources, particularly in Indonesia's tropical forests.

The research considers the emission reductions from low-impact logging compared to conventional logging techniques, focusing on forest management methods tailored to the ecological features of managed forests. It argues that effective sustainable forest management requires a strategy that integrates both ecological and economic aspects, thereby enhancing the resilience and regeneration capacity of tropical forests to mitigate climate change and ensure long-term sustainability of forest resource.

In examining strategies for carbon balance, the study considers the potential of HWPs offset logging-related carbon loss. Recognizing the negative effects of logging on tropical forest cover, such as slower growth rates and longer rotations, it argues that forest management practices need to be reassessed to minimize logging losses and enhance carbon sequestration efforts. The study emphasizes the importance of adaptive forest management techniques, such as optimizing harvesting cycle, reducing wood wastage, and promoting material recycling, to enhance the climate mitigation potential of HWPs. Furthermore, it outlines how product durability, processing methods, and recycling processes determine the carbon storage capacity of HWPs while advocating for the effective use of wood residues for energy generation and as a material substitute.

The research then analyses the roles of FLEGT-VPA and REDD+ in promoting sustainable forest management in Indonesia. Combining these two schemes is projected to ensure strong forestry regulations, promote responsible logging, and increase carbon sequestration efforts. However, it also points out the limitations of FLEGT-VPA, which focuses mainly on legal compliance without ensuring sustainability, highlighting the need for a holistic approach like the EU Timber Regulation (EUTR). Lastly, the study underscores the urgent need for effective monitoring mechanisms, accurate carbon accounting methods, and strong governance institutions to ensure the successful implementation of REDD+.

In conclusion, this thesis argues that Indonesia can significantly enhance the sustainability of its forest sector by adopting innovative forest management practices, policy tools, and effective enforcement measures. By leveraging the synergies among REDD+, SFM, and sustainable timber use, Indonesia can contribute to global climate goals while simultaneously enhancing the economic resilience of its forest industry.

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Acronyms and abbreviations

AGB	Above-ground biomass
CL	Conventional logging
CoP	Conference of Parties
DBH	Diameter at breast height (1.3 m)
FAO	Food and Agricultural Organization of the United Nations
FLEGT-VPA	Forest Law Enforcement, Governance and Trade-Voluntary Partnership Agreement
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
HWP	Harvested Wood Product
IPCC	Intergovernmental Panel on Climate Change
ITTO	International Tropical Timber Organization
LULUCF	Land Use, Land Use Change, and Forestry
MR	Mortality rate
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RIL	Reduced Impact Logging
SFM	Sustainable Forest Management
SMF	Sustainable Management of Forests
UNFCCC	United Nations Framework Convention on Climate Change

Part 1. Thematic Context

1. Structure of the thesis

The thesis explores how sustainable forest management in tropical forests can contribute to the mitigation of climate change by increasing carbon stocks in forests and reducing emissions through the utilization of harvested wood products (HWP). The research findings are presented in four interconnected peer-reviewed journal articles, that extending the literature on tropical forest carbon dynamics and the impact of sustainable forest management and wood production. This introduction provides an overview of the individual articles and contextualizes their results within the broader field of forest management and climate change mitigation.

The thesis is divided into three parts. The first part presents the background on tropical forests, climate change, and forest governance with a comprehensive literature review, highlighting research gaps and underscoring the relevance of the thesis. The first issue addressed is the significance of tropical forests in the context of global climate change and the carbon cycle. The second issue is dedicated to the essential role of sustainable forest management as a strategic tool in maintaining resource production and mitigating climate change, emphasizing the interconnectedness between sustainable forest management practices and carbon dynamics. The widely disregarded impact of sustainably harvested timber on carbon dynamics is also analyzed, highlighting its role in the carbon cycle along with the implications for sustainable forest management. The thesis critically assesses the potential of reducing emissions from deforestation and forest degradation. It also examines the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks within the framework of REDD+ policy in tropical developing countries. This framework serves as a platform for integrating sustainable forest and carbon management to develop comprehensive strategies aimed at addressing the adverse impacts of climate change. The research questions are presented within this thematic context.

In the second part, the principal findings of each of the four peer-reviewed articles are discussed. A concise overview of the research approach, major findings, and contribution to the thematic question are also provided. The peer-reviewed articles examined are:

Butarbutar, T., Soedirman, S., Neupane, P. R., & Köhl, M. (2019). Carbon recovery following selective logging in tropical rainforests in Kalimantan, Indonesia. *Forest Ecosystems*, 6(1), 1-14. DOI <https://doi.org/10.1186/s40663-019-0195-x>

Butarbutar, T., Köhl, M., & Neupane, P. R. (2016). Harvested wood products and REDD+: looking beyond the forest border. *Carbon balance and management*, 11(1), 1-12. DOI 10.1186/s13021-016-0046-9

Butarbutar, T., Köhl, M. (2023 – in review). The substitution effect of harvested wood products from tropical timber producer countries. Submitted to *Carbon Balance and Management*.

Neupane, P. R., Wiati, C. B., Angi, E. M., Köhl, M., Butarbutar, T., & Gauli, A. (2019). How REDD+ and FLEGT-VPA processes are contributing towards SFM in Indonesia—the specialists' viewpoint. *International Forestry Review*, 21(4), 460-485. DOI: <https://doi.org/10.1505/146554819827906807>

In the third part, a conclusion is drawn that summarizes the overarching themes and recommendations, arising from the diverse topics explored throughout the thesis. This conclusion emphasizes that recommendations are needed for action that account for the various facets of sustainable forest management in tropical forests.

2. Background Context: Tropical Forest, Climate Change and Forest Governance

Tropical rainforests play a central role in economic development and climate change mitigation, as they are significant carbon reservoirs and provisioners of forest resources. This chapter discusses the complex relationship between the harvesting of tropical timber, the carbon cycle, and global climate

change policies, with a focus on Indonesia. It synthesizes current literature to determine strategies for sustainable forest management that can reconcile timber production demands with climate change goals. The study emphasizes the significance of HWPs, REDD+ design, and combined policy tools for sustainable forest management and tackling the impacts of climate change in the context of Indonesia.

2.1. Tropical Forests: Balancing Development and Climate Change Mitigation

Timber extraction in the tropics has historically been a key driver of economic development and the global timber market. The demand for wood, fueled by the construction, furniture, and industrial sectors, surged after the Industrial Revolution and intensified with post-war reconstruction and mid-20th century population growth (Chudnoff, 1984). Future population growth and economic development are projected to increase the demand for tropical timber (FAO 2020, 2022b; ITTO 2021).

Recent research suggests that tropical forests significantly influence climate change, acting as both carbon sinks and sources of greenhouse gas (GHG) emissions (Mitchard, 2018; Pan et al., 2011; van der Werf et al., 2009). They regulate the global carbon cycle by sequestering and storing substantial amounts of carbon dioxide (CO₂) in biomass and soils. Activities like deforestation, particularly forest conversion to commercial agriculture, and forest degradation due to unsustainable timber extraction release significant amounts of carbon into the atmosphere (Pan et al. 2011; Sasaki et al. 2016).

Balancing economic development with sustainable forest management requires meeting the increasing wood and biomass demand while conserving forest ecosystems, to retain their protective and regulating services, and biodiversity. Effective policies, responsible forest land use, and sustainable forest management practices are essential for balancing continued economic growth against maintaining forest ecosystem functions.

Understanding the impact of forest management on climate mitigation is essential for optimizing the role of forests in both climate change mitigation and adaptation, and economic development. Reducing timber industry residues and incorporating HWPs into carbon accounting can create a more comprehensive approach. This approach acknowledges the continuous carbon sequestration of forests, and the climate-positive carbon storage and emission reduction properties of timber products, reinforcing the importance of sustainable forestry in addressing climate change.

2.2. Tropical Forest and the Global Carbon Cycle

2.2.1. Carbon Storage and Sequestration

Tropical forests significantly contribute to the global carbon cycle, acting as significant reservoirs of stored carbon. These forests, covering 45% of the global forest area, store an estimated 200-300 Gt C in aboveground biomass and around 54 Gt C belowground biomass (Baccini et al. 2012; Harris et al. 2021; Mitchard 2018; Pan et al. 2011; Saatchi et al. 2011). Tropical forests actively sequester atmospheric CO₂ through photosynthesis and store it in living and dead biomass, as well as in forest soil (Anderson-Teixeira et al., 2016; Harris et al., 2021b; Pearson et al., 2017a; Sasaki et al., 2016b). The gross carbon sequestration by forests is estimated to be around 15.6 GtCO₂ per year globally (Harris et al., 2021b). Study focused on tropical regions estimate carbon sinks of 1.3 ± 0.3 and 1.0 ± 0.5 Gt C year⁻¹ for 1990 to 1999 and 2000 to 2007, respectively (Pan et al. 2011). Other studies on forest GHG fluxes for the period 2001 to 2019 revealed average annual gross carbon emissions of 5.3 ± 2.4 Gt CO₂e and removals of -7.0 ± 7.6 Gt CO₂e, indicating a net GHG sink of -1.7 ± 8.0 Gt CO₂e per year in tropical forests (Harris et al., 2021b). Those differences reflect the uncertainties inherent in quantifying the carbon balance of tropical forests. Methodological variations, data limitations, and the complex interplay of factors influencing forest carbon dynamics contribute to the disparities.

2.2.2. Carbon Emissions from Forest Management Practices and Land Use Change

Despite their critical role in carbon sequestration, tropical forests are also significant sources of greenhouse gas emissions, primarily due to deforestation and forest degradation. Deforestation, driven by the conversion of forest areas for commercial and subsistence agriculture, expansion of settlements, and industrial uses, accounts for a substantial proportion of land-use change emissions (IPCC, 2023a). Between 1990 and 2000, approximately 161 million hectares of forest were deforested, corresponding to an annual deforestation rate of 16 million hectares. The annual rate of deforestation was slightly reduced to an estimated 15 million hectares per year from 2000 to 2010, and further reduced to 12 million hectares per year from 2010 to 2015 (FAO, 2020c).

In tropical forest, forest degradation contributes approximately 25% of total forest emissions with unsustainable timber harvesting playing a significant role in GHG emissions (Pearson et al. 2017; Sasaki et al. 2016). Global tropical and subtropical timber harvesting emits 0.85 GtCO₂ annually (Ellis et al. 2016b). Between 2005-2010, forest degradation across 74 developing countries emitted nearly 2.1 billion tons of CO₂, with timber harvesting contributing about 53% of this emission. The remaining emission came from wood fuel harvest which accounted for 30% and forest fires which contributed 17% (Pearson et al. 2017).

Poor logging practices pose substantial challenges to the sustainability and carbon balance of tropical forests. Timber harvesting emissions consist of emissions from the extracted logs, incidental damage to the surrounding forest, and emissions from logging infrastructure (Pearson et al., 2014). Extensive harvesting intensity can damage the remaining forest stands, hindering their ability to regenerate and store carbon in the long term. Insufficient rotation periods can lead to overexploitation (Sasaki et al., 2012). The timber extraction chain, encompassing harvesting, transportation, and processing, also contributes to carbon emissions (Healey et al., 2009; Pearson et al., 2017a; Winjum et al., 1998).

2.3. Mitigating Climate Change through Sustainable Forest Management

2.3.1. Sustainable Forest Management Practices

Mitigating the potential carbon emissions along different stages in the forest management cycle and forest products supply chain is crucial for ensuring efficient and sustainable forest management. Sustainable forest management (SFM) integrates ecological, economic, and social aspects of forest management to enhance forests as long-term carbon sinks while supporting sustainable timber production and biodiversity conservation (FAO, 2020c). Reduced-impact logging (RIL), for instance, reduces damage to residual trees and lowers timber losses, thereby enabling faster regeneration and increased biomass growth (Peña-Claros et al., 2008; Putz et al., 2008). RIL reduces soil disturbance, minimizes canopy gaps, and maintains residual trees intact, thereby preserving forest structure, composition, and carbon sequestration potential (P. W. Ellis et al., 2019; Griscom et al., 2019). Furthermore, appropriate harvest rotation periods allow sufficient time for biomass and carbon recovery, promoting long-term sustainable timber production while maximizing carbon storage (Bonnell et al., 2011; Vidal et al., 2016). Moreover, sustainable forest management contributes to biodiversity conservation by maintaining the ecological integrity of the forest ecosystem.

2.3.2. The Role of Harvested Wood Products

Harvested wood products are recognized as a carbon sequestration option in global climate policy (IPCC, 1997). HWPs contribute to climate change mitigation in several ways: (i) carbon storage effect, (ii) material substitution effect, and (iii) energy substitution effect (Butarbutar et al., 2016; Hurmekoski et al., 2022; Jordan et al., 2018; Johnston & Radeloff, 2019; Pingoud et al., 2010; Sato & Nojiri, 2019; Sikkema et al., 2013). Material substitution of HWPs entails replacing more GHG-intensive materials like concrete, steel, and plastic with wood in buildings, furniture, and packaging. This results in a net emission reduction as wood products manufacturing is generally less energy-intensive than the products being replaced (Leskinen et al., 2018; Sathre & O'Connor, 2010). Energetic substitution is the process

where wood biomass is used as a renewable substitute for fossil fuels. However, the carbon neutrality of woody biomass is disputed, and some studies raise concerns that combustion emissions may outweigh forest regrowth and forest carbon sequestration (Searchinger et al., 2018).

The Intergovernmental Panel on Climate Change (IPCC) provides guidelines on accounting for GHG emissions from biomass combustion, stating that if carbon neutrality of woody biomass is assumed, emissions should be accounted for at the time of harvest to prevent double counting (IPCC, 2019). The IPCC also offers accounting guidelines for HWPs, and the production approach is recommended as the default approach. The production approach allocates emissions and removals to the country where forest products are harvested, which is consistent with national greenhouse gas inventories under agreements such as the Paris Agreement (IPCC, 2006, 2013). In addition, the cascading use of HWPs following circular economy principles reduces emissions through the continued reuse of the wood resource (Mantau, 2015; Sathre & Gustavsson, 2006; Sikkema et al., 2013).

Figure 1 illustrates schematically the carbon cycle from forest management to the utilization of harvested wood. Forests capture atmospheric CO₂ during growth, with both young and mature forests contributing, although mature forests do so at a reduced rate. Emissions are generated by timber harvesting and forest management practices, as well as the processing of timber and production of harvested wood products by the timber industry. While consumer products release CO₂, long-lived products store carbon for the duration of their use. For this reason, material substitution of energy-intensive products combined with cascade use can offset emissions from forest degradation. Overall, this process highlights the potential for forest management and wood utilization practices to maximize carbon capture and minimize net carbon emissions.

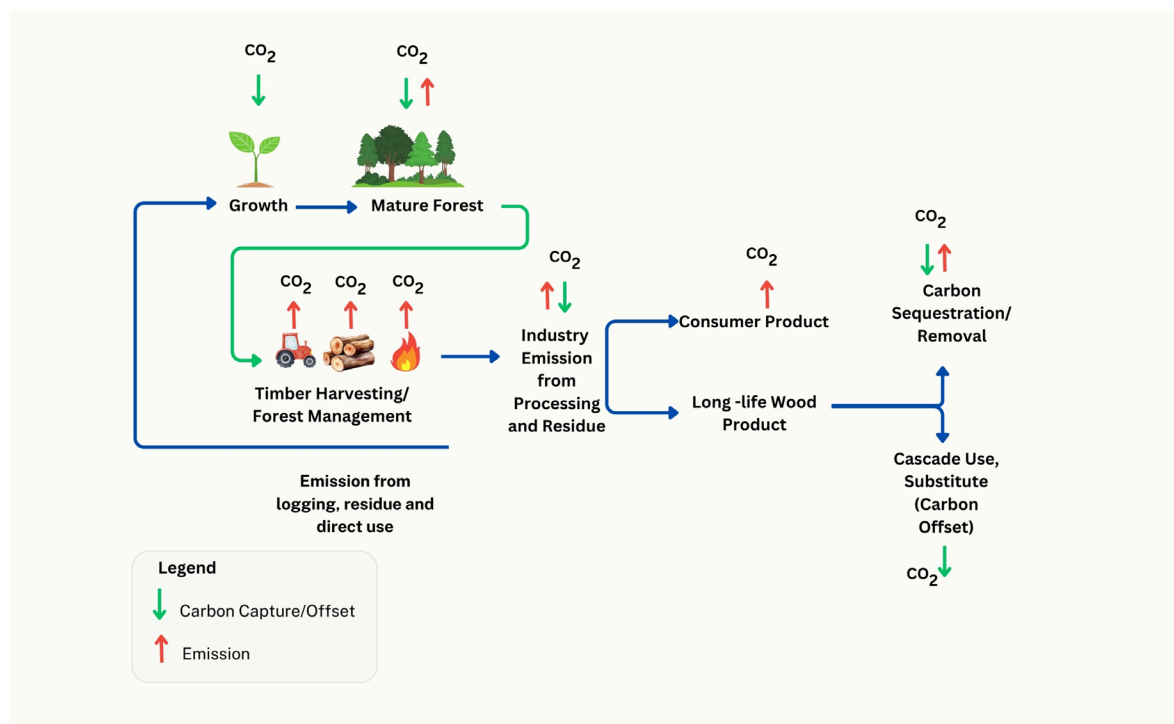


Figure 1. The schematic overview of carbon capture and emission in forest management and forest product use (adapted and expanded from Smith (Smyth et al., 2014)

2.4. REDD+, Global Climate and Forest Policy

Global climate initiatives and forest policy regimes have evolved significantly over the last decades with the aim of ensuring the long-term sustainability of forests, contributing to ecosystem recovery, and supporting a transition towards a sustainable economy. The interconnected issues of forest conservation, climate change, biodiversity, governance, and socioeconomic development have encouraged the development of a wide range of policies and international initiatives that reflect different facets of forest protection and management (Arts & Babili, 2013; Muthee et al., 2022). Various policies and initiatives have been developed focusing on the role of tropical forests in conservation and climate (IPCC 2007, 2023; Muthee et al. 2022; Sotirov et al. 2020).

REDD+ is one such policy. The concept of REDD+ emerged in the early 2000s as a response to the alarming rate of deforestation and forest degradation, particularly in developing countries. The “+” components broaden the scope of the REDD+ mechanism by including the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries. Adopted at the 19th Conference of the Parties (COP 19) to the United Nations Framework Convention on Climate Change (UNFCCC) in Warsaw in 2013, the Warsaw Framework for REDD+ offers methodological and financial guidance for the mechanism’s implementation. Further, the Paris Climate Agreement 2015 recognizes REDD+ as a critical nature-based solution for climate change mitigation, with the potential to mitigate over 5 Gt CO₂ per year from avoided forest loss and degradation. The Paris Climate Agreement (Article 5) further recognizes REDD+ and the central role of forests in mitigating climate change.

Five different activities are eligible for REDD+, which are:

1. Reducing emissions from deforestation;
2. Reducing emissions from forest degradation;
3. Conservation of forest carbon stocks;
4. Sustainable management of forests; and
5. Enhancement of forest carbon stocks.

To date, at least 80 countries have engaged in emission reduction through REDD+ (Coalition for Rainforest Nations, 2024), and significant progress has been made in developing monitoring and verification frameworks (UNCC, 2024). However, REDD+ has shown mixed results in its achievement and effectiveness. Implementing REDD+ has faced several challenges including inadequate funding, slow disbursement of available funds, and the need to comply with additional standards on top of the Cancun REDD+ safeguards, to access readiness and carbon funds from multilateral banks. Associated with this, REDD+ projects have recently been criticized for lacking credibility and environmental integrity (Wyburd Inigo & Dufrasne Gilles, 2023).

REDD+ is not an isolated policy element; it is deeply intertwined with various international policies to mitigate climate change and promote sustainable forest management. While REDD+ is expected to reinforce the interconnected policies, their synergy often encounters significant challenges. Aligning REDD+ with various international forest policies poses numerous challenges. International forest and climate change policies often have varying objectives, timelines, and implementation strategies (Miah, 2021). Securing and coordinating funding from different resources to ensure its effectiveness present additional challenges to the complexities of REDD+ implementation (Morita & Matsumoto, 2023). Furthermore, inadequate integration with other sectors or regions renders successful coordination and implementation challenging (FAO, 2020c, 2022b; ITTO, 2021b).

One notable policy initiative regarding tropical forests is FLEGT VPA (Forest Law Enforcement, Governance and Trade Voluntary Partnership Agreement). The FLEGT initiative was launched by the European Union (EU) to combat illegal logging and to promote sustainable forest management. The Voluntary Partnership Agreement (VPA) is a central component of FLEGT, which provides a legally binding agreement between the EU and timber-exporting countries to address illegal logging (Neupane et al., 2020; Tegegne et al., 2018).

As both REDD+ and FLEGT VPA shared a common goal of conserving tropical forests and promoting sustainable forest management by addressing the main drivers of forest degradation and deforestation, they also present significant interlinkages that must be managed effectively to realize the policies' potential. One of the primary synergies lies in their focus on governance reform and institutional strengthening in forest management (Conway et al., 2014). FLEGT aims to create a Timber Legality Assurance System (TLAS) that verifies the legal origin of timber products, enhancing transparency in the timber supply chain. This system can support the REDD+ initiative by providing more transparent accountability and law enforcement, which is essential for achieving REDD+'s emissions reduction goals (Neupane et al., 2020). Furthermore, both initiatives emphasize a multistakeholder approach, which is necessary for inclusive decision-making, benefit-sharing mechanisms, and the inclusion of the local communities' needs and rights. However, various challenges are identified, ranging from the institutional setup, to governance, and at the operational level. The most significant challenges are the lack of communication and coordination at the national and sub-national levels during the implementation of both, as well as the differences in their core objectives (Conway et al., 2014; Korhonen-Kurki et al., 2012; Tegegne et al., 2018).

The European Union also recently released the European Union Deforestation Regulation (EUDR), aimed at ensuring that products consumed within the EU do not contribute to deforestation or forest degradation globally. The EUDR mandates that commodities such as cattle, cocoa, coffee, oil palm, soya, rubber, and wood must be deforestation-free. This policy is strongly aligned with the Forest Law Enforcement, Governance, and Trade Voluntary Partnership Agreement (FLEGT VPA), which seeks to curb illegal logging activities and enhance sustainable forest management through legally binding agreements between the EU and timber-producing countries. The EUDR and FLEGT VPA share the same goal of improving governance and transparency in the timber value chain, which is imperative for achieving emission reduction targets within the REDD+ program. By providing a robust policy framework for legal and sustainable timber trade, EUDR, and FLEGT VPA consolidate international forest policy regimes to support the conservation of tropical forests and combating climate change. The EUDR shall be applied from 30 December 2026 by medium and large companies, and from 30 June 2027 by small and micro businesses. Unlike FLEGT VPAs, EUDR covers not only timber but also agricultural commodities, thus addressing the conversion of forest to agricultural land use.

2.5. Overarching research question

The overarching research question examined in this study is how various approaches to tropical forest management can contribute effectively to climate change mitigation.

To answer this overarching question, this thesis addresses the following specific research questions:

1. What timeframe is required for tropical forests to recover using natural regrowth from the carbon losses generated by timber harvesting?
2. To what extent can the carbon losses associated with timber harvesting in tropical forests be mitigated by the substitution and storage functions of harvested wood products (HWPs)?
3. What substitution and storage benefits are realized through the utilization of harvested wood products from tropical timber?
4. How do the REDD+ and FLEGT-VPA initiatives enhance sustainable forest management in Indonesia?

Part 2. Integration of the articles into the thematic context

Part 1 examined the complex role of tropical forests in GHG emissions and mitigation, and how global policy responses have been formulated to integrate forests into climate-related policies and processes. Although global climate policies recognize the key role of forests in climate change mitigation and have established mechanisms to address this, these mechanisms are typically formulated and implemented in isolation. This leads to insufficient integration and cooperation among sectors which can result in inefficiencies, conflicting objectives, and lost opportunities for scalable climate action.

Part 2 explains how the articles add thematic context that is relevant to and deals with the chosen research questions by analyzing four main dimensions: the recovery of carbon in logged forests, the mitigation potential for harvested wood products (HWPs), the substitution and storage value of HWPs, and the impacts of international policy frameworks like REDD+ and FLEGT on sustainable forest management.

1. Butarbutar et al., 2019: Carbon recovery following selective logging in tropical rainforest in Kalimantan, Indonesia

The paper was written by Tunggul Butarbutar, Soeyitno Soedirman, Prem Raj Neupane, and Michael Köhl. The article was published in *Forest Ecosystems* (Issue 6, Article number 36) in 2019 (<https://doi.org/10.1186/s40663-019-0195-x>) (Butarbutar et al., 2019).

2.1. Summary of the paper

This study examined the rate of post-logging above-ground biomass and carbon recovery in secondary forests maintained by a forest concession holder. The study was conducted in PT Gunung Gajah Abadi concession utilizing the Indonesian TPTI system with a 35-year rotation cycle and 50 cm minimum cutting diameter at breast height (DBH). Four permanent sample plots (PSPs) with six sub-plots (200 m x 200 m) were assessed at four sites. Three sub-plots within the northern half of each PSP received silvicultural treatments: liberation (removal of shrubs and liana), refinement (removal of shrubs, liana, and non-commercial saplings), and thinning (removal of larger non-commercial trees). The southern half served as control as shown in Figure 2.

Data containing DBH and tree species was collected from 10,415 trees. Above-ground biomass (AGB) was estimated using Chave's allometric equation (Chave et al., 2014) as follows:

$$AGB_{est} = \exp [-1.803 - 0.976 E + 0.976 \ln(\rho) + 2.673 \ln(d) - 0.0299 [\ln(d)]^2]$$

Where:

AGB = total oven-dry above-ground biomass in (kg)

d = diameter at breast height (cm)

ρ = wood-specific gravity in (gcm^{-3})

E = environmental factor

Logging carbon loss was estimated using Pearson et al.'s gain-loss approach derived from the IPCC, considering emissions from extracted logs (ELE), emissions from logging damage (LDE), and emissions from logging infrastructure (LIE) (Pearson et al., 2014). Three logging damage scenarios were simulated: Scenario 1 represents a condition of moderate logging-induced disturbance, whereas Scenario 2 and Scenario 3 simulate conditions with twofold and threefold increases in logging impact, respectively). Carbon recovery times were determined using site-specific carbon growth rates, based on periodic growth data. For further details, see the article attached in Annex I.

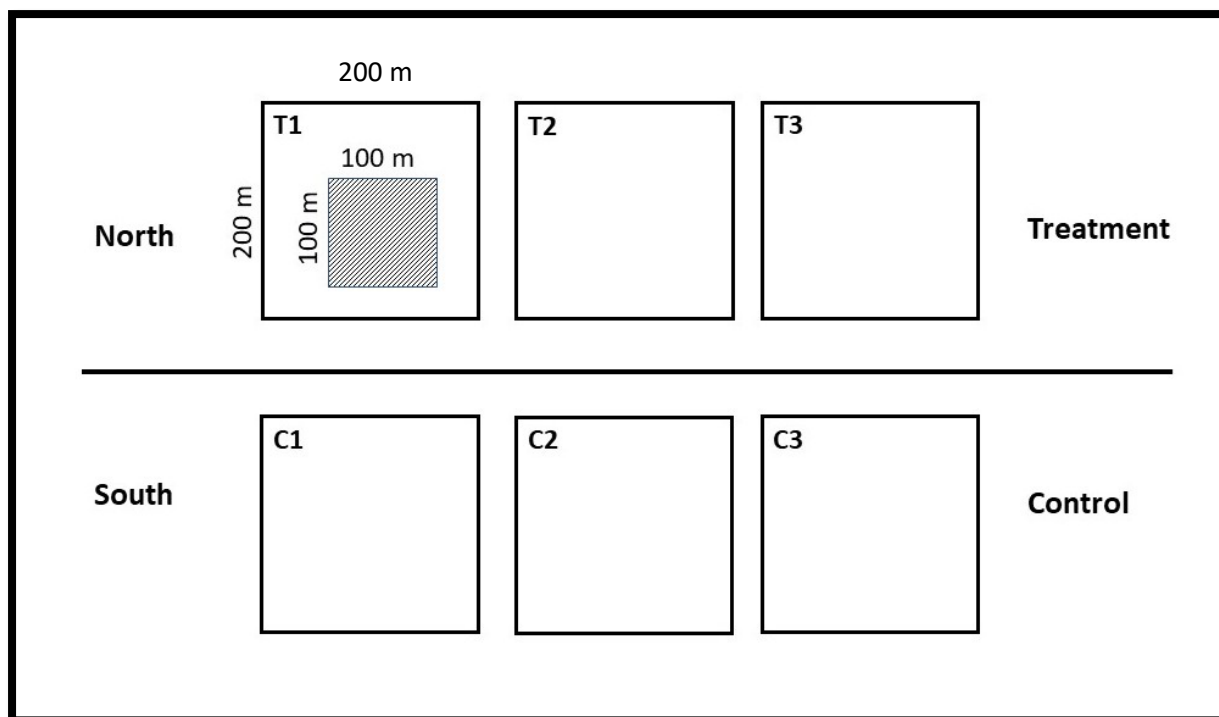


Figure 2. A schematic overview of the plot and subplot design. T1, T2, and T3 represent three treatments: liberation, refinement, and thinning. C1, C2, and C3 represent control sub-plots.

The total harvested wood from 1985 to 2016, for a site with 37,563 ha, was 1,333,922 m³, with annual log yields ranging from 33.36 to 35.86 m³·ha⁻¹·year⁻¹. Overall logging emissions (TEi) were 51.18 tC·ha⁻¹ under Scenario 1, 70.76 tC·ha⁻¹ under Scenario 2, and 90.34 tC·ha⁻¹ under Scenario 3. The ELE varied between 8.34 to 8.69 tC·ha⁻¹, while LIE varied from 22.35 to 24.03 tC·ha⁻¹. Rates of carbon growth varied significantly across sites (1.82–4.45 tC·ha⁻¹·year⁻¹, ANOVA, $\alpha = 0.05$) but not amongst silvicultural treatments. Scenario 1 average carbon recovery time was 26 years (range: 7–104 years), while Scenario 2 and 3 extended recovery times to 36 years (10–143 years) and 46 years (13–183 years), respectively. Liberation treatment had the shortest recovery time (20–36 years), while untreated controls had longer recovery times.

The research concluded that the present 35-year logging cycle might not permit complete carbon recovery in situations of higher-impact logging. Site-specific data were identified to have more influence on carbon recovery than the silvicultural treatments. The results highlight that implementing reduced-impact logging (RIL) techniques and adapting intervention cycles based on site-specific factors, are required for successful sustainable forest management and carbon stocks through initiatives like REDD+.

2.2. Discussion of the first paper in the thematic context

REDD+ is a comprehensive mechanism that includes five eligible activities (see 2.4) for reducing forest emissions and enhancing forest carbon stocks. Decision 1/CP.16 from the 16th session of the Conference of the Parties to the UNFCCC highlights reducing emissions from forest degradation as a core strategy in lowering emissions from the forestry sector. This strategy focuses on reducing forest emissions and increasing carbon stocks through improved forest management practices.

Tropical forests in Latin America, sub-Saharan Africa, and Southeast Asia contribute significantly to global carbon stocks, accounting for 49 percent, 25 percent, and 26 percent, respectively (Saatchi et al., 2011b). The research underscores the effectiveness of sustainable management practices in reducing forest emissions and storing carbon, emphasizing the interconnectedness of forest management, carbon

sequestration and storage, and forest carbon recovery. Carbon enhancement or recovery in logged forests can be achieved through natural regeneration and silvicultural interventions. Carbon sequestration is influenced by several factors, including forest age, forest type, and management approaches to manage the forest.

Over the next few decades, the potential for forests to regenerate naturally and store carbon is projected to rise substantially. Forests are estimated to have the capacity to sequester up to 70 billion tons of carbon in soil and vegetation globally by 2050 (Cook-Patton et al., 2020), although the degree of potential restoration is contingent upon the intensity and type of previous disturbances. Sustainable practices, such as RIL, provide various benefits, including reduced damage to remaining forest stands, reduced emissions from harvesting operations, and accelerated carbon recovery. Logging rate and efficiency significantly impact carbon recovery, as higher logging intensities with greater incidental damage will delay the forest's carbon pool recovery when compared to unlogged forests (Chazdon, 2016; Roopsind et al., 2017).

In contrast, lower logging rates leave more trees standing, which preserves forest degradation, limits soil disruption, and minimizes carbon loss from decomposing vegetation, thereby enabling a quicker return to pre-logging carbon levels, which fosters long-term forest health. Unsustainable management practices on the other hand, where biomass loss surpasses the recovery capacity of remaining forest stands, slow carbon recovery.

The study also demonstrates that standard 30-year harvesting cycles can hinder biomass and carbon recovery, particularly under high-intensity logging conditions. This result corroborates previous findings that cutting cycles need to be reassessed and extended where required, based on the respective recovery rates and standing stocks on the site (Blanc et al., 2009; Yamada et al., 2013). The study further demonstrates that adaptive management plans must consider local ecological conditions, historic disturbance intensity, and operational efficiency. In addition, the study also shows that it is essential to control losses from harvest residues and infrastructure to minimize overall carbon emissions during the logging operation.

The role of forestry in economic growth and resource availability is projected to grow significantly in the coming decade (FAO, 2022b). Thus, having sustainable timber harvesting practices that harmonize economic, ecological, and social goals is crucial. This study describes carbon losses through different phases of the harvesting cycle and provides valuable guidance for policymakers, forest concessionaires, and management organizations. The guidance can be used to enhance the post-selective-logging recovery of above-ground carbon reservoirs while ensuring the production activities are compatible with climate mitigation initiatives. To summarize, the integration of sustainable forest management within climate policies like REDD+ not only reduces emissions from deforestation and forest degradation but also enables the gradual regeneration of forest carbon stocks, providing long-term positive outcomes for both natural systems and human society.

2. Butarbutar et al., 2016: Harvested wood products and REDD+: looking beyond the forest border

The paper by Tunggul Butarbutar, Michael Köhl, and Prem Raj Neupane is published in the *Carbon Balance and Management* in 2016- (DOI 10.1186/s13021-016-0046-9) (Butarbutar et al., 2016).

2.1. Summary of the paper

This study discusses the potential role of harvested wood products (HWPs) in mitigating GHG emissions under the REDD+ mechanism. Though REDD+ traditionally emphasizes maintaining forest carbon stocks through strategies like reducing deforestation, avoiding forest degradation, and enhancing carbon stock, this paper broadens the REDD+ scope (activities) by including the use of harvested wood products. It discusses how HWPs help to minimize carbon emissions under three processes: long-term carbon storage, material substitution, and energy substitution.

The first scenario, focusing on wood fuel, examines the direct energetic use of timber, including the associated emissions from combustion and logging residues. The second scenario considers HWP for durable products, such as construction materials, which offer material substitution benefits by replacing emission-intensive alternatives like steel and cement. Sub-scenarios reflect low and high-efficiency utilization, incorporating variables such as logging and mill residues, displacement factors, and end-of-life energy recovery from HWPs.

Results show that the direct use of wood for energy does not directly compensate for forest carbon stock loss because emissions from the combustion of timber fuel are greater than those of fossil fuels like natural gas and lignite. Logging residues, which can be left to decay, contribute significantly to total emissions, and thus a more effective residue management is required. In contrast, the HWP scenario demonstrates climate mitigation potential, particularly under high-efficiency scenarios. High emission savings are achieved when HWPs displace high-carbon products and are subsequently used for energy at their end-of-life. The displacement factor, or reduction in emissions per unit of wood consumed, is key to determining the climate mitigation benefit of HWPs.

The study emphasizes that while forests are valuable carbon sinks, the role of timber utilization in global carbon budgets is overlooked under the REDD+ mechanism. The inclusion of HWPs in REDD+ offers an opportunity to expand the scope of carbon accounting beyond forests, enhancing mitigation benefits by also considering the emissions savings achieved throughout the lifecycle of these products. The findings demonstrate that the application of innovative wood technologies, reduced-impact logging, and effective timber utilization approaches can significantly enhance the mitigation potential of HWPs. Moreover, sustainable forest management policies must incorporate the benefits of HWPs in accordance with global climate objectives. A sensitivity analysis is performed to assess the influence of different input variables on the resulting CO₂ emissions. This analysis helps identify the most significant factors affecting emission reductions and highlights the importance of managing logging residues and optimizing the use of HWPs.

This research highlights the importance of expanding REDD+ beyond its traditional limits to cover the whole value chain from forest carbon to harvested wood products (HWPs). By conserving both standing forests and harvested wood through utilization, this multi-disciplinary method can increase the contribution of the forestry sector to global climate change mitigation. The inclusion of HWPs in REDD+ is crucial for building sustainable and effective climate mitigation mechanisms.

2.2. Discussion of the second paper in the thematic context

The primary objective of REDD+ is to encourage developing countries to participate in climate change mitigation by decreasing their greenhouse gas (GHG) emissions and enhancing their carbon sequestration. REDD+ policies tend to prioritize forest carbon stocks, which undervalues the immense potential for climate change mitigation by harvested wood products (HWPs), through carbon storage, material substitution, and energy substitution. This narrow focus overlooks the emissions, sequestration, and offsets that happen with timber harvesting and along the wood product lifecycle.

This study highlights two pathways toward emission abatement: (1) the substitution of logging residues for fossil fuel in energy production; and (2) the substitution of energy-intensive commodities such as steel and concrete with wood products. The findings indicate that utilizing harvested wood for energy and material can achieve substantial emission savings through substitution effects. This can partially compensate for the immediate carbon loss from forest harvesting. The extent of this compensation, however, hinges on the logging practices employed, transport distances, and the type of energy or material substituted.

Including HWPs in REDD+ inventories provide a more complete picture of emissions and carbon sequestration in the forest sector. This overall approach avoids understating emissions or overstating carbon sequestration, which would compromise the effectiveness of REDD+.

Although manufacturing hardwood products (HWPs) can yield environmental gains, the underlying drivers of deforestation and illegal logging need to be tackled. Focusing on HWPs without properly addressing forest management could compromise conservation efforts, so a comprehensive approach is required.

It is essential to coordinate energy conservation efforts and carbon accounting practices between sectors. Presently, the emission savings associated with harvested wood products (HWPs) are commonly credited only to the energy sector without considering their extensive contribution to forest management. Moreover, HWP accounting is based on comprehensive data and life cycle assessments, which in developing countries can be a cause of concern due to limited data availability, inadequate resources for conducting thorough assessment and potential inaccuracies in emission reporting. This lack of reliable information may lead to underestimating the benefit of HWPs and hinder effective climate change mitigation practices.

Including HWP in REDD+ policy can stimulate sustainable forest management regimes, that balance maintaining forest timber yields with the carbon sequestration capacities of forests. This approach fosters both forest conservation and income streams for the local communities over the long term while safeguarding their livelihoods and supporting the expansion of the national economy. The forest sector is crucial for generating national income and creating job opportunities; thus, neglecting harvested wood products could have economic consequences for communities dependent on forestry.

Linking REDD+ policies and HWPs provides a more complete picture of the forest sector's role in climate change mitigation but requires careful consideration of data availability and the challenges involved in life cycle assessments, particularly in developing countries.

3. Butarbutar and Köhl (2023): The Substitution effect of harvested wood products from timber producer countries (submitted)

This paper by Tunggul Butarbutar and Michael Köhl is being submitted to the '*Carbon Balance and Management*' journal.

3.1. Summary of the paper

In this study, we assessed the HWP emissions and removals contributed by tropical wood-producer countries. Tropical timber production is considered one of the primary sources of GHG emissions, particularly with respect to emissions from logging residue and the wood extracted from the forest. HWPs, however, could contribute to achieving net-zero GHG emissions by sequestering atmospheric carbon in the goods themselves and reducing the embodied carbon construction products through material substitution. Since tropical timber is projected to remain a significant contributor to global future material consumption by 2050 (ITTO, 2021b), the impact of HWPs from tropical forests on climate change mitigation has been inadequately investigated.

This study uses data from the FAOSTAT-Forestry database on harvested wood (www.faostat/en/#home) to determine the magnitude of wood production and its subsequent transfer into the HWP pool, as well as their potential substitution effect. The database provides detailed information on global wood production, imports, and exports for several categories of HWPs. This study focused on computing the fraction of wood in three specific wood products: industrial roundwood, wood pulp, and recovered paper.

Table 1. List of Countries Involved in the study by region.

Africa	Southeast Asia and the Pacific	Latin America
Benin	Cambodia	Brazil
Cameroon	Fiji	Colombia
The Central African Republic	India	Costa Rica
Congo	Indonesia	Ecuador
Côte d'Ivoire	Malaysia	Guatemala
The Democratic Republic of the Congo	Myanmar	Guyana
Gabon	Papua New Guinea	Honduras
Ghana	Philippines	Mexico
Liberia	Thailand	Panama
Madagascar	Vietnam	Peru
Mali		Suriname
Mozambique		Trinidad and Tobago
Togo		Venezuela (the Bolivian Republic of)

The FAO database provides annual data for raw wood and wood products dating back to 1961. Following the 2019 IPCC refinement, the carbon content of HWPs was determined using three categories of semi-finished wood products: Sawnwood, Wood-based Panel, and Paper and Paperboard. These production figures are represented in units of volume (m³) and weight (t). Given that Paper and Paperboard commodities are typically not substitutes for non-wood materials, they are excluded from the substitution effects calculation but are included in the HWP stock calculation.

IPCC (2019) provides each category's standard carbon conversion factors (cf). We utilize primary regional data from FAOSTAT to construct displacement factors (DFs), which quantify the reduction in emissions resulting from the substitution of a non-wood product with a wood product that is functionally comparable. DFs are essentially equal to the mass of carbon in the substituted wood and are calculated following the methodology detailed in the original paper. These factors are determined by considering the carbon mass within the substituted wood and calculated as follows.

$$DF = \frac{f_{NW} - f_W}{C_W}$$

Where f_{NW} and f_W are the GHG emissions from non-wood use and use of wood. C_W is the carbon mass content of the wood product, all expressed in mass units of carbon equivalents. The calculation of the substitution effect requires detailed information on wood utilization, which is not available for most selected countries. Therefore, we use a scenario approach based on the average DFs from existing studies (Sathre & O'Connor, 2010). We use three scenarios, applying values of $DF = 0.7$ for the conservative scenario, $DF = 4.4$ for the optimistic scenario, and $DF = 2.0$ representing the intermediate scenario (Sathre & Gustavsson, 2009). To estimate CO₂ emissions and removals from HWPs, the study uses methodology outlines in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). A modified production approach is used since the analysis aims to consider the corresponding substitution and storage effect globally. We extend the production approach by considering only the production of HWPs in a country, regardless of whether the timber is of domestic origin. The emissions and removals are calculated according to the IPCC refinement. Due to the limited space, the detailed calculation can be referred to in the original paper.

Carbon inflow into the HWP pool increased initially but began to decline from 1980 to 2018. In 2017, the inflow totaled 33.6 million tons (Mt), including 10.85 Mt of Sawnwood, 8.98 Mt of wood-based

panels, and 13.77 Mt of paper and paperboard. Southeast Asia led HWP production (58%), followed by Latin America (38.6 %) and Africa ((3.4%). CO₂ emissions from HWPs averaged 26.7 Mt CO₂ per year, with Southeast Asia contributing 19 Mt CO₂ to emissions in 1961 before reversing to reductions by 1980. Latin America accounted for a 2.4 Mt CO₂ sink from 1961 to 2017. Sawnwood positively affected HWP stock from 1982 to 1998 and 2001 to 2006, albeit with some negative impacts. . The average annual potential impact of HWP substitution ranged from 998.60 to 6276.93 Mt C, with a median of 2,853 Mt CO₂ per year. The top emitters were Indonesia, India, and Malaysia, while Mexico, Brazil, and Thailand were the main contributors to CO₂ removal.

The carbon content of HWP was determined by calculating the annual output of the three essential HWP commodities: Sawnwood, wood-based panels, and paper and paperboard products, based on data provided by FAO (<https://www.fao.org/faostat/en/#home>). Southeast Asia and the Pacific Islands accounted for 61.6 percent of the global HWP production in 2018, followed by Latin America (34.6 %) and Africa (3.6 %). Wood production increased inflow to the HWP pool by 28 MtC, contributing to an annual carbon sink of 35.61 MtCO₂ y⁻¹.

Southeast Asia and the Pacific led global HWP carbon stocks during 1990–2017, with an average annual contribution of 281 Mt C (53.43%), followed by Latin America (219 Mt C, 41.86%) and Africa (24 Mt C, 4.71%). The region also functioned as the largest annual carbon sink, with 21.76 Mt CO₂ per year, significantly surpassing contributions from Latin America (12.82 Mt CO₂) and Africa (1.01 Mt CO₂). By 2017, the net potential effects of HWPs ranged from 624 Mt CO₂eq (low DF) to 9953 Mt CO₂eq (high DF), demonstrating the critical importance of displacement factors in amplifying climate mitigation benefits.

3.2. Discussion of the third paper in the thematic context

Harvested wood products (HWPs) play a crucial role in mitigating climate change by sequestering carbon and reducing emissions. They serve as sustainable alternatives to carbon-intensive materials like steel and cement, while also enabling long-term carbon storage (FAO, 2022a, 2022c; IPCC, 2019; (IPCC), 2023).

The FAOSTAT statistics (FAO, 2020a) show that carbon inflow into the HWP pool initially increased before beginning to decline in the 1980s. The HWP pool accounted for 33.6 million tons of carbon in 2017, with sawnwood, wood-based panels, and paper products making up the majority. Southeast Asia led HWP production globally, followed by Latin America and Africa. However, unsustainable tropical logging emissions remain an issue, at an estimated 26.7 million tons of CO₂ in 2017 ((IPCC), 2023). These emissions stress the importance of sustainable logging alongside the carbon sequestration of HWPs.

HWPs have enormous potential to substitute for fossil fuel-based materials and products, and to contribute significant emissions reductions. Estimates from studies place annual emissions reductions from HWP substitution between nearly 1,000 and over 6,000 million tons of CO₂, depending on the wood product and displacement efficiency (Smith et al., 2020). Incorporating HWPs into carbon accounting frameworks like REDD+ would improve insight into the role of sustainable forestry and wood utilization in climate change mitigation, as it would allow for accurate quantification of emission reduction achieved through these practices.

To achieve maximum climate benefits from HWPs, forest management must be founded on sustainability. Some of the practices that must be tracked include reduced-impact logging, promoting longer-lived wood products, and elevating the use of wood residues. Some techniques meet multiple objectives, for instance, silvicultural treatments aimed at improving forest recovery and efficiency in wood production also raise sequestration rates as a co-benefit. However, HWP production must not come at the cost of forest health, and unsustainable logging can nullify the long-term benefit of HWPs (Chang et al., 2018; Kayo et al., 2015; Zhao et al., 2022).

Decision-makers have a crucial role to play in promoting sustainable forest management and in incentivizing HWP substitution for emission-intensive products. Including HWPs within REDD+'s

scope would enhance the contribution of the forestry sector to global emissions reduction. This aligns with international climate action under the Paris Agreement, which suggest mitigation action to account for all carbon pools and reservoirs. Additionally, the increasing demand for green materials in urban and industrial sectors offers a particular opportunity for HWPs to contribute to the low-carbon and circular economy transitions. Wood, having long been used in construction, is well positioned to fulfill increasing demand while alleviating the climate problem.

Through the application of emerging technologies and optimized processing, HWPs can provide scalable solutions toward cleaner energy systems and minimized emissions. As important as tropical forests are for carbon sequestration, combining with HWPs further increases their climate mitigation potential, and a balance of both will be required to effectively combat climate change. By incorporating HWPs into REDD+'s mechanisms and overall carbon management plans, a balance between conservation and sustainable resources use can be achieved. This holistic strategy guarantees that forests remain at the forefront of global climate objectives while promoting sustainable economic growth.

4. Neupane et al., 2020: How REDD+ and FLEG-VPA processes are contributing toward SFM in Indonesia- the specialist's viewpoint

This paper by P. R Neuphane, C.B. Wiati, E.M. Angi, M. Köhl, T. Butarbutar, Reonaldus and A. Gauli. The paper was published in a peer-reviewed journal, International Forestry Review Vol.21(4), 2019. <https://doi.org/10.1505/146554819827906807>.

4.1. Summary of the paper

This paper looks at the contributions of international forest and climate regimes, in particular REDD+ and FLEGT-VPA, to sustainable forest management in Indonesia. Deforestation and forest degradation are major contributors to climate change due to the significant emissions produced by these activities. To address this, the Sustainable Forest Management (SFM) framework is proposed, with the goal of sustainably managing forests and reversing deforestation trends. Despite the implementation of various policies and the resulting progress over the last decade, high rates of deforestation and forest degradation persist, especially in biodiverse regions like Indonesia. Several initiatives, including forest certification and the FLEGT Action Plan, have been attempted to address these issues.

The study uses a mixed-methods approach, including informal discussions and formal semi-structured interviews with specialists involved in FLEGT-VPA and REDD+ processes. Specialists were selected from various sectors, including government, academia, private sector, community, and civil society organizations. The interviews were conducted in two stages: the first stage involved questionnaires exploring the contributions of REDD+ and FLEGT-VPA towards SFM, while the second stage involved in-depth interviews with selected specialists.

The results show that FLEGT-VPA has contributed to SFM through improved governance, policy reinforcement, and enhanced capacity for SFM. The engagement of stakeholders from different sectors in planning, policy dialogue, and implementation is considered a revolutionary approach to forest governance. The adoption of RIL and the establishment of a Timber Legality Assurance System (TLAS) have addressed some drivers of deforestation and forest degradation. The study also highlights the role of the Joint Implementation Committee (JIC) in overseeing the implementation of the VPA and the FLEGT licensing scheme.

REDD+ implementation has brought positive improvements towards SFM by strengthening institutions, reinforcing policies and regulations, and mobilizing additional funding. The establishment of Forest Management Units (FMUs) and the reinforcement of RIL practices have contributed to better forest governance and reduced carbon emissions. REDD+ has also promoted higher commitments to conserve High Conservation Value (HCV) and High Carbon Stock (HCS) forests, enhancing social and ecological resilience.

The study identifies opportunities for synergy between REDD+ and FLEGT-VPA by harmonizing their processes, tools, methodologies, and funding mechanisms. Both regimes contribute to SFM by providing enabling conditions, ensuring forest ecosystem health and vitality, maintaining multiple forest functions, and integrating social, cultural, and economic aspects. However, challenges remain, such as limited local-level guidance, slow integration into regional plans, and varying levels of institutional development across provinces.

Both REDD+ and FLEGT-VPA have made significant contributions towards SFM in Indonesia. Continued efforts are required to address challenges and fully realize the potential of these initiatives in promoting sustainable forest management. The study emphasizes the importance of harmonizing REDD+ and FLEGT-VPA processes to foster synergies and enhance the overall effectiveness of SFM efforts in Indonesia.

4.2. Discussion of the fourth paper in the thematic context

The study highlights the significant contributions of REDD+ and FLEGT-VPA towards SFM in Indonesia and emphasizes the necessity of integrating forest and climate policies to effectively address these interconnected challenges. The REDD+ and FLEGT-VPA initiatives demonstrate how forest and climate policies can complement each other. REDD+ focuses on reducing emissions from deforestation and forest degradation, while FLEGT-VPA aims to improve forest governance and ensure the legality of timber. By harmonizing their processes, tools, and methodologies, these initiatives can create synergies that enhance their overall effectiveness. For instance, REDD+ can benefit from the improved governance and legality frameworks established by FLEGT-VPA, while FLEGT-VPA can leverage the financial resources and policy support provided by REDD+.

Integrated forest and climate policies can address multiple objectives simultaneously, including biodiversity conservation, sustainable livelihoods, and climate mitigation. Forests are home to a vast array of biodiversity and provide essential ecosystem services, such as water regulation and soil protection. By integrating forest and climate policies, we can ensure that these multiple functions are maintained and enhanced. For example, REDD+ promotes the conservation of HCV and HCS forests, which are critical for both biodiversity and carbon storage.

The paper highlights several challenges in implementing REDD+ and FLEGT-VPA, such as limited local-level guidance, slow integration into regional plans, and varying levels of institutional development. An integrated approach can help overcome these challenges by providing a more coherent and coordinated framework for action. For instance, integrated policies can streamline data collection, processing, and analysis, reducing costs and increasing the efficiency of monitoring and reporting systems. Additionally, integrated policies can enhance capacity building and stakeholder engagement, ensuring that local communities and indigenous peoples are actively involved in forest and climate initiatives.

Integrated forest and climate policies can also help mobilize additional financial resources for sustainable forest management. REDD+ has already demonstrated its potential to attract significant funding from public, private, and philanthropic sources. By aligning forest and climate policies, we can create more attractive investment opportunities and leverage existing funding mechanisms more effectively. This can provide the necessary financial support for implementing sustainable forest management practices, such as RIL and forest certification.

Finally, integrated forest and climate policies can strengthen political commitment to addressing deforestation and climate change. The study outlines the essential role of strong political will at the national, provincial, and local levels. By integrating forest and climate policies, we can create a more

compelling narrative that highlights the numerous benefits of sustainable forest management for climate mitigation, biodiversity conservation, and sustainable development. This can help garner broader support from policymakers, stakeholders, and the public, ensuring that forest and climate initiatives receive the attention and resources they deserve.

The necessity of integrating forest and climate policies is evident from the contributions of REDD+ and FLEGT-VPA towards SFM in Indonesia. By enhancing synergies, addressing multiple objectives, overcoming implementation challenges, mobilizing financial resources, and strengthening political commitment, integrated policies can provide a more effective and holistic approach to managing forests sustainably and mitigating climate change (Soto Golcher & Visseren-Hamakers, 2018).

Part 3. Conclusions of the cumulative dissertation:

In this part, conclusions from the four papers are synthesized to address the research questions regarding the linkages of sustainable forest management, HWP, and policy mechanisms like REDD+ and FLEGT-VPA. Each sub-chapter presents data on the recovery time of tropical forests from logging, the potential for reducing carbon losses through HWP, the substitution and storage benefit of the products, and the contributions of REDD+ and FLEGT-VPA to improve sustainable forest management in Indonesia. These findings collectively underscore the critical role that integrated approaches like REDD+ and FLEGT-VPA play in balancing climate change mitigation with sustainable forest management and wood product utilization.

1. The importance of comprehensive sustainable forest management for climate change mitigation

The first research question addressed possible synergistic interlinkages between SFM and carbon management, especially in the tropics. SFM can provide a framework for reducing carbon emissions and sequestering carbon while providing various environmental services and economic functions. Many forest management activities both sequester and emit carbon, making SFM a powerful tool for managing forest carbon while maintaining critical forest functions. Most carbon emissions from tropical forest degradation are generated by logging-related activities including timber harvesting, logging damage, logging infrastructure development, and inefficient wood use. In contrast, efficient wood utilization and improved methods of harvesting promote regrowth and biomass accumulations, reducing emissions from logging activities, while conserving forest carbon stocks.

The study emphasizes that rotation cycles and harvest volumes are indispensable parts of sustainable timber production, as well as of effective post-harvest recovery of carbon; hence, decisions on these aspects should be guided by integrated, stand-level data regarding forest regrowth and carbon stock accumulation following logging. This requires monitoring systems capable of providing rapid feedback regarding tree volume growth, and carbon accumulation, which can be used to support allowable cut decisions. By integrating such monitoring systems, SFM can better ensure that timber production is optimized, carbon emissions are minimized, and post-harvest carbon recovery can be achieved.

Further, the study highlights the difference in carbon emissions and post-harvest recovery times attributed to various logging techniques. Intensive logging has high losses and emissions from infrastructure, which prolongs the recovery of carbon stocks. RIL on the other hand has, been found to reduce emissions by as much as 44% without influencing timber yield (P. W. Ellis et al., 2019). Additionally, RIL also promotes improved residual stand conditions, enabling the recovery of biomass at an earlier stage (Sasaki et al., 2016b; West et al., 2014). These improved logging techniques are essential for efficiently incorporating SFM into carbon management systems.

The research identifies site variability as one of the main determinants of carbon recovery time in tropical rainforests. Soil property, microbial populations, and ecosystem functions all have profound influences on the recovery of biomass and carbon pools after logging (Sniegocki et al., 2022). This variation indicates the need for site-specific management interventions, tailored to the specific characteristics of each forest ecosystem. This circumvents the limitations imposed by the one-size-fits-all approach and enables resource management optimization, with minimal consequences. The results in this thesis suggest that the development of residual stands following harvest is more dependent on the condition of the residual stand than on specific treatments applied. However, the role of silvicultural treatments on forest regeneration is complex and is mediated through various ecological and environmental processes (Latterini et al., 2023). Understanding these relationships is imperative for achieving an optimum equilibrium between timber production and carbon sequestration. This work adds

to the growing literature on carbon recovery in forests, demonstrating that successful SFM necessitates an approach that is both economically viable and integrated with the ecological process. Such an approach improves the capacity of tropical forests to regenerate from environmental disturbances while contributing significantly to climate change mitigation and resource sustainability (Butarbutar et al., 2019).

2. Mitigating Carbon Losses Through Harvested Wood Products (HWPs)

The second research question examines the extent to which carbon losses through timber harvesting in tropical forests can be compensated by the substitution and storage function of HWPs.

HWPs play an important role in climate change mitigation as they sequester carbon in wood products and reduce emissions through material and energy substitution. Their effectiveness is, however, dependent on forest management and type. HWPs in tropical forests have a lower carbon sequestration capacity due to logging techniques, slower growth rates, and longer rotation production periods compared to temperate and boreal forests (Butarbutar et al., 2019; Keith et al., 2015). These limitations restrict the potential of HWPs for climate change mitigation.

This research highlights that under the present tropical forest management, HWPs do not adequately compensate for carbon loss from timber harvesting. Selective logging, the extraction of a few select species, leads to excessive biomass loss and wastage, and thus, produces significant carbon emissions (Köhl et al., 2015). In addition to this, traditional logging operations in tropical forests are still very carbon-intensive (Butarbutar et al., 2019). Though direct energy use of harvested wood produces net emissions, harvested wood products (HWPs) offer significant climate change mitigation potential through material substitution. Their success, however, relies on enhanced forest management practices to reduce logging residue and optimize carbon sequestration. Reduce logging residue and optimize carbon sequestration by increasing forest density, improving tree species diversity, and extending rotation periods to allow trees to store more carbon before harvest.

To enhance the mitigation potential of HWPs, forest management strategies must be restructured to minimize logging losses and maximize carbon sequestration. SFM practices, such as RIL and extended rotation periods, can contribute significantly to maintaining forest carbon stocks while optimizing the climate benefits of HWPs (Graaf et al., 1999; Sist et al., 2014). Nonetheless, the recovery of above-ground carbon remains prolonged, with studies indicating recovery periods ranging from 26 to 46 years post-harvest (Butarbutar et al., 2019).

Moreover, site-specific forest management is essential. Implementing strategies like optimizing harvesting cycles, minimizing wood waste, and promoting recycling and reuse can substantially enhance HWPs' contribution to climate change mitigation (Keith et al., 2015; Peña-Claros et al., 2008). Utilizing logging residues for bioenergy and prioritizing material substitution effects can further reduce emissions. However, it is crucial to account for displacement effects, ensuring that harvested wood substitutes only for fossil fuel-based materials to maximize climate benefits (Pearson et al., 2017a).

3. Substitution and Storage Benefits of Harvested Wood Products from Tropical Timber

The third research question examines the substitution and storage benefits realized from utilizing harvested wood products from tropical timber. HWPs can store carbon for extended periods while also reducing emissions by replacing more carbon-intensive materials and energy sources. However, these benefits are contingent on following sustainable strategies for production and usage.

The carbon sequestration potential of HWP is influenced by factors including the product lifespan, processing efficiency, and recycling practices. Long-lived wood products, such as engineered wood and construction materials, offer greater carbon storage benefits compared to short-lived products like paper and fuelwood. Maximizing the utilization of wood residues for bioenergy while prioritizing material substitution effects enhances HWP's overall climate impact (Butarbutar et al., 2019).

However, the effectiveness of HWP in mitigating emissions is highly dependent on forest management and wood processing efficiency. Conventional logging methods in tropical forests often lead to high waste levels and carbon losses, reducing HWP's mitigation potential. Improved sawmilling techniques, enhanced processing efficiency, and better utilization of wood residues can significantly improve carbon storage and substitution benefits (Peña-Claros et al., 2008).

To optimize HWP's role in climate mitigation, tropical forest management should focus on extending product lifespans, increasing recycling rates, and minimizing waste. Wood cascading—where wood products are reused, remanufactured, and eventually converted into bioenergy—can maximize carbon storage and substitution effects. Additionally, integrating HWP into national carbon markets could create economic incentives for sustainable forest management and carbon sequestration (Murray et al., 2009).

4. Enhancing Sustainable Forest Management in Indonesia Through REDD+ and FLEGT-VPA

The fourth research question assesses how the REDD+ and FLEGT-VPA initiatives contribute to sustainable forest management in Indonesia. Global forest policy frameworks, including the Forest Stewardship Council (FSC), SFM standards, and the European Union's FLEGT-VPA, play a crucial role in shaping sustainable forestry practices. However, policy fragmentation and weak enforcement mechanisms often hinder their effectiveness (McDermott, 2014; Schmithusen, 1993).

REDD+ and FLEGT-VPA offer complementary approaches to improving forest governance. While REDD+ focuses on reducing emissions from deforestation and degradation, FLEGT-VPA addresses illegal logging and enhances timber legality verification. Integrating these policies can strengthen forest law enforcement, promote sustainable harvesting practices, and enhance carbon sequestration in Indonesia (Tegegne et al., 2018).

Despite these benefits, FLEGT-VPA has limitations. It primarily addresses legality rather than sustainability, leaving gaps in forest conservation efforts. As a response, the European Union introduced the EU Timber Regulation (EUTR), which broadens the scope beyond timber to include other deforestation-linked commodities such as beef, soy, and coffee. This shift aims to ensure that commodities entering the EU market must be sourced from regions with zero deforestation since 2020. By moving from a legality-based approach to one focused on maintaining forest cover, EUTR more effectively tackles deforestation and strengthens forest sustainability efforts.

For Indonesia, it is crucial to integrate REDD+ with sustainable forest management practices. RIL techniques can help maintain forest carbon stocks while ensuring the continued economic viability of timber production (F. E. Putz et al., 2012). Additionally, improving biomass efficiency, optimizing sawmilling processes, and promoting sustainable wood utilization can further enhance Indonesia's contribution to climate mitigation.

Effective REDD+ implementation requires robust monitoring systems, transparent carbon accounting, and strong governance frameworks (Ochieng et al., 2018). Addressing land tenure conflicts and ensuring stakeholder participation, particularly for Indigenous and local communities, is also key to achieving successful policy outcomes. By aligning REDD+ with national forestry policies and

integrating sustainable harvesting practices, responsible forest management can be the vehicle through which Indonesia can enhance its climate resilience while fostering economic development.

5. Conclusion and Implication for Indonesia

The research highlights the critical role of harvested wood products, sustainable forest management, and integrated policy frameworks in mitigating climate change. While HWP offer carbon storage and substitution benefits, their effectiveness is limited by tropical logging practices and processing inefficiencies. Policy mechanisms such as REDD+ and FLEGT-VPA play a vital role in promoting sustainable forest governance, but challenges remain in harmonizing these frameworks and ensuring their long-term effectiveness.

Indonesia can enhance its forest sector's sustainability by improving management strategies, policy integration, and enforcement mechanisms. By leveraging the synergies between REDD+, SFM, and responsible wood utilization, Indonesia can contribute significantly to global climate goals while fostering economic resilience in its forestry sector.

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Annex I: Scientific articles

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RESEARCH

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Carbon recovery following selective logging in tropical rainforests in Kalimantan, Indonesia

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Abstract

Background: The knowledge gap regarding post-logging carbon recovery by increased growth is becoming more crucial to understand the significant contribution of forest to climate change mitigation. We assessed the ability of tropical forests in Indonesia to recover carbon following conventional logging. We evaluated carbon re-growth of 10,415 trees in permanent sample plots (PSPs) in East Kalimantan. Four different post-harvesting silvicultural treatments including liberation, refining, thinning, and control were applied in the PSPs. We estimated the carbon recovery period using three different scenarios of total carbon losses due to logging. In the first scenario, we used an existing factor of logging damage and increased it for assuming the range of carbon losses due to different logging practices.

Results: Under the existing conventional logging practice, the concession annually emits $51.18 \text{ tC}\cdot\text{ha}^{-1}$, of which 16.8% are extracted from the forest as raw timber, 38% are logging losses, and 45.2% are emissions due to infrastructure development for logging operation. Increasing the logging damage factor two and three times led to an increase in carbon emission to 70.76 and $90.34 \text{ tC}\cdot\text{ha}^{-1}$, respectively. The recovery time of the aboveground carbon is 26 years in Scenario 1, 36 years in Scenario 2, and 46 years in Scenario 3. We found no significant effect of the silvicultural treatment type on carbon recovery, but significant effect of the sites was observed.

Conclusions: We found that the time taken to restore the carbon to the level found in undisturbed forests is considerably longer than the current intervention cycles. The time needed to recover biomass and carbon-stock noticeably depends on the intensity of logging interventions, demonstrating the benefits of using improved harvesting e.g., reduced impact logging to reduce emissions. The study found that site variability has a significant effect on the carbon recovery time. Different silvicultural treatments, on the other hand, have no effect on the recovery time. The study suggests that it is not appropriate to establish an intervention cycle based on arbitrary choice; the time between interventions must be based on logging losses and site specific growth potential to ensure sustainable management of forests.

Keywords: Timber growth, Carbon recovery, Silvicultural treatment, Logging cycle, Above-ground biomass

Background

Forests play a significant role in the global carbon cycle due to their dual ability to act as a sink and a source of atmospheric carbon. From 1990 to 2007, forests sequestered 2.4 ± 0.4 gigatons of carbon (Gt C) annually (Pan et al.

2011). Globally, forests store an estimated $471 \pm 93 \text{ Gt C}$ (West et al. 2014), of which more than half (247 Gt C) is stored in the tropical forests of Latin America (49%), sub-Saharan Africa (25%), and Southeast Asia (26%) (Saatchi et al. 2011). While Pan et al. (2011) suggested that forests function as a carbon sink, Baccini et al. (2017) cautioned that the carbon balance of tropical ecosystems remains uncertain, and that the world's tropical forests are a net source of carbon.

Human-induced disturbances in tropical forests contribute 8%–15% to global greenhouse gas (GHG) emissions

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(Houghton et al. 2015), with gross tropical deforestation emission of $2.9 \pm 0.5 \text{ Gt C-year}^{-1}$ and compensation by re-growth of $1.6 \pm 0.5 \text{ Gt C-year}^{-1}$. However, the role of forest degradation by disturbances is also considered to be significant. Emissions by forest degradation, though varying from region to region, is dominated by emissions from timber harvesting and wood fuel (Köhl et al. 2015). Pearson et al. (2017) estimated total annual emissions of 2.1 Gt C of carbon dioxide (CO_2) from forest degradation, of which 53% came from timber harvest, 30% from wood fuel harvest, and 17% from forest fires. With the continuous expansion of selective logging (Blanc et al. 2009), the carbon emission from degradation will be more significant in the dynamic carbon of forests. In 2010, around 403 million hectares (ha) of tropical forests were managed under selective logging, and around 183 million ha were managed with a management plan (Blaser et al. 2011).

While the emissions of forest management and respective carbon accounting systems have often been discussed, the ability of forests to recover biomass and carbon after logging interventions has not received much attention. Carbon fluxes from tropical deforestation and regrowth are subject to high uncertainties (DeFries et al. 2002; Sierra et al. 2012). Pan et al. (2011) estimated the re-growing of tropical forests to be about $1.65 \pm 0.71 \text{ Gt C-year}^{-1}$. Several studies showed an increase in the growth of carbon in logged compared to non-logged forests (Chapman and Chapman 1997; Pélisier et al. 1998; Bischoff et al. 2005; Berry et al. 2010; Mazzei et al. 2010; Hawthorne et al. 2012; Gourlet-Fleury et al. 2013). The reasons for this increase in growth vary. The volume of timber extracted and the level of disturbance or the intensity of logging have an impact on the rate of recovery in such a way that growth has slowed down with increased magnitude of disturbances (Chapman and Chapman 1997; Pena-Claros et al. 2008; Villegas et al. 2009; Bonnell et al. 2011; Sist et al. 2014; Vidal et al. 2016). Post-silvicultural treatment, including the integration of sustainable harvesting practices such as the implementation of reduce impact logging (RIL), is reported to show a positive impact on C-recovery (de Graaf et al. 1999; Priyadi et al. 2005; Pena-Claros et al. 2008; Villegas et al. 2009; Gourlet-Fleury et al. 2013).

Information about the ability of tropical forests to regrow after logging interventions is crucial to understand the contribution of tropical forest management practices to the global carbon budget and its consideration under Reducing Emissions from Deforestation and Forest Degradation in developing countries (REDD+) mechanism. Considerable uncertainty remains about the rate of biomass recovery in secondary forests and the influence of prior interventions on recent recovery rates (Poorter et al. 2016). Forests are widely recognized as a source of

renewable resources, and the use of wood is considered carbon-neutral. However, this assumption only applies if the amount of carbon removed by timber harvesting from the forest C-pool is compensated by timber growth processes. Hence, the decisive questions are how a forest grows after interventions and how much time is needed at given growth to compensate for carbon losses of the remaining stand. We are referring to the change in carbon due to timber growth which includes diameter growth of the survivor trees, ingrowth and mortality.

This study contributes to the forest carbon recovery literature by conducting an analysis of post logging carbon recovery in the context of selective/conventional logging followed by four different treatments: liberation, refining, thinning, and control (no treatment). More specifically, the paper: (i) assesses the magnitude of carbon emissions in the existing selective logging practice, (ii) examines the rate of carbon recovery after the selective/conventional logging, (iii) explores whether the existing logging cycle provide sufficient time for carbon recovery, and (iv) evaluates the impact of different treatments on the post logging carbon recovery.

Methods and materials

Study area and sites

The study was conducted in a logging concession holder, i.e., PT¹ Gunung Gajah Abadi (GGA) in East Kalimantan Province, Indonesia. The GGA is geographically located at $1^{\circ}20' - 1^{\circ}35'$ North latitude and $116^{\circ}4' - 117^{\circ}2'$ East longitude (Fig. 1). Based on the Köppen classification (Köppen 1884), the forest type in the GGA is classified as fully humid equatorial rain forest. Based on the data from 1971 to 1997, the mean annual rainfall in the study area is 1928 mm with dry season of less than a month (0.5 to 0.9 month) in a year. Figure 2 presents a climate diagram showing the mean monthly temperature and precipitation in the study area. The soil types of the study area are alluvial soil, latosol soil and podzolic soil.

The GGA is covered by mixed dipterocarp lowland forest which is characterized by the domination of trees in the Dipterocarpaceae. The dipterocarp trees are usually late successional and somewhat shade tolerant hardwood species. For the management of this forest, low intensity logging that opens small canopy gaps is a potentially sustainable approach (Ruslandi and Putz 2017). Over the past decades, the GGA has been selectively harvesting the fots management conducted in Indonesia (Budiaman and Pradata 2014). The cutting cycle is presently at 35 years. In the system, selective logging is followed by the post-logging treatments in the residual stands. The treatments may include liberation thinning, refining, enrichment planting etc.

¹PT is stand for Perseroan Terbatas (a term that represents a limited liability company in Indonesia).

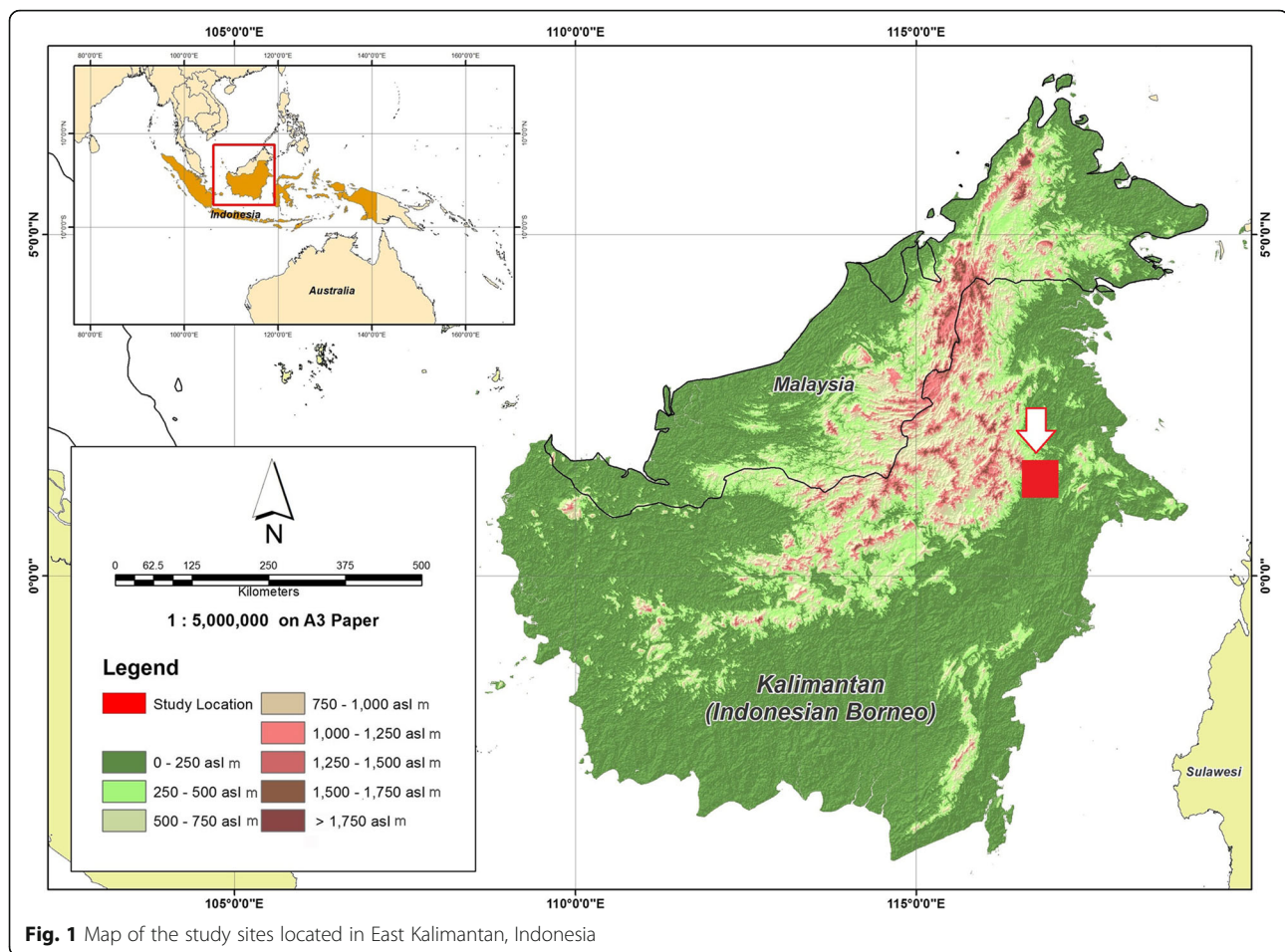


Fig. 1 Map of the study sites located in East Kalimantan, Indonesia

Permanent sample plots, plot design and silvicultural treatments

Under the TPTI system, permanent sample plots (PSPs) are established and distributed in the logging area to monitor logged-over forests. Ministerial Guidelines (Keputusan Menteri) No. 237/Kpts-II/1995 (Anonim 1995) mandates the forest concessions to establish a series of PSPs in the logging areas. Since 1995, the GGA has implemented a range of silvicultural treatments and monitored their impacts on the productivity by establishing a number of PSPs in its logging areas.

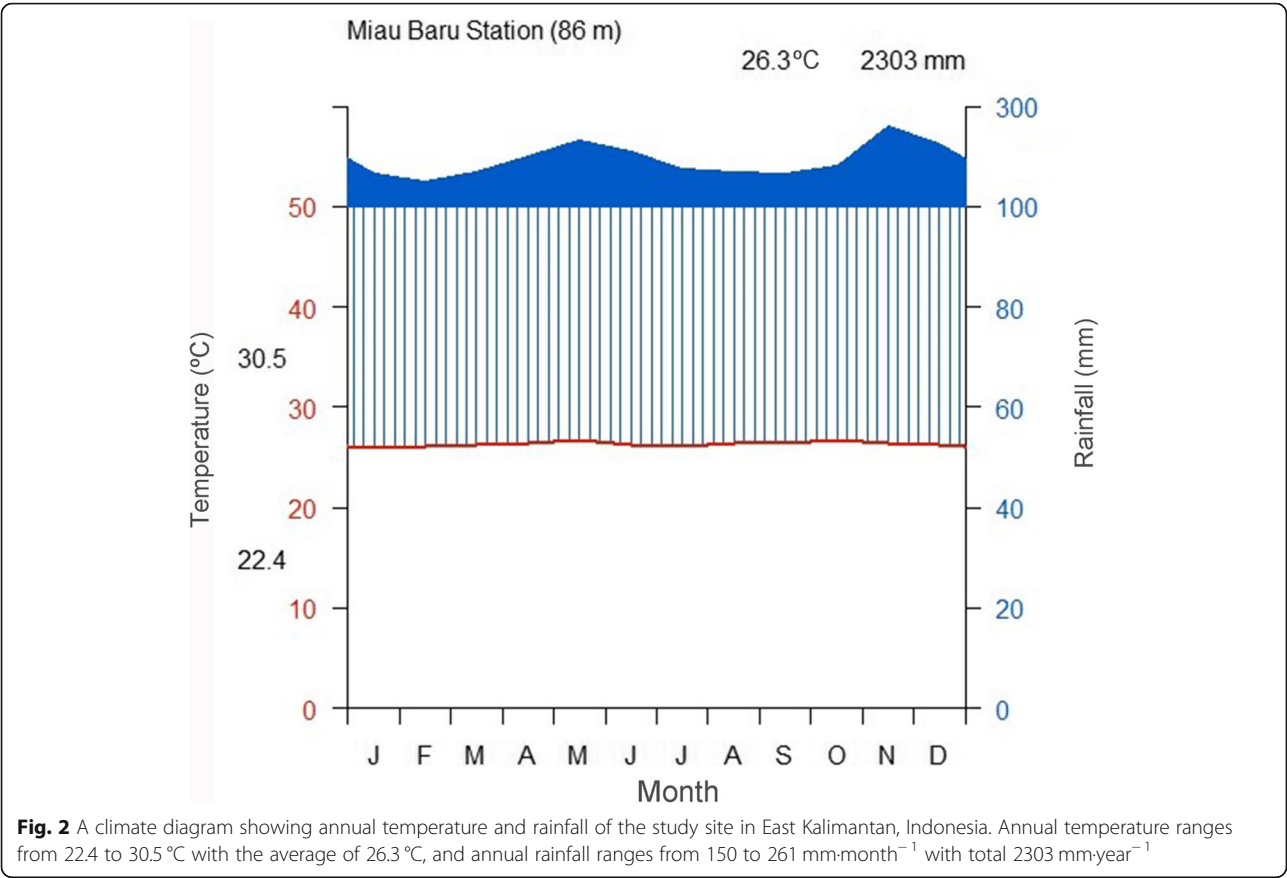
This study focuses on four PSPs established in four different sites in the logging area of the GGA. Each PSP consists of six sub-plots with the same plot size of 200 m × 200 m. Three sub-plots are located in the North and three in the South of each PSP. Within each sub-plot, the tree attributes are recorded in a 100 m × 100 m measurement area located in the center of the sub-plot. The response design allows a big buffer area surrounding the measurement area within each sub-plot (Fig. 3).

The three sub-plots in the North of the PSP received three different silvicultural treatments: (i) liberation

(perapihan), involves a very light cleaning of the area as to remove shrubs and liana, (ii) refinement (pembebasan), which is meant to remove all shrubs and lianas and non-commercial young trees (saplings) with a diameter at breast height (DBH) (d) less than or equal to 5 cm, and (iii) thinning (penjarangan), which involves the selective removal of non-commercial trees ($d > 20$ cm) that compete with neighboring commercial trees. In the South of the PSP, three control sub-plots are paired with each of the sub-plots in the North. Figure 3 presents the layout of the PSP and sub-plots.

Assessment of the permanent sample plots

The Ministerial Guidelines postulates that the PSPs should be established and assessed one year after logging after being subjected to a silvicultural treatment. However, this did not happen in the study area in practice. For three sites, the first PSP assessment is postponed for several years. For example, in site 1, the PSP was assessed in 1995 one year after harvesting (1994) and assessed six times between 1996 and 2007. In site 2, logging took place in 1985, but the PSP was assessed in



1999 for the first time after 11 years of logging. Table 1 presents the years of PSP assessments for the four different sites.

Data collection

In the measurement area (100 m × 100 m) within the sub-plot, all trees > 10 cm diameter (*d*) were tagged,

identified to species, and monitored for diameter increments. The tree positions were not recorded. Recruits were treated in similar ways once they reached the 10 cm diameter threshold.

We received the entire data sets for the four sites. The total set includes 10,415 trees (Site 1: 3,068, Site 2: 3,396, Site 3: 1,714 and Site 4: 2,237 trees). We were able

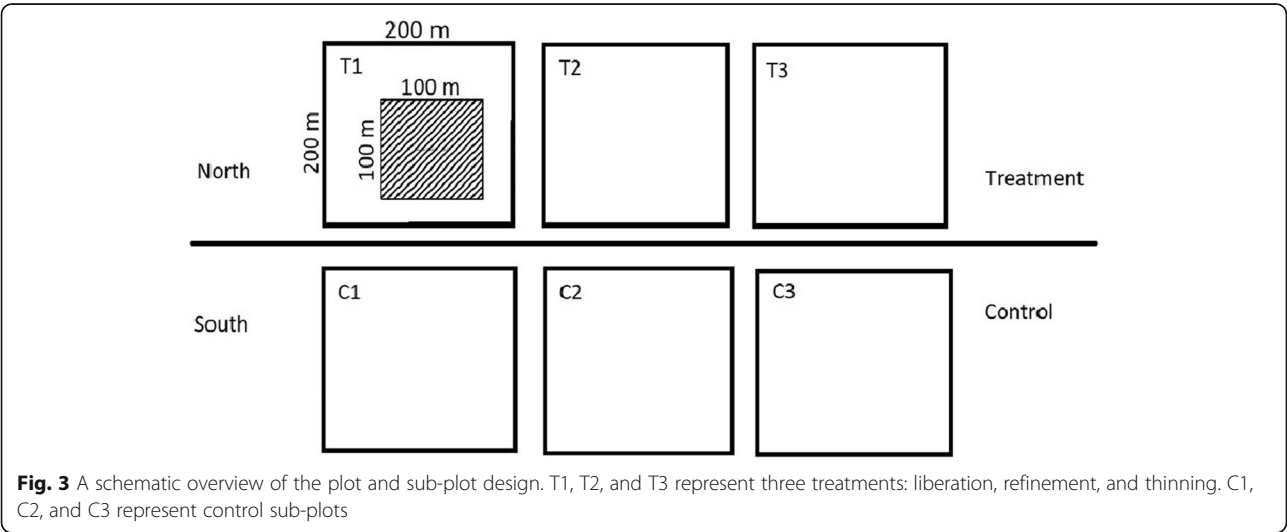


Table 1 Location of permanent sample plots (PSPs), logging years and PSPs measurement years. The Table describes the logging year, first measurement year and the subsequent years of the PSPs measurements after the logging in the PSPs in four different sites

Sites	Logging year	First measurement (years after logging)	Measurement year
1	1994/1995	1	1995, 1996, 1997, 1998, 1999, 2001, 2007
2	1985/1986	11	1999, 2000, 2003, 2006, 2011
3	2004	4	2008, 2009, 2012
4	2008	5	2011, 2013, 2014

to trace the missing trees (i.e., mortality of trees) in the datasets of subsequent assessments for a site.

Moreover, we received the records of the volume harvested in the harvested area for the period of 1985–2016 (Table 2). The information on total growing stock for each site was also available for the study (Table 2).

Estimating above-ground biomass

Above-ground biomass (AGB) for each tree was estimated using Chave et al.'s (2014) Eq. 7 (Eq. 1). The model needs input DBH (d), wood-specific gravity (ρ), and an environmental stress factor (E). E is used to predict AGB of a single tree as input to derive emission factors (EFs) for natural forests. E is a linear function of

Table 2 Volume of timber extracted from the study area for the period 1985–2016. The Table presents the year of harvesting, harvested area and the timber volume extracted

Year	Area (ha)	Volume (m ³)		Year	Area (ha)	Volume (m ³)	
		Total	Per ha			Total	Per ha
1985	1,100	41,592.87	37.81	2001	1,320	48,186.25	36.5
1986	1,199	36,916.91	30.79	2002	1,826	53,025.64	29.04
1987	1,104	38,010.93	34.43	2003	1,238	45,193.08	36.5
1988	796	27,707.04	34.81	2004	1,233	33,033.03	26.79
1989	753	31,261.76	41.52	2005	1,774	41,113.47	23.18
1990	900	46,020.3	51.13	2006	1,374	48,719.25	35.46
1991	740	35,616.05	48.13	2007	1,466	45,204.86	30.84
1992	1,054	39,193.93	37.19	2008	1,440	47,739.63	33.15
1993	220	8,090.32	36.77	2009	1,216	50,035.89	41.15
1994	1,215	37,078.19	30.52	2010	1,290	47,500.58	36.82
1995	1,612	66,483.84	41.24	2011	1,405	47,746.96	33.98
1996	1,417	59,346.59	41.88	2012	1,280	43,764.52	34.19
1997	1,745	73,142	41.92	2013	1,335	40,247.18	30.15
1998	931	35,903.14	38.56	2014	956	33,749.7	35.3
1999	1,429	53,036.62	37.11	2015	579	23,142.57	39.97
2000	1,380	45,676.89	33.1	2016	236	10,442.78	44.25
				Total	37,563	13,33,923	

temperature seasonality, climatic water deficit, and precipitation seasonality, and is available in the form of a global raster map. As the geographic position of the study site was known, the value of E was extracted from the map and was attached to the trees found in the study site. Chave et al. (2014) considered the overestimates in calculation and provide 0.5%–6.5% of bias.

$$\text{AGB}_{\text{est}} = \exp [-1.803 - 0.976 E + 0.976 \ln(\rho) + 2.673 \ln(d) - 0.0299 [\ln(d)]^2] \quad (1)$$

where

AGB = total oven-dry above-ground biomass in (kg)

d = diameter at breast height (cm)

ρ = wood-specific gravity in (g·cm⁻³)

E = environmental factor

There are other calculation models for the region provided by Manuri et al. (2014) and Basuki et al. (2009). Manuri et al. (2014), however, differentiate the equation based on the dipterocarps and non-dipterocarps families while Basuki et al. (2009) present the model for the genera of commercial and mixed species.

Calculating growth-related carbon stock change

Growth-related carbon stock change relates to carbon accumulation due to biomass growth and is calculated by applying the periodic growth equations proposed by Beers (1962):

$$G = V_2 + I - V_1 - M \quad (2)$$

where

G = the net growth

V_1 = volume at first occasion

V_2 = volume at second occasion

M = mortality

I = ingrowth, or recruitment

Carbon emissions scenarios

To calculate the carbon emissions caused by selective logging, we used an accounting method proposed by Pearson et al. (2014), which is based on the IPCC's gain-loss approach (IPCC 2006). Pearson et al. (2014), provide the estimation of forest degradation emissions using the data from 74 developing countries, which can be considered as the most comprehensive study currently available. The method accounts separately for emissions (i) from the extracted log, (ii) from dead biomass carbon left behind in the gap from felled trees and incidental damage to the surrounding forest, and (iii) from logging

infrastructure, e.g. skidding trails. The total emission from logging is estimated as the sum of the three sources of emissions.

$$TE = ELE + LDE + LIE \quad (3)$$

where

TE = total emission resulting from timber harvest (tC)
 ELE = extracted log emissions (tC)
 LDE = emission from logging damage (tC)
 LIE = emission related to logging infrastructure development (tC)

ELE is considered a committed emission, meaning that estimated emissions occur fully at the time of the harvest (Pearson et al. 2014). It is related to the volume of timber extracted from the forest and the specific wood gravity, which then gets converted into carbon. LDE occurs where trees are felled and includes both non-utilized biomass of the harvested trees and incidental damages to surrounding forest during felling. LIE results from the logging infrastructure, for example, construction of logging roads, skid trails and logging decks. For calculating ELE, LDE, and LIE, we used the emission factors ($\text{tC} \cdot \text{m}^{-3}$) presented by Pearson et al. (2014) for Indonesia: extracted log emissions factor (ELE factor) of 0.25, logging damage factor (LDF) of 0.57, and logging infrastructure factor (LIF) of 0.67.

$$ELE (\text{tC}) = 0.25(\text{tC} \cdot \text{m}^{-3}) \times \text{timber extracted} (\text{m}^3) \quad (4)$$

$$LDE (\text{tC}) = 0.57(\text{tC} \cdot \text{m}^{-3}) \times \text{timber extracted} (\text{m}^3) \quad (5)$$

$$LIE (\text{tC}) = 0.67(\text{tC} \cdot \text{m}^{-3}) \times \text{timber extracted} (\text{m}^3) \quad (6)$$

Emissions associated with logging damages depend on the precaution with which harvesting operations are carried out (Sist and Nguyen-Thé 2002; Feldpausch et al. 2005; Medjibe et al. 2011; Griscom et al. 2014, 2019; Sasaki et al. 2016). We assumed various level of logging damage, which might reflect the transition from conventional logging to reduced impact logging (RIL). In addition to the emission factors presented by Pearson et al. (2014) for logging losses, we increased the corresponding emissions by a factor of two to three:

$$LDE_i(\text{tC}) = (0.57 \times i)(\text{tC} \cdot \text{m}^{-3}) \times \text{timber extracted} (\text{m}^3) \quad (7)$$

where, LDE_i is the adjusted logging damage expansion factor and i is an expansion factor with $i = \{1, 2, 3\}$.

The total emission, TE_i , for each scenario, LDE_i is calculated with the equation:

$$TE_i = ELE + LDE_i + LIE \quad (8)$$

Carbon recovery period

Carbon recovery period refers to the period needed for the remaining growing stock to be able to compensate the total losses of carbon caused by the timber harvest through growth. The loss of carbon per ha is represented by TE_i . The growth of the remaining growing stock is deduced from the PSPs in terms of the periodic annual increment. The periodic annual increment of volume is converted into annual carbon accumulation per ha. This can be used to calculate the time required to compensate for a carbon loss of TE_i .

Results

Extracted timber and carbon emission

Timber harvesting in the study area follows the TPTI System, which limits the minimum cutting at DBH (d) to 50 cm for a cutting cycle of 35 years. During the period 1985–2016, an area of 37,563 ha was logged, resulting in the total harvested timber of 1,333,922 m^3 . On average, 1,174 ha and 41,685 m^3 had been logged annually. The average log production for each of the four sites is 34.78, 33.36, 35.86 and 33.41 $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$, respectively (Table 3).

The extracted timber in those four sites results in extracted log emission (ELE) ranging from 8.34 to 8.69 $\text{tC} \cdot \text{ha}^{-1}$ and emission from infrastructure (LIE) from 22.35 to 24.03 $\text{tC} \cdot \text{ha}^{-1}$. We used three scenarios for logging damage emissions (LDE) (average of four sites); 19.58 $\text{tC} \cdot \text{ha}^{-1}$ for scenario LDE_1 , 39.16 $\text{tC} \cdot \text{ha}^{-1}$ for scenario LDE_2 , and 58.74 $\text{tC} \cdot \text{ha}^{-1}$ for scenario LDE_3 . The resulting total emissions (average of four sites), TE_i , are 51.18, 70.76 and 90.34 $\text{tC} \cdot \text{ha}^{-1}$, respectively (Table 4).

Biomass and carbon growth

The average annual carbon growth observed is 1.82 $\text{tC} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (Site 1), 3.55 $\text{tC} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (Site 2), 2.08 $\text{tC} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (Site 3), and 4.45 $\text{tC} \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (Site 4).

Carbon growth for the different sites is shown in Fig. 4 and Table 5. The growth of carbon shows a steady increase. However, in Site 1 a decrease in growth can be observed for the period from 1997 to 1999 for treatment refinement and for the period from 1997 to 1998 in all other treatments. This decrease is due to the mortality of individual trees. However, it should be borne in mind that Site 1 covers the longest time series, and thus the growing stock dynamics are considered over much longer periods than for the other three sites.

Table 3 Average annual log production for the four study sites for the period 1985–2016

Site	Forest area (ha)	Total harvested volume (1985–2016) (m ³)	Average annual log production (m ³ ·ha ⁻¹ ·year ⁻¹)
Site 1	18,745	648,065	34.78
Site 2	18,391	606,212	33.36
Site 3	6,631	236,788	35.86
Site 4	4,976	165,508	33.41

Average annual carbon growth for the control ranges from 0.52 tC·ha⁻¹·year⁻¹ (Site 3 Control 2) to 6.90 tC·ha⁻¹·year⁻¹ (Site 4 Control 1). For liberation treatment, the annual carbon growth is 1.06, 3.07, 5.82, and 6.72 tC·ha⁻¹·year⁻¹ for the respective sites with a mean growth of 4.17 tC·ha⁻¹·year⁻¹, which is the highest rate among all treatments and controls. For refinement, the lowest growth was found for Site 1 (1.19 tC·ha⁻¹·year⁻¹), followed by 2.52 tC·ha⁻¹·year⁻¹ (Site 3), 4.25 tC·ha⁻¹·year⁻¹ (Site 2), and 4.30 tC·ha⁻¹·year⁻¹ (Site 4) with a mean annual growth across all sites of 3.06 tC·ha⁻¹·year⁻¹. The growth due to thinning ranges from 1.28 tC·ha⁻¹·year⁻¹ (Site 3) to 3.70 tC·ha⁻¹·year⁻¹ (Site 2).

Silvicultural treatment

Figure 5 shows the growth-related performance of each treatment in the four sites. The average growth over all treatments in all sites ranges from 1.87 tC·ha⁻¹·year⁻¹ (Control 2) to 4.17 tC·ha⁻¹·year⁻¹ (liberation).

There is no common pattern of growth across the sites. The largest annual carbon growth is found for Control 1 in Site 4. In the other sites, different treatments show the highest and lowest values (Site 1: Control 3 highest, Liberation lowest; Site 2: Control 1 highest, Control 3 lowest; Site 3: Liberation highest, Control 2 lowest) (Table 6).

No statistical difference in carbon growth is found between the treatments, whereas growth between sites are statistically significant (ANOVA, $\alpha = 0.05$). No significant difference is found for the interaction between treatment and site (Table 7).

Recovery time

We calculated the time needed for recovering the total carbon emissions from harvesting, including extracted

timber and logging losses (Table 3), by assuming the above carbon growth shown in Table 5.

Under scenario LDE₁ (LDF = 0.57), the mean of carbon recovery time ranges from 7 to 104 years with an average of 26 years. When LDF is doubled (Scenario 2) and tripled (Scenario 3), the recovery time increases to 10–143 years (average = 36 years) and 13–183 years (average = 46 years), respectively. The mean recovery time between sites varies from 13 to 44 years in Scenario 1, 18 to 61 years in Scenario 2, and 24 to 78 years in Scenario 3. Regarding the three silvicultural treatments, liberation requires the shortest recovery time of 20, 28, and 36 years for LDE₁, LDE₂, and LDE₃, respectively. The longest recovery time is found in Control 2 and ranges from 42 years in LDE₁ to 75 years in LDE₃ (Table 8).

Discussion

Harvesting and carbon emission

The average timber production for each of the four sites ranges between 33.36 and 35.86 m³·ha⁻¹·year⁻¹. This is the common average timber production of concessions in the region, which is confirmed by other studies such as Griscom et al. (2014) with the production of 39.1 m³·ha⁻¹ and Pearson et al. (2014) which range from 26 to 38 m³·ha⁻¹. They also correspond with production volume of 38.9 observed in Brazil (West et al. 2014). Higher timber production (50–250 m³·ha⁻¹·year⁻¹) has been reported by Sist et al. (1998) and Sist et al. (2003a, 2003b), which, however, investigate earlier stages of timber production.

The carbon stock of the four sites studied is estimated to have been between 100 and 173 tC·ha⁻¹ before logging. Measurements started after logging interventions and showed an initial C-stock between 50 and 126 tC·ha⁻¹.

Table 4 Logging harvest and related carbon losses in each site. Related carbon losses are given as ELE= extracted log emission, LIE = emission related to infrastructure, LDE= emission from logging damage and TE = total emission

Site	Harvest (m ³ ·ha ⁻¹)	ELE (tC·ha ⁻¹)	LIE (tC·ha ⁻¹)	LDE ₁ (tC·ha ⁻¹)	LDE ₂ (tC·ha ⁻¹)	LDE ₃ (tC·ha ⁻¹)	TE ₁ (tC·ha ⁻¹)	TE ₂ (tC·ha ⁻¹)	TE ₃ (tC·ha ⁻¹)
1	34.779	8.69	23.30	19.82	39.65	59.47	51.82	71.64	91.47
2	33.356	8.34	22.35	19.01	38.03	57.04	49.70	68.71	87.73
3	35.859	8.96	24.03	20.44	40.88	61.32	53.43	73.87	94.31
4	33.406	8.35	22.38	19.04	38.08	57.12	49.78	68.82	87.86
Mean	34.35	8.58	23.16	19.58	39.16	58.74	51.18	70.76	90.34

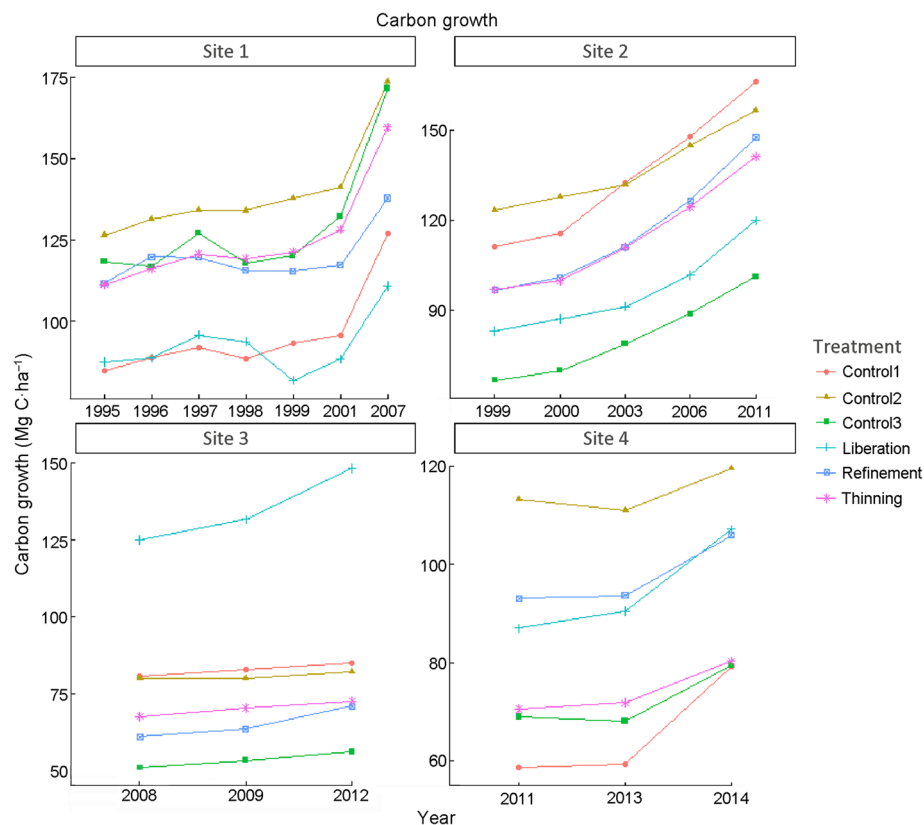


Fig. 4 Carbon stocks estimated in the first measurement years and for the following years based on the subsequent periodic measurements in four different sites ($\text{tC}\cdot\text{ha}^{-1}$). The carbon stocks are estimated for four different treatments—liberation, refinement, thinning, and control

Scenario LDE_1 is based on the total emission reported by Pearson et al. (2014) that corresponds to common interventions and the resulting emissions from logging, infrastructure, and logging losses in the region. Those emissions from the four different sites studied range from 49 to 53 $\text{tC}\cdot\text{ha}^{-1}$, with an average of 51.18 $\text{tC}\cdot\text{ha}^{-1}$. C-stock before logging and related C-stock losses by harvesting are comparable to magnitudes reported by Sasaki et al. (2016), which report 172.5 (± 16.8 $\text{tC}\cdot\text{ha}^{-1}$) for the initial C-stock and losses of 52.2 $\text{tC}\cdot\text{ha}^{-1}$. Between the four sites studied, no significant difference in emission was found. Scenario LDE_1 is conservative by assuming comparatively low forest harvesting emissions.

Larger logging losses (Bertault and Sist 1997; Chapman and Chapman 1997; Sist and Nguyen-Thé 2002; Priyadi et al. 2005; Pinard and Putz 2006; Medjibe et al. 2011) and logging intensities (Sist et al. 1998; Sist et al. 2003a, 2003b; Bischoff et al. 2005) are reported for the Kalimantan. To understand the magnitude of the potential carbon emissions associated with larger logging losses, the study defined additional scenarios that anticipate emissions that exceed the emissions of the conservative Scenario 1. Scenarios LDE_2 and LDE_3 assume larger logging intensities and larger harvesting-related carbon losses. Scenario 2 assumes two

times higher logging damage (LDE), while Scenario 3 assumes three times higher LDE than the LDE in Scenario 1. Under these scenarios, the total C-losses per hectare increase to 70.76 and 90.34 $\text{tC}\cdot\text{ha}^{-1}$ (138% and 176% of Scenario 1).

The scenarios and associated findings suggested that unsustainable and destructive harvesting practice severely undermine sustainable forest management (SFM). On the one hand, low-or reduced-impact logging, characterized by less dead biomass carbon left behind gaps created by felled trees and reduced incidental damage to the surrounding forest, brings significant ecological benefit including reduced carbon emissions. On the other hand, leaving less biomass behind the forest means a higher timber recovery rate can be realized. Therefore, the intensity and the way of timber harvesting are crucial factors to influence SFM.

Regrowth

The growth observed for the four sites and different silvicultural treatments showed no uniform pattern and ranged between 1.65 and 4.61 $\text{tC}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$. In other studies, conducted in Kalimantan, increases in C-stock of 4.5 ± 1.5 $\text{tC}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$ (Mazzei et al. 2010; Poorter et al. 2016) or in aboveground wood production of 6.3 Mg

Table 5 Average growth of diameter (*d*), basal area (*G*), biomass, and carbon (*C*) by site and treatment

Site	Treatment	Annual increment/growth			
		<i>d</i> (cm·year ⁻¹)	<i>G</i> (m ² ·ha ⁻¹ ·year ⁻¹)	Biomass (t·ha ⁻¹ ·year ⁻¹)	<i>C</i> (t·ha ⁻¹ ·year ⁻¹)
1	Liberation	0.12	0.15	2.16	1.06
1	Refinement	0.11	0.19	2.42	1.19
1	Thinning	0.15	0.37	4.48	2.20
1	Control1	0.09	0.36	3.88	1.90
1	Control2	0.16	0.37	4.38	2.14
1	Control3	0.13	0.44	4.94	2.42
	Mean	0.13	0.31	3.71	1.82
2	Liberation	0.29	0.61	6.26	3.07
2	Refinement	0.33	0.79	8.68	4.25
2	Thinning	0.23	0.69	7.56	3.70
2	Control1	0.28	0.84	9.39	4.60
2	Control2	0.26	0.55	5.67	2.78
2	Control3	0.30	0.60	5.87	2.88
	Mean	0.28	0.68	7.24	3.55
3	Liberation	-0.06	1.20	11.88	5.82
3	Refinement	0.02	0.57	5.13	2.52
3	Thinning	-0.13	0.31	2.55	1.25
3	Control1	0.17	0.18	2.28	1.12
3	Control2	-0.01	0.05	1.05	0.52
3	Control3	0.13	0.30	2.60	1.28
	Mean	0.02	0.44	4.25	2.08
4	Liberation	0.34	1.91	13.72	6.72
4	Refinement	0.00	1.17	8.77	4.30
4	Thinning	0.69	0.78	6.64	3.25
4	Control1	0.52	2.48	14.08	6.90
4	Control2	-0.13	0.64	4.20	2.06
4	Control3	0.07	0.79	7.11	3.48
	Mean	0.25	1.29	9.09	4.45

dry mass per ha per year (Banin et al. 2014) are reported. Values equivalent to or slightly higher than the values of our study have been found in other tropical forests in Sabah (1.4 tC·ha⁻¹·year⁻¹), Southern Mexico, Brazil (0.5 tC·ha⁻¹·year⁻¹ for conventional logging and 2.8 tC·ha⁻¹·year⁻¹ for RIL), and Suriname (0.64 tC·ha⁻¹·year⁻¹) (Lobo et al. 2007; Berry et al. 2010; Aryal et al. 2014; West et al. 2014; Roopsind et al. 2017).

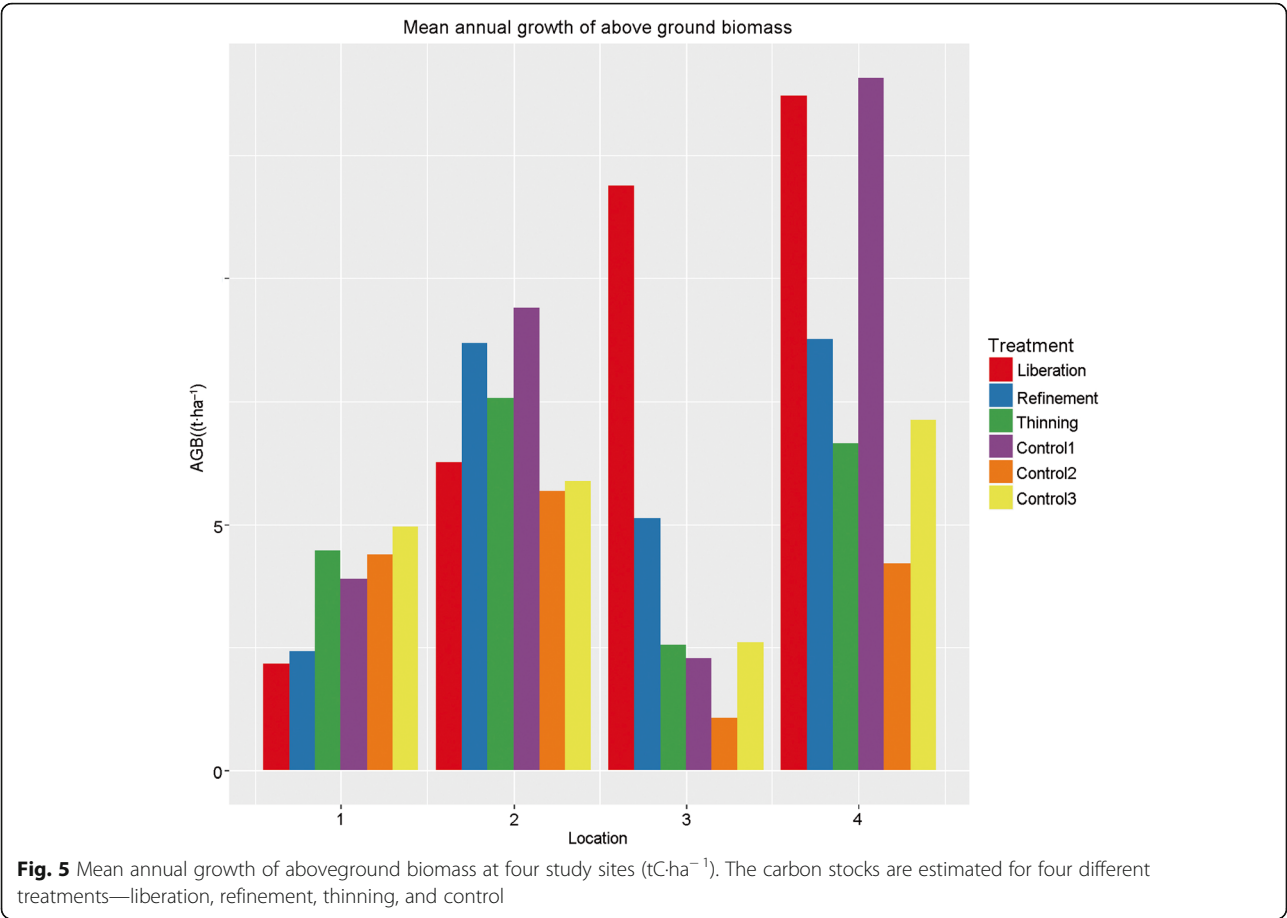
We found no significant differences between the treatments applied, but of the four sites ($\alpha = 0.1$), Site 4 showed the highest growth and Site 1 the lowest. The time after logging covers four years in Site 4 and 12 years in Site 1. Figueira et al. (2008) describe the impact of light availability on growth. This effect is particularly strong shortly after interventions. Considering that the levels of logging interventions are about the same in the four sites, we presume that the differences in growth are not only due to specific local

site conditions, but they may also depend on the time under consideration after interventions.

Effects of silvicultural treatments

Silvicultural treatment is often seen as a controlling element of stand growth (Graaf 1986; Lamprecht 1989). However, in our study silvicultural treatments do not significantly influence the forest stand growth. For example, liberation, which is a light silvicultural treatment, shows the largest average growth over all treatments and site combinations (4.17 tC·ha⁻¹·year⁻¹) but the lowest growth in Site 1. Even between controls, where no treatments are applied, the performance with respect to growth shows considerable contrasts between the four sites.

Each treatment shows a different behavior in the four sites. Since a mix-up between the growth implications of



the individual treatments and the period under consideration cannot be excluded, statements about the influence of silvicultural treatments on forest growth are only possible with reservations. The lack of impact of treatment on forest growth is also confirmed by our statistical analysis, which shows no significance.

These findings stand in contrast to other studies, which found at least moderate treatment effects (Forshed et al. 2008; Peña-Claros et al. 2008; Villegas et al. 2009). Krisnawati and Wahjono (2010) describe a positive influence of purposive liberation of future crop trees. The stimulating effect of silvicultural treatment on individual tree growth was observed

Table 6 Mean carbon growth by site and treatment ($\text{tC}\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$)

Treatment/Site	Site 1	Site 2	Site 3	Site 4	Treatment mean
Liberation	1.06	3.07	5.82	6.72	4.17
Refinement	1.19	4.25	2.52	4.30	3.06
Thinning	2.20	3.70	1.25	3.25	2.60
Control1	1.90	4.60	1.12	6.90	3.63
Control2	2.14	2.78	0.52	2.06	1.87
Control3	2.42	2.88	1.28	3.48	2.51

after a period of 20 years by de Graaf et al. (1999). Our results, as well as those from other studies, suggest that post-harvest stand growth depends more on the condition of the remaining stand than on the silvicultural treatment. This view is also shared by other authors (Chapman and Chapman 1997; Bonnell et al. 2011; Sist et al. 2003a, 2003b; West et al. 2014).

Recovery time

An estimation of the recovery time facilitates an overall assessment of carbon emissions from harvesting and carbon removals due to the growth of the remaining stand. It is thus an important indicator for SFM. A recovery time of more than 100 years was found for logged stands in Mexico (Aryal et al. 2014) and Africa (Bonnell et al. 2011). In studies carried out in other tropical forests,

Table 7 Analysis of variance (ANOVA)

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Treatment	5	57.03	11.41	1.418	0.2738
loc	3	116.20	38.73	4.816	0.0153*
Residuals	15	120.65	8.04		
Signif. codes	0 '***', 0.001 '**', 0.01 'x', 0.05 '.', 0.1 ' ', 1				

Table 8 Carbon emissions and recovery time under three scenarios

Site	Treatment	Annual Carbon Growth (tC·ha ⁻¹ ·year ⁻¹)	Harvest (m ³ ·ha ⁻¹)	Total emission (tC·ha ⁻¹)			Recovery Time (years)		
				TE ₁	TE ₂	TE ₃	TR ₁	TR ₂	TR ₃
1	Liberation	1.06	34.78	51.82	71.65	91.47	49	68	86
1	Refinement	1.19	34.78	51.82	71.65	91.47	44	60	77
1	Thinning	2.20	34.78	51.82	71.65	91.47	24	33	42
1	Control1	1.90	34.78	51.82	71.65	91.47	27	38	48
1	Control2	2.14	34.78	51.82	71.65	91.47	24	33	43
1	Control3	2.42	34.78	51.82	71.65	91.47	21	30	38
	Loc1. Mean						32	44	56
2	Liberation	3.07	33.36	49.71	68.72	87.74	16	22	29
2	Refinement	4.25	33.36	49.71	68.72	87.74	12	16	21
2	Thinning	3.70	33.36	49.71	68.72	87.74	13	19	24
2	Control1	4.60	33.36	49.71	68.72	87.74	11	15	19
2	Control2	2.78	33.36	49.71	68.72	87.74	18	25	32
2	Control3	2.88	33.36	49.71	68.72	87.74	17	24	30
	Loc2. Mean						15	20	26
3	Liberation	5.82	35.86	53.43	73.87	94.31	9	13	16
3	Refinement	2.52	35.86	53.43	73.87	94.31	21	29	37
3	Thinning	1.25	35.86	53.43	73.87	94.31	43	59	75
3	Control1	1.12	35.86	53.43	73.87	94.31	48	66	84
3	Control2	0.52	35.86	53.43	73.87	94.31	104	143	183
3	Control3	1.28	35.86	53.43	73.87	94.31	42	58	74
	Loc3. Mean						44	61	78
4	Liberation	6.72	33.41	49.78	68.82	87.87	7	10	13
4	Refinement	4.30	33.41	49.78	68.82	87.87	12	16	20
4	Thinning	3.25	33.41	49.78	68.82	87.87	15	21	27
4	Control1	6.90	33.41	49.78	68.82	87.87	7	10	13
4	Control2	2.06	33.41	49.78	68.82	87.87	24	33	43
4	Control3	3.48	33.41	49.78	68.82	87.87	14	20	25
	Loc4. Mean						13	18	24
	Mean						26	36	46
	Minimum						7	10	13
	Maximum						104	143	183

recovery rates between 16 and 30 years were described (Mazzei et al. 2010; West et al. 2014; Poorter et al. 2016; Raymond et al. 2015).

Under scenario LDE₁, we found an average recovery time of 26 years, which is shorter than the cutting cycle of 35 years mandatory in Indonesia. However, the wide range of recovery time under scenario LDE₁, which extends from 7 to 104 years, leaves large uncertainties. In Scenarios LDE₂ and LDE₃, the recovery times are correspondingly longer, which might be due to higher losses by logging damage and extend beyond the Indonesian cutting cycle. Martin et al. (2015) conducted a meta-

analysis to study at what age following forest clearance carbon pools in secondary tropical forests reach equivalent values to those of undisturbed forests. They found that above-ground carbon pool recovered within 85 years, and that soil carbon remained largely unchanged over time. In our findings, the longer recovery period for LDE₂ and LDE₃ scenarios supports the findings of Martin et al. (2015).

Losses due to extracted timber, logging residuals, and infrastructure measures thus have a decisive impact on the recovery time. Timber harvesting measures that are not carried out gently need recovery periods that are

longer than the usual harvesting cycles. Therefore, forests cannot recover before the next harvesting intervention, leading to long-term losses of biomass and C-stocks and thus to forest degradation.

Sustainability is the goal of forest management. Sustainable forest management means the balance of ecological, economic, and sociocultural function of forests for present and future generations. It implies that the need for long-run growing C-stock maintenance to recover the biomass losses. Unsustainable forest management occurs when biomass loss from growing stock cannot be recovered by the growth of the remaining stand. Our study shows that the amount of timber extracted does not suffice to make statements about the time needed to recover the growing stock and the C-stock.

Of crucial importance is the amount of biomass and carbon losses caused by harvest residuals and infrastructure measures. In general, these quantities are of no economic significance and at best reduce the costs of wood harvesting operations. Therefore, these influencing components must be given a greater importance, e.g. through timber harvesting guidelines or financial incentives to reduce the amount of timber felled but not used.

REDD+ mechanism and harvesting losses

Indonesia is participating in the REDD+ mechanism. One of the five activities of the REDD+ mechanism includes reducing emissions from forest degradation (Decision 1 of the 16th session of the Conference of the Parties to the UNFCCC (decision1/CP.16)). To achieve the goal of the REDD+ mechanism, reducing logging losses from logging damage and logging infrastructure development through the implementation of improved harvesting and /or RIL is crucial. At the same time, a country might decide to reduce timber harvesting in order to reduce forest degradation and consequently reduction in forest carbon emissions. In this case, a reduction in harvest intensity leads to a reduction in revenues from timber harvesting. Considerable investments are needed to design and implement measures like RIL and might impose a high economic burden to the country in the initial years of REDD+ implementation. The forgone benefits and investment might exceed the REDD+ revenues generated from accountable carbon credits (emission reductions). However, the realization of long-term financial and ecological benefits of RIL and other co-benefits of the REDD+ mechanism encourages adopting such measures. Improved harvesting practices and RIL stimulates the accomplishment of sustainable management of forests, which is another designated REDD+ activity (decision1/CP.16). For C-stock dynamics, the improved harvesting and/or RIL even play a greater role by reducing the carbon recovery period than the biomass growth after conventional harvesting interventions

(See 'Regrowth' section of this Chapter). As a result, measures to reduce harvesting losses account for a greater, if not the most important, share of sustainable forest management within the scope of REDD+.

Conclusions

This study has analyzed the rate of above-ground biomass and carbon recovery in post-logging secondary forests managed by a forest concession holder in East Kalimantan, Indonesia. The study has shown that above-ground carbon pool may take only 26 years to recover following selective logging. In secondary forests undergoing high-intensity logging associated with larger incidental damage, above-ground carbon pool takes a longer time to reach equivalent values to those of unlogged forests.

This study provides new information regarding the recovery of above-ground carbon pools after selective logging for policy and forest management entities including forest concessions holder and forest management units. Such information has increasing relevance in the context of climate change mitigation policies designed to reduce carbon emissions from forest degradation such as REDD+.

Future discussions concerning the reduction of intervention cycles can only be conducted against the background of the losses of the remaining stock caused by logging. Our study shows that arbitrarily determined intervention cycles of 30 years, which is currently applied in some sites in Kalimantan, is very risky in terms of biomass and carbon recovery. Owing to the wide growth performance after logging interventions, site-specific specifications of intervention cycles are necessary. An important influencing factor is the amount of biomass losses from previous cutting operations. This calls for mandatory reduced impact logging and specific management regimes instead of uniform annual allowable cut.

In our study, silvicultural treatments, i.e. liberation, refinement, and thinning, do not significantly influence forest stand growth. This does not mean that we argue in favor of passive restoration of tropical forests. Further research is needed to explore the impacts of such silvicultural treatments on biomass recovery.

Our study did not show the impact of carbon storage of harvested wood products or emission reductions by the material and energetic use of timber. Butarbutar et al. (2016) showed that carbon offsets by timber utilization are a major component of the C-balance of logging interventions. However, only reduced impact logging that minimizes logging residuals and losses by infrastructure offers the possibility for carbon offsets.

Abbreviations

AGB: Above-ground biomass; *d*: Diameter at breast height (130 cm); ELE: Extracted log emission (tC); LDE: Emission from logging damage (tC); LIE: Emission related to logging infrastructure development (tC); TE: Total emission resulting from timber harvest (tC)

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Authors' contributions

TB, MK and PN designed the research. TB and SS worked on data preparation and TB and MK performed data analysis. TB, MK, SS, and PN drafted the article. TB, MK and PN reviewed the drafts. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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RESEARCH

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Harvested wood products and REDD+: looking beyond the forest border

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Abstract

Background: The focus of REDD+ is sensu stricto on maintaining forest carbon stocks. We extend the scope of sustainable management of forest from forests to timber utilization, and study carbon offsets resulting from the utilization of harvested timber for bio energy or harvested wood products (HWPs). The emission budget of harvesting operations depends on the loss of standing biomass by timber extracted from the forest site and logging losses on the one side, and on the other on the wood end use and the utilization of processing residues. We develop two scenarios to quantify the magnitude of CO₂ emissions by (1) energetic utilization, and (2) energetic and material utilization of harvested timber and compare the substitution effects for different fossil energy sources.

Results: The direct energetic use of harvested timber does not compensate for the losses of forest carbon stock. Logging residuals and displacement factors reflecting different wood use constitute by far the most important factor in potential emission reductions. Substitution effects resulting from energetic use of mill residuals and from HWPs have only a subordinated contribution to the total emissions as well as the type of fossil fuel utilized to quantify substitution effects. Material substitution effects associated with harvested wood products show a high potential to increase the climate change benefits.

Conclusions: The observation and perception of REDD+ should not be restricted to sustainable management and reduced impact logging practices in the forest domain but should be extended to the utilization of extracted timber. Substitution effects from material and energetic utilization of harvested timber result in considerable emission reductions, which can compensate for the loss of forest carbon, and eventually contribute to the overall climate change mitigation benefits from forestry sector.

Keywords: REDD+, HWP, Material substitution, Energetic substitution, Sustainable forest management, Emission reductions, Displacement factor

Background

Forests provide a multitude of ecosystem services and functions, among which are their role in the global carbon cycle, the supply with timber and fuel wood, or safeguarding biodiversity. The current promotion of bioeconomy and the related extension of renewable energies are likely to increase the demand for timber. Decisions about the appropriate management and utilization of forests create a vigorous area that is fueled by differences in social, cultural, environmental and ecological aspects

concerning “optimal” forest management and utilization strategies for enhancing the contribution of forests to the mitigation of climate change.

Forest related options for mitigating climate change include the sequestration of atmospheric carbon dioxide (CO₂) by forest growth, the conservation and enhancement of forest carbon stocks as well as the substitution, and C-storage resulting carbon effects from the utilization of harvested timber. This offers three ways for treating forest carbon stock in order to achieve mitigation: (i) maintaining and enhancing forest biomass stock and avoiding emissions from forest degradation and deforestation, (ii) use as a renewable source of energy (bioenergy) for substitution of fossil fuels, or (iii) use as renewable material (harvested wood products, HWPs) for substitution of alternative

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products and materials, production of which is associated with higher energy consumption and thus emissions.

In the Kyoto Protocol's second commitment period (2013–2020) [1], C-stock changes in the HWPs pool are explicitly included in the calculation of the country's greenhouse gas (GHG) emissions and removals. The reducing emissions from deforestation and forest degradation (REDD+) mechanism, which has been under negotiation by the United Nations Framework Convention on Climate Change (UNFCCC) since 2005, focuses on activities that developing countries may implement to reduce emissions and enhance removals of greenhouse gases. Five “eligible activities” have been defined under REDD+ [2]:

- a. Reducing emissions from deforestation;
- b. Reducing emissions from forest degradation;
- c. Conservation of forest carbon stocks;
- d. Sustainable management of forests; and
- e. Enhancement of forest carbon stocks.

The formal and strong recognition of the role of forests mitigating climate change and the explicit recognition of REDD+ as a mechanism to contribute to reducing emissions and enhancing carbon sinks in Article 5 of Paris Agreement encouraged parties, particularly developing countries, to reduce carbon emissions, and conserve and sustainable management of their standing forests. The universal and landmark climate deal also calls on parties to adhere already agreed REDD+ related COP decisions of the Conference of the Parties (COP) to the United Nations (Article 5.2). Along with such international policy developments and involvements, research into carbon balancing pertaining to HWPs and consideration of relevant climate change mitigation strategies are increasingly growing [3].

The focus of REDD+ is *sensu stricto* on maintaining forest carbon stocks. Measurement, reporting and verification in the scope of REDD+ are related to carbon released from and carbon sequestered by forests. Under REDD+ every carbon removals from the managed forest area are considered as emissions; whereas the long-lived carbon storage by harvested wood products or material substitution effects induced by the use of timber instead of non-renewable resources is not accounted for. HWP so far is part of the national GHG-reporting, but not considered in REDD+. However, the Paris Agreement strongly encourages all parties to consider the entire sinks and reservoirs of greenhouse gas while developing the nationally appropriate mitigations actions, pathways to implement the agreement, and policy approaches [4].

We extend the scope of sustainable management of forest from forests to timber utilization, and study carbon offsets resulting from the utilization of harvested timber

for bioenergy or HWPs. We develop scenarios to quantify the magnitude of CO₂ effect in different uses of HWP and elaborate on the potential impact on emission reduction accounting under REDD+ in a future (post 2015) international treaties.

Contribution of harvested wood products (HWPs) to climate change mitigation

The “Revised 1996 IPCC Guidelines” recommend a default approach under which all CO₂ emissions and removals associated with forest harvesting and the oxidation of wood products are accounted for by the country in the year of harvesting (i.e., removal from the forest biomass pool). This approach laid the foundations for the widely shared supposition that the use of timber is carbon neutral. However, there is no common understanding of the term “carbon neutrality”. Treating harvested timber as carbon neutral is only justified when the loss of carbon from the forest C-stocks has already been accounted for at the time of harvest.

Following the IPCC Guidelines for National Greenhouse Gas Inventories [5] carbon contained in harvested timber can be transferred from the forest C-pool to the C-pool of HWPs. Under this approach burning of timber would result in CO₂ emissions. These CO₂ emissions can be compared to fossil fuel emissions for producing a unit amount of energy in order to see whether the use of timber results in an emission reduction. However, this direct comparison does not take into account the release of carbon content from biomass decay to the atmosphere, regardless of whether it is utilized or not.

HWPs contribute to the climate change mitigation in three ways: (i) carbon storage effect, (ii) material substitution effect, and (iii) energy substitution effect. Wood fuel can be used as a renewable source of energy to substitute fossil fuels, which reduces additional CO₂ emissions to the global carbon cycle, as the combustion of wood fuel releases only carbon that is already part of the global carbon balance. This energy path can contribute to renewable energies in different forms: (i) energy provision directly from wood, (ii) bioenergy production from logging and processing residues, and (iii) use of the wood contained in HWPs for energy production at the end of their lifecycle [6–8]. In 2011, for wood fuel 1343 million m³ of harvested timber were used [9].

Timber as renewable material allows for the physical storage of carbon and for producing wooden products. According to Maraseni [10, 11] carbon is locked for another 46 years in HWPs. Wooden products are compared to alternative materials of equal functionality generally associated with lower energy input in the production process. Studies show, for example, that substitution of CO₂ and energy intensive materials (steel, alloys, concrete) by wood

is associated with substantially lower emissions of CO₂ [12–14]. Moreover, a substantial reduction in the consumption of fossil fuels in the production and transportation of high energy-consuming materials can be realized [15]. Thus, the analysis of forestry contribution to climate change mitigation should take to account the important role of HWP [16, 17]. Emission reductions per unit biomass can generally be enhanced if material substitution effects and energy substitution effects attributed to HWPs are combined. This can be realized when the timber contained in HWPs is used for energy at the end of the life-cycle of the product [18]. In addition, HWPs can be recycled and used in successive products. The so-called cascade use of HWPs has a successive potential for emission reduction.

Approaches for emission accounting

Current discussions of the REDD+ mechanism give a major priority to C-stock losses in forests induced by forest degradation and deforestation. This is justified in situations where REDD+ is seen as an instrument to maintain and enhance forest carbon stocks and thus any degradation and deforestation activity is to be treated as emission (Fig. 1).

However, timber harvesting can be seen as a transition of carbon from the forest carbon pool to the harvested wood products pool [19–21]. For Annex I countries the second commitment period of the Kyoto Protocol (2013–2020) explicitly allows for the consideration of the C-stock and C-stock changes in HWPs pools. This calls for a revision of the concept of “carbon neutrality” of HWPs and wood fuel. The carbon contained in harvested biomass is no longer treated as direct emission from the forest C-stock to the atmosphere at the time of harvesting. HWPs serve as an intermediate C-stock and any combustion of timber, either of HWPs at the end of their lifetime or of wood fuel, is regarded as emission.

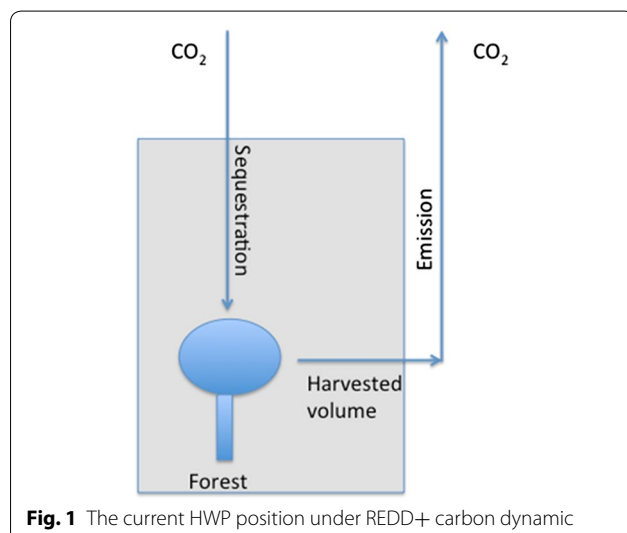


Fig. 1 The current HWP position under REDD+ carbon dynamic

As the underlying processes and interrelationships are complicated, much attention is given to consistent and transparent accounting rules [15]. Any accounting rule under the UNFCCC is the result of a consensus between different actors, and has to take into account the higher order set of rules and regulations. What allows for consistent and reliable national GHG-reporting is negotiated and implemented for different sectors. C-stock changes in forests and HWPs are accounted for in the LULUCF/forestry sector, while emissions from energy are accounted for in the energy supply sector. This hampers a direct link to emission reductions associated to the forest-timber chain. Compared to alternative materials with similar function, HWPs generally show lower energy consumption and emissions in their production processes. In national GHG inventories, these emission reductions are accounted for in the energy sector. Therefore, it might be advisable to decouple the general reflection of the mitigation potential of HWPs from the UNFCCC accounting framework.

Energetic use

When studying the energy substitution effect of timber, it is crucial to consider which type of fossil fuel is compared. Our comparison follows a study conducted by [22] and utilizes natural gas, lignite, and residual fuel oil as references for energetic substitution (Box 1). Table 1 presents the net caloric values (TJ/Gg) and CO₂ emission factors (kg/MWh) associated with different types of fossil fuels. The presented effective CO₂ emission factors are default values taken from [5]. The IPCC default values assume dry matter biomass and are considerably lower than those given by other authors (e.g., <http://www.engineeringtoolbox.com>).

Direct or effective emissions account for the emissions associated with energy combustion, but do not account for emissions arising from manufacturing, infrastructure or transport associated with energy technologies and fuels [23]. Indirect emissions are a consequence of the activities that occur at sources controlled by other entities than the end user and comprise all the emissions from the final use back to raw material extraction. Life cycle CO₂ emissions combine direct and indirect emissions and depend strongly upon details of supply chains, production techniques, forestry practices, or transport distances [23, 24]. The life-cycle analysis can adopt different analytical methodologies and are affected by data availability and uncertainties surrounding the value of key attributes. This holds especially true for life-cycle analysis carried out in developing countries [25]. For the current study, we utilize values presented by the biomass energy centre (<http://www.biomassenergycentre.org.uk>) in order to approximate life cycle CO₂ emissions.

Timber is an inhomogeneous fuel. Its caloric value depends on the content of water, cellulose, lignin, resin, acids, oils, and minerals and varies between 4.17 and

4.72 kWh per kg [28]. Decisive for the caloric value is the water content of timber. When timber is burnt firstly the water contained in timber is evaporated. In order to evaporate a kg of water contained in the wood, 0.68 kWh (2.45 MJ) energy is needed at 20 °C. For our scenario analysis we assumed air-dried timber with a water-content of 15 % and a caloric value of 4.33 kWh per kg. Caloric values are linked to tree biomass weight and volume by wood density. We selected three different wood densities (500; 750; 1000 kg/m³) to present the potential range of wood densities found in tropical tree species.

When timber is used to replace natural gas, lignite, or residual fuel oil for energy production the respective emissions have to be compared for a unit reference. The results presented in Table 2 allow for quantifying the direct CO₂ emissions of alternative energy sources with reference to the caloric value produced by the combustion of 1 m³ of timber of different wood densities. For the current study both, effective and lifecycle CO₂ emissions were utilized with the purpose of demonstrating the sensitivity of findings with respect to imputed emission factors.

Box 1: Reference types of fossil fuels

Natural gas is a naturally occurring gas mixture, which consists mainly of methane.

Lignite is the lowest rank of coal, often referred to as brown coal, used almost exclusively as fuel for steam-electric power generation. It is brownish-black and has high inherent moisture content, sometimes as high as 45 %. The heat content of lignite ranges from 2600 to 5000 kWh per ton on a moist, mineral-matter-free basis [26].

Residual fuel oil is a general classification for heavier oils that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It is used in steam-powered vessels in government service and inshore power plants, the production of electric power, space heating, vessel bunkering, and various industrial purposes [27].

Table 1 Default values for net caloric value, effective CO₂ emission factors (Source: IPCC 2006), and life cycle CO₂ emissions (Source: <http://www.biomassenergycentre.org.uk>)

Energy source	Net caloric value (TJ/Gg)	Effective CO ₂ emissions (kg/MWh)	Life cycle CO ₂ emissions (including production) (kg/MWh)
Lignite	11.9	364	414
Residual fuel oil	40.4	279	314
Natural gas	48.0	202	227
Wood/wood waste	15.6	403	403 ^a

^a Assuming utilization for subsistence with only manual interventions

Emissions due to logging residues

Harvesting operations may induce pronounced reductions of the growing stock and thus forest carbon stocks. In a study conducted in Malaysian State of Sarawak, Noack [29] showed that on average about 54 % of the total above ground wood volume of trees removed from a stand was extracted in the form of logs. These findings are supported by McLeish and Sustany [30]. For tropical countries felling recovery rates related to aboveground wood volume were estimated to be 54 % in Africa, 46 % in Asia/Pacific, 56 % in Latin America and the Caribbean, and 50 % on average for all tropical areas [31, 32]. Noack [33] found, in a similar study for Ghana, Cameroon, East Kalimantan and Sarawak, that on average 53.5 % of the total extracted volume was logs of the trees those having a diameter at breast height greater than 20 cm. Of the remaining volume 4.6 % was stump, 5.2 % buttress, 10.4 % stem off-cuts and 26.3 % were parts of the crown. For Malaysia and Sri Lanka, Enters [34] showed that between 30 and 48 % of the timber of felled trees is utilized. He notes that as a “traditional rule-of-thumb” for “every cubic meter of wood extracted from the forest another is left behind”.

These figures are related to the timber extracted from felled trees. Carbon stock reductions resulting from harvesting operations include logging residues additional to non-utilized components of felled trees that remain in the forests. Additional logging residues may be caused by the felling of trees for the creation of skidding trails and road infrastructure, trees damaged or killed in connection with the felling of crop trees, or non-merchantable woody parts of crop trees that remain in the forest. Thurland [35] reported for an unsupervised logging operation in the Malaysian State of Terengganu growing stock reductions of 50–70 % to the residual stands. According to a study reported by Pearson et al. [36], the volume of logging residues in Belize, Bolivia, Brazil, Indonesia, Guyana, and Republic of the Congo is 2–5 times higher than the volume of extracted timber. The substantial variations in felling recovery rates reported are subject to operational efficiency and skill of workers, available markets for lower grade logs, or differences in the definition of merchantable wood [37]. The application of reduced impact logging is a relevant factor for recovery rates [38–40]. Logging residues inside the forest may also remain as an organic carbon. However, we applied a conservative approach by treating the logging residues as immediate emissions in order to avoid the strenuous and arduous emission benefits associated with the residues.

Emissions due to processing residues

Processing of logs in sawmills results in final products and residues. Mill residues include woody material generated

when round wood is processed into primary wood products. The composition of mill residues depends on the primary product and on processing technologies. The mill residues include among others slabs, edgings, trimmings, sawdust, or veneer clippings and cores. Plywood mills produce quite different residues than saw-mills. According to Enters [34], mill waste can be divided into bulk waste, which is made up of larger pieces, and fine wood particles, which consists of shavings, sawdust and sander dust.

The volume of mill residues is affected by numerous factors. The recovery rate in timber processing is especially dependent on log dimensions. Ravn and Jensen [41] reported that for logs in the range of 30–70 cm in diameter, recovery rates drop to about half when the log diameter is halved. Additional decisive factors for recovery rates are tree species, log quality, timber defects, sawmilling equipment, mill maintenance, production methods, grading, storage and drying [34, 42]. Enters [34] analyzed detailed studies in numerous developing countries and found sawmill recovery rates in a range from 42 to 60 % with an average of 50.8 % and plywood recovery rates in a range from 43 to 50 % with an average of 46.9 %.

Emissions related to HWP

According to Sathre and O'Connor [19], the “comparative analysis of the carbon balances of wood vs. non-wood products is a complex issue”. The analysis depends on the definition of the appropriate functional unit and the effective system boundaries. Functional units can be individual wood products, entire buildings or services provided by the built environment. System boundaries relate to the activity and the temporal and spatial dimension. The activity based life cycle processes include material production, product operation, and the post-use material management. Temporal system boundaries can extend from the production of the raw material, the product processing and product life-cycle, the duration of carbon storage in the product, recycling of the product, the availability of residue biofuels, and the fate of the wood product at the end of the product's lifetime (e.g., energetic use, decay, or disposal). Therefore, life cycle analysis generally relates to specific HWP and takes into account their entire life cycle including production, use, and disposal. Knauf et al. [6] quantified the GHG impacts of different HWP in the regional environment of north-western Germany. The post-use of HWP is “the single significant source of variability in the GHG impacts of the wood product life cycle” [19].

To what extent the HWP contribute to reduce the GHG emission is a key issue while quantifying the amount

to which GHG emission can be reduced by the use of forest biomass to mitigate climate change. The displacement factor is an index that quantifies the efficiency of emission reductions per unit of wood use. In a meta-analysis Sathre and O'Connor [19] found displacement factors of wood products ranging between -2.3 and 15 . The use of timber in this analysis varies from construction, housing, apartment, hotel and energy. Negative displacement factors indicate that the wood products lead to greater GHG emissions than the use on non-wood products, which is mostly caused by inappropriate disposal. In general, disposal of wood products typically require less energy than products made from other high energy-consuming materials [16]. According to Sathre and O'Connor [19] the displacement factor for wood being used directly as biofuel to replace fossil fuel ranges from less than 0.5 to about 1.0 , with an average value of 0.8 . Based on the results of their meta-analysis, Sathre and O'Connor [19] found an average middle estimate for the displacement factor of 2.1 . A displacement factor of 2.1 corresponds to 3.9 kg CO₂e emission reduction per kg of oven-dry wood used or 1.9 t CO₂e per m³ of wood product [19]. For our study we selected displacement factors of 0.8 and 2.1 .

Results and discussion

Based on a scenario approach the carbon effects of logging and mill losses as well as HWP were studied. The results presented for the two scenarios “Wood fuel” and “HWP” show the potential CO₂ emission effects of the simultaneous consideration of harvesting induced losses in forest carbon stocks and substitution effects by timber utilization. Negative values in the result tables indicate that the use of timber results in higher emissions than those from utilizing the three selected non-renewable energy sources, while positive values indicate emission reductions. All values are based on a standard unit of 1 m³ of solid wood.

Scenario 1 “wood fuel”

Scenario 1 assumes that all harvested timber is used as wood fuel without logging residues or with logging residues of the same amount as extracted timber. Table 2 presents the differences between CO₂ emissions from the non-renewable energy sources (lignite, residual fuel oil, and natural gas) and timber. Both, effective emissions and lifecycle CO₂ emissions of timber exceed the corresponding emissions of the selected non-renewable energy sources (Table 3). This holds especially true where the harvesting of wood fuel is associated with logging losses. Thus the energetic substitution effect of wood fuel generally does not compensate for forest C-stock losses.

Table 2 Scenario “wood fuel”: emission savings (kg CO₂)

Logging residues	None			1 m ³		
	500 kg/m ³	750 kg/m ³	1000 kg/m ³	500 kg/m ³	750 kg/m ³	1000 kg/m ³
Effective CO ₂ emissions						
Lignite	−130	−194	−259	−1048	−1570	−2094
Residual fuel oil	−314	−470	−628	−1232	−1846	−2463
Natural gas	−480	−720	−960	−1398	−2096	−2795
Lifecycle CO ₂ emissions						
Lignite	−21	−30	−41	−939	−1406	−1876
Residual fuel oil	−238	−355	−474	−1156	−1731	−2309
Natural gas	−426	−638	−851	−1344	−2014	−2686

Table 3 CO₂ emissions (kg CO₂) from combustion of 1 m³ of timber and corresponding alternative energy sources

Energy source	Wood density		
	500 kg/m ³ (2.17 MWh)	750 kg/m ³ (3.25 MWh)	1000 kg/m ³ (4.33 MWh)
Effective CO ₂ emissions			
Lignite	788	1182	1576
Residual fuel oil	604	906	1207
Natural gas	438	656	875
Wood (1 m ³)	874	1310	1747
Lifecycle CO ₂ emissions			
Lignite	897	1346	1794
Residual fuel oil	680	1021	1361
Natural gas	492	738	984
Wood (1 m ³)	874	1310	1747

Scenario 2 “harvested wood products”

Scenario 2 utilizes HWP's under two levels of efficiency (Table 4). The low efficiency sub-scenario 2a (Table 5) is characterized by substantial logging losses, a low displacement factor, and no energetic use of residues and HWP's at the end of their lifetime. Emissions savings by substitution effects associated with the use of HWP are low under this sub-scenario (displacement factor = 0.8) and do not have the ability to compensate for emissions from logging and mill residues. The displacement factor compensates roughly for the emissions originating from the decay of HWP's at the end of their lifetime.

Sub-scenario 2b represents a high efficiency in timber utilization by adopting moderate logging losses, energetic use of residues and HWP's at the end of their lifetime, and a displacement factor of 2.1 (Table 6). Reduced impact logging and the energetic use of logging residuals and HWP's at the end of their lifetime result in substantially lower total emissions. More sophisticated utilization of timber results in higher displacement factors and thus increasing substitution effects. Compared to the low efficiency scenario the total emissions are

considerably reduced and are for lignite life-cycle CO₂ emissions almost balanced. A moderate increase of substitution effects could result in emission gains. Under the emission assumptions given for scenario 2b, a displacement factor larger than 2.2 would result in emission savings, if lifecycle CO₂ emissions for lignite are considered. A displacement factor of 2.9 would compensate for effective CO₂ emissions compared to natural gas as an alternative energy source. This indicates a potential to increase climate benefits through the changes in displacement factor driven by promoting and sophisticated use of wood products harvested from the domestic managed forests.

The results of the partial sensitivity analysis are presented in Table 7. For a reference unit of 1 m³ with a density of 500 kg, the effective CO₂ emissions are calculated taking into consideration 17 factors (see Table 7). The factors were varied according to the range specified in the first column of Table 7.

The sensitivity analysis showed the contribution of different factors on the total emission budget. Substitution effects resulting from energetic use of mill residuals

Table 4 Assumptions for scenario 2—harvested wood products

Component	Low efficiency scenario (sub-scenario 2a)	High efficiency scenario (sub-scenario 2b)
Logging residuals	5 times the amount of extracted timber (conventional logging)	Same amount as extracted timber (reduced impact logging)
Mill residues	60 %, no energetic use	40 %, energetic use
Displacement factor	0.8 (corresponds to 1.48 kg CO ₂ e emission reduction per kg of wood)	2.1 (corresponds to 3.9 kg CO ₂ e emission reduction per kg of wood)
Proportion of HWP for energetic use at end of lifecycle	0 %	60 %
Proportion of C-stock of HWPs emitted at end of life cycle	100 %	40 %

Table 5 Scenario 2a “harvested wood product (HWP), low efficiency”: emissions (kg CO₂)

Wood density (kg/m ³)	Emissions			Emission reduction with displacement factor = 0.8	Total emissions
	Logging residues ^a	Mill residues ^b	HWP end of lifecycle ^c		
500	−4590	−551	−367	300	−5208
750	−6880	−826	−550	449	−7807
1000	−9175	−1101	−734	599	−10,411

^a 5 m³^b 60 %, no energetic use^c No energetic use**Table 6 Scenario 2b “harvested wood product (HWP), high efficiency”: emissions (kg CO₂)**

Wood density (kg/m ³)	Emissions (kg CO ₂)		Emission reduction with displacement factor = 2.1 (kg CO ₂)	Substituted emissions for energy (kg CO ₂)			Total emissions (kg CO ₂)		
	Logging residues ^a	HWP end of lifecycle		Lignite	Residual oil fuel	Natural gas	Lignite	Residual oil fuel	Natural gas
Effective CO ₂ emissions									
500	−918	−220	1170	−64	−204	−331	−122	−262	−389
750	−1376	−330	1755	−96	−306	−496	−182	−392	−582
1000	−1835	−440	2340	−128	−408	−661	−244	−523	−777
Lifecycle CO ₂ emissions									
500	−918	−220	1170	18	−146	−290	−40	−205	−348
750	−1376	−330	1755	27	−220	−434	−59	−306	−521
1000	−1835	−440	2340	36	−293	−579	−79	−408	−695

^a 1 m³

and from HWPs have only a minor contribution to the total emissions as well as the type of fossil fuel utilized to quantify the substitution effect. This is in line with [43] which considers wood energy to be carbon neutral if it is originated from sustainably managed forests and processed using proper technology. Similarly, it plays a subordinated role if effective or lifecycle CO₂ emissions are considered. Logging residuals and displacement factor constitute by far the most important factor in potential emission reductions. As a consequence logging residuals and the type of wood use expressed by the displacement

factor are driving the benefits from REDD+ in a holistic emission budget.

Numerous studies have shown [6, 44] the potential role of HWP for emission reduction by both replacement of fossil fuels as source of energy as well as replacement of material that is associated with high emissions in the production process [19]. In the scope of REDD+ where emissions from deforestation and forest degradation are to be reduced, the carbon storage effect and material substitution effect attributed to HWPs can be substantial components to compensate for losses of forest carbon

Table 7 Results of sensitivity analysis: emissions (kg CO₂)

Factor	Minimum	Maximum	Mean	Std. dev
Logging residues (1–5 times extracted timber)	874.0	4370.00	2622.00	1236.16
Mill residues (10–50 % of extracted timber)	87.40	437.00	262.200	123.61
Energy from mill residuals (10–50 % of mill residuals converted for energetic use)	8.74	218.50	78.660	55.28
Lignite substituting energy from mill residuals (effective CO ₂)	7.88	197.00	70.920	49.84
Oil substituting energy from mill residuals (effective CO ₂)	6.04	151.00	54.360	38.20
Gas substituting energy from mill residuals (effective CO ₂)	4.38	109.50	39.420	27.70
Lignite substituting energy from mill residuals (lifecycle CO ₂)	8.97	224.25	80.73	56.74
Oil substituting energy from mill residuals (lifecycle CO ₂)	6.80	170.00	61.20	43.01
Gas substituting energy from mill residuals (lifecycle CO ₂)	4.92	123.00	44.28	31.12
Displacement factor (1–5)	812.82	8778.46	3982.82	2139.98
Energy from HWP _s at end of lifecycle (10–60 %)	43.70	417.96	214.13	115.05
Lignite substituting energy from HWP _s ^a (effective CO ₂)	39.40	425.52	193.060	103.73
Oil substituting energy from HWP _s ^a (effective CO ₂)	30.20	326.16	147.980	79.51
Gas substituting energy from HWP _s ^a (effective CO ₂)	21.90	236.52	107.310	57.65
Lignite substituting energy from HWP _s ^a (lifecycle CO ₂)	44.85	482.38	219.77	118.08
Oil substituting energy from HWP _s ^a (lifecycle CO ₂)	34.00	367.20	166.60	89.51
Gas substituting energy from HWP _s ^a (lifecycle CO ₂)	24.60	265.68	120.54	64.77

^a HWP_s 50–90 % of extracted timber

stocks, and consequently, to increase the climate change mitigation benefits substantially. Maraseni and Cockfield [11] compare the economic returns from three land use options, i.e., ‘carbon’ plantation (*Corymbia citriodora* subspecies *Variegata*) which includes value of carbon stored in harvested wood products, pasture, and cultivation of peanut-maize in the Kingaroy area of Queensland. The study found that the ‘carbon’ plantations are the most profitable land use option.

Logging residues cause direct CO₂ emissions to the atmosphere. Reducing logging residues is of uttermost importance. Griscom et al. [45] report potential emission savings of 30–50 % by the adoption of reduced-impact logging. However, where logging residues are used for energy the nutrient balance of pristine forest stands has to be carefully monitored [46]. Trade-offs relationships should be investigated between the carbon storage (carbon in forests, carbon in dead organic matter and soil) and energy substitution (increasing energy generation from the logging residues) effects attributable to HWP_s.

The direct energetic use of harvested timber does not compensate for the losses of forest carbon stock, while material substitution effects by HWP_s result in considerable emission reductions. Innovative wood technologies can improve the substitution effects considerably and should become a substantial component in improving the mitigation potential of HWP_s. Emission reductions can be further increased if mill residues and HWP_s at the

end of the lifetime are not used for energy but are further converted into timber products [47].

Though, the climate change mitigation benefits generated by the harvested wood products are not directly linked with and explicitly covered by the five REDD+ activities outlined by the UNFCCC, it is strongly linked with the clean development mechanism (CDM) and joint implementation (JI) mechanism under the Kyoto Protocol, and with the voluntary carbon market. Considering the emission reduction potentials of the material substitution effect associated with the harvested wood products, our study strongly recommends this missing carbon pool should be fully realized and included under the extended REDD+ mechanism. However, caution should be taken to accommodate the uncertainty and complexity while developing forest reference level, and credible, reliable and applicable MRV system for REDD+ mechanism.

However, these findings do not take into account the growth of forests after logging interventions. From managed forests it is widely known that moderate growing stock reductions by thinning stipulate the growth of the remaining stand. The remaining stand compensates higher emissions of wood fuel by a woody biomass increment between 0.09 (Lignite, no logging residues) and 1.43 m³ (natural gas, 1 m³ logging losses). Under most tropical forest conditions those increments can be realized under sustainable forest management regimes within 1 year [48].

Conclusions

A final answer to the role of HWP in the scope of REDD+ can only be found if the framework for CO₂ considerations is clearly defined. If one confines any observations to the forest carbon stock, any utilization will result in carbon loss and CO₂ emissions. Where the focus is on the global carbon cycle, shifts between carbon pools and the resulting change of their sizes are considered. Under these conditions the utilization of timber is a mere shift within the system, while any utilization of fossil fuels will result in an increase of the total amount of carbon in the system. The negative effects of increasing atmospheric carbon are widely known. Thus REDD+ will have a positive contribution to emission reductions only, if on one hand the harvested timber is used to substitute emissions from fossil fuels, and, on the other hand, the time lag between reductions of the forest carbon stock due to logging and the release of the respective carbon to the atmosphere can be extended in time, in a way that the remaining forest stock has enough time to compensate for carbon losses by carbon sequestration due to forest growth.

Under the scenario considering all harvested timber is used as wood fuel, CO₂ emissions of timber exceed the corresponding emissions of the selected non-renewable energy sources. This implies that the energy substitution effects associated with the harvested wood products by the direct energetic use of timber does not compensate for the loss in forest carbon stock.

This poses a particular problem in forests where the procurement of wood fuel is the driving factor of forest degradation and deforestation. As 1343 Mio m³ or 80 % of the global timber harvest in 2011 was utilized for energy [9] the problem is particularly clear. The utilization of harvested wood as well as the improvement of harvesting systems play a decisive role in the carbon dynamics in the entire lifecycle of forest carbon. In regard to the material substitution effects associated with the HWPs, the study shows potentials to increase the climate change mitigation benefits by reducing logging residues and through the increase in displacement factors driven by innovative wood technologies, and promoting and sophisticated use of harvested wood products.

Wherever forests are deforested and converted to other land-use the incidental growing stock needs to be utilized. In Africa and South America alone deforestation involves an estimated growing stock of almost 500 Mio m³.

The analysis of forestry contribution to climate change mitigation renders accounting for the essential role of HWPs is necessary [12]. Holistic and integrative approaches combining the reduction of emissions from logging, efficiency in biomass use as well as the efficient

use of HWPs are to be implemented as policy measures. This renders a systemic approach necessary that links emissions from timber extraction in the agriculture, forest and land-use sector (AFOLU) with emission savings in the energy sector.

A report published by the Grantham Research Institute on Climate Change and the Environment, and ESRC Centre for Climate Change Economics and Policy at London School of Economics and Political Science concluded that there has been progress compared with hypothetical 'business as usual' global emissions pathways [49]. However a huge 'gigatonne gap' of 12 to 14 GtCO₂e between the emissions pathway that would result from current ambitions and plans, including those goals outlined by the submitted Intended Nationally Determined Contributions (INDCs), and emission pathway that is consistent with a reasonable chance of achieving the planetary goal of staying below 2 °C temperature rise above pre-industrial levels [49, 50]. Increasing urban population, particularly in emerging economies and world's most populous countries such as China and India, has created additional boost in annual global energy and infrastructure demand. In the contexts, energy substitution and material substitution effects associated with harvested wood products offer cleaner, safer and renewable energy source, and could be considered as an element of INDCs, and nationally appropriate mitigation actions.

Methods

For our study we do not consider the problem of appropriate national accounting rules and reporting. Instead we use an emission balance approach, in which we extend the current scope of REDD+ and study by means of a scenario analysis (i) the reduction of forest C-stocks by logging residues, (ii) the transfer of carbon from the forest to the HWPs C-pool, and (iii) emission reductions by the production and use of timber as a replacement for energy-intensive materials and non-renewable energy sources. One solid cubic meter (m³) of wood is used as a standard unit for the analyses. As wood density is decisive for the further use of harvested timber, we included three different wood densities in the analyses, i.e. 500, 750 and 1000 kg/m³. These figures take into account the differences in wood densities found in tropical tree species and regions and reflect broad density classes. However, different forest with different species has a different capacity to store carbon and to increase carbon sequestration [51].

Scenario analyses

Based on the assumptions presented above we developed three scenarios that quantify the carbon offsets by using wood for energy or as HWP. Emissions and mitigation

potentials for both, the forest and timber sector are analyzed. Based on the standard unit of 1 m^3 the substitution effects compared to natural gas, lignite, and residual fuel are presented for the three selected wood densities (i.e. 500, 750 and 1000 kg/m^3). In addition to the extracted timber, the volume of logging residuals is considered as well. Logging residuals remain in the forest and result in emissions due to decay.

Values for logging and mills residues, emissions for energetic use, and displacement factor were taken from the literatures presented in the “Background” section of this paper.

Scenario 1. wood fuel

In scenario 1 the extracted timber is solely used for energy (Fig. 2). This represents a typical situation where harvesting of wood fuel leads to forest degradation. Wood fuels are still a major source of energy for people in Africa and Subtropical Asia, and wood fuel harvesting is the most important cause of forest degradation in African countries [52]. Wood fuel is typically showing smaller dimensions than logs for timber production and is associated with lower destruction by felling and skidding. Therefore we implement two sub-scenarios: in sub-scenario 1a, all biomass removed from the forest carbon stock is utilized for energy, and in sub-scenario 1b, logging losses are of the same amount as the extracted timber.

Scenario 2. harvested wood products

Scenario 2 focuses on the use of the extracted timber for construction timber as an example for HWPs

(Fig. 3). Potential emission reductions are driven by the amount of logging and mill residuals, the displacement factor for HWPs, and the proportion of timber in HWPs that is used for energy at the end of the lifecycle of the HWP (Table 2). We implemented two conceptual structures of assumptions for the scenario analysis. A conservative approach is underlying sub-scenario 2a. This low efficiency scenario reflects a reserved attitude towards the potential emission reductions. Logging and mill residues are comparably large, no energetic use is assumed for mill residues and HWPs at the end of their lifecycle, and the displacement factor is low (Table 5). Sub-scenario 2b anticipates a more efficient use of timber. Reduced impact logging results in logging residues that are two times the amount of the extracted timber, mill residues amount to 40 % of the processed timber and are used for energy, 60 % of the timber in HWPs is used for energy at the end of the lifecycle, and the displacement factor is set to 2.1 (Table 6). We choose the two sub-scenarios to give insight in the range of emission reductions that is likely in the context of developing countries.

Sensitivity analysis

Sensitivity analysis is an approach to assess the influence of the variance of input variables on the variance of the output variable [53]. The objective is to describe the influence of individual input variables on the resulting output. In a partial sensitivity analysis one input variable is selected and its values are changed while holding the values of the other input variables constant. The procedure is repeated for each input variable. We performed

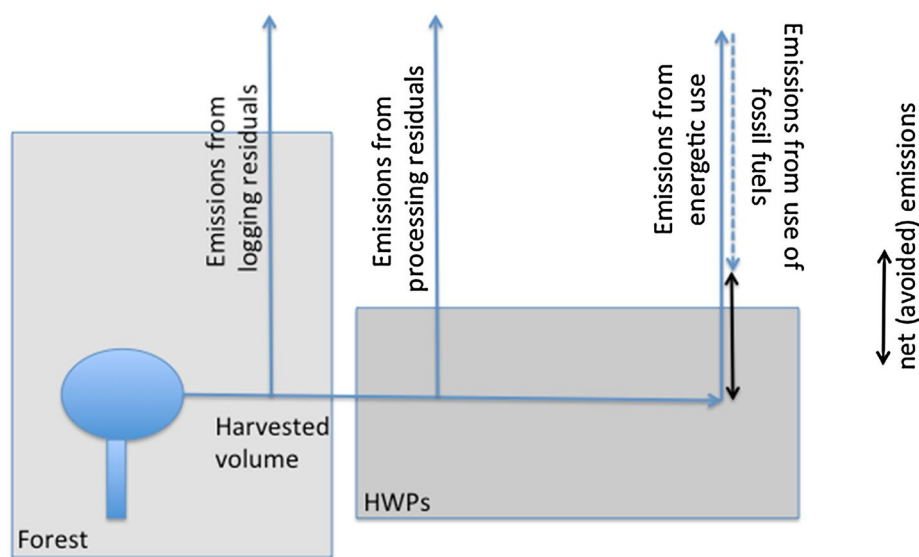
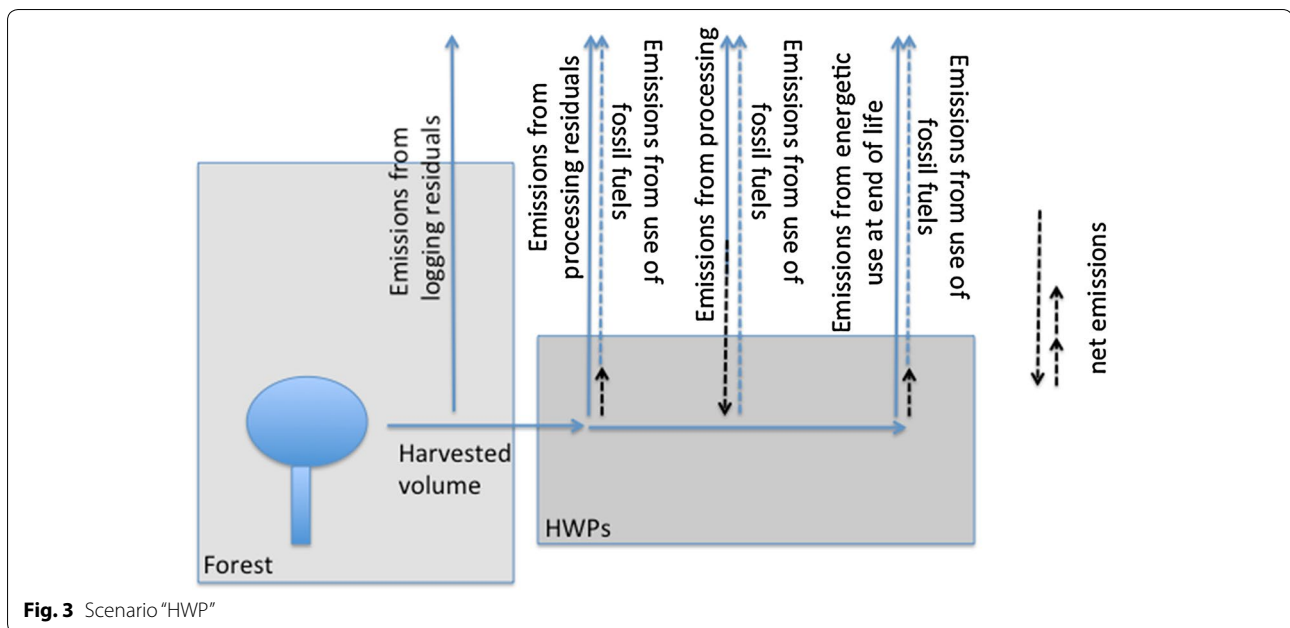


Fig. 2 Scenario “woodfuel”



a partial sensitivity analysis using the input variables (1) logging residuals, (2) displacement factor, (3) energy from logging residuals, (4) energy from HWP's, and (5) type of fossil fuel for substitution minor and studied their effect on CO₂ emissions. The ranges used for the individual input variables are given in Table 7.

Authors' contributions

TG and MK carried out the modeling/scenario analysis and prepared the manuscript. PRN helped TG and MK for scenario analysis and writing the manuscript. All authors have read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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The substitution effect of harvested wood products from tropical timber producer countries

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Abstract

Background:

Harvested Wood Products (HWPs) may contribute to reaching net-zero (Green House Gas) GHG emissions by sequestering atmospheric CO₂ and lowering emissions in manufacturing processes in comparison to functionally comparable items. The relevant mitigating impacts for HWPs produced from wood harvesting in tropical and subtropical forests have been inadequately examined, even though tropical nations are anticipated to contribute 12% of the global timber output by 2050 and that more than 40% of the world's 4 billion hectares of forests are in tropical regions, encompassing 1.73 billion hectares, or about half of the tropical land area. Here, we examine the effect of HWPs produced by tropical nations and their significance in terms of lowering atmospheric CO₂ concentrations.

Results:

The carbon content of HWP was determined by calculating the annual output of the three essential HWP commodities: sawnwood, wood-based panels, and paper and paperboard products based on data provided by FAO (source). Southeast Asia and the Pacific Islands accounted for 61.6% of the global HWP production in 2018, followed by Latin America (34.6%) and Africa (3.6%).

Wood production annually added the inflow to the HWP pool by 28 MtC, contributing to an annual carbon sink of 35.61 MtCO₂ y⁻¹

Southeast Asia and the Pacific led the average carbon stock in HWP during 1990-2017, with 281 Mt C y⁻¹ (53.43%), followed by Latin America with 219 Mt C y⁻¹ (41.86%) and Africa with 24 Mt C y⁻¹ (4.71%). In the reference period, Southeast Asia annually provides 21,76 MtCO₂ to the sink, followed by Latin America with 12,82 MtCO₂ and Africa with 1.01 MtCO₂.

In 1961, the net potential effect of harvested wood products ranged from 624 Mt CO₂eq with a low displacement factor to 3928 Mt CO₂eq with a high displacement factor and from 1605

Mt CO₂eq with a low displacement factor to 9953 Mt CO₂eq with a high displacement factor in 2017.

Conclusions:

In mitigating climate change, tropical forests play a multifaceted function. Due to deforestation and forest degradation, they are a significant source for global CO₂ emissions. For sustainably managed tropical forest, the contribution to climate change mitigation must consider the entire life cycle of wood. The energy-substitution effects of harvested wood products and other renewable energy sources such as solar and wind offer prospects for reaching net-zero emissions by the energy transition.

Our findings indicate that the mitigating effect of wood consumption cannot be disregarded when making policy decisions and seeking trade-offs between competing forest management objectives. Instead, an effective mitigation approach needs a comprehensive understanding of the possible carbon stock changes in the pool of harvested wood products and the replacement impact.

Keywords:

HWP, Tropical Forest producers, Displacement factor, Emission reductions, carbon, sustainable forest management, tropical forest, carbon inflow.

Background

With the Paris Agreement, 196 parties have committed to keeping global warming at 1.5 to 2 degrees Celsius above pre-industrial levels. The measures also cover activities to maintain and improve the sinks and reservoirs of greenhouse gases, including forests (Article 5, Paris Agreement). Furthermore, the European Union has formulated a long-term strategy to confirm Europe's commitment to lead in global climate action and presented a vision of achieving net-zero greenhouse gas (GHG) emissions by 2050. This vision includes the compensation of unavoidable residual emissions, by either technical (Carbon Capture and Storage, CSS) or nature based solutions (1,2). Beside peatlands, forests are considered as a leading example for supporting nature-based solutions to combat climate change. Forests remove CO₂ from the atmosphere through photosynthesis and convert it into C, which is stored in. After timber harvests a considerable amount of carbon remains stored in harvested wood products (HWPs) for a time span that varies depending on the type of HWPs between months and decades (3). According to Johnston & Radeloff, (2019) the global HWP pool was a net annual sink of 335 Mt of CO₂e in 2015 and represents less than 1% of total annual GHG emissions.

HWPs are not only a storage of C, but also contribute to the reduction of emissions, since the manufacture of wood products is generally associated with substantially lower emissions than manufacturing functionally equivalent products from non-renewable resources, such as steel, aluminum, or cement. HWPs thus make a dual contribution to achieving net-zero GHG emissions: (1) as a sink for atmospheric CO₂ and (2) by reducing emissions in manufacturing processes compared to functionally equivalent products. In general, the use of HWPs produces lower emissions than functionally equivalent products. Life cycle analyses are used to quantify the emissions generated in the manufacturing process. The decisive factor here is the energy mix used for producing the energy used in the production process.

The Intergovernmental Panel on Climate Change (IPCC) provides guidance for including HWPs in national Greenhouse Gas (GHG) emission reports (5,6). However, only the change

in the C pool of HWPs is considered in national accounting. The emission reductions resulting from the use of HWPs are mainly attributed to the energy sector. To assess the overall contribution of HWPs to achieving net-zero emissions, it is necessary to consider both the storage and the substitution effect.

The contribution of the forest-wood chain to mitigating climate change has been widely studied. Geographically, the studies concentrate on European countries (7–13), the US and Canada (14,15), Japan (16–18), China and Taiwan (19–22). The corresponding mitigation effects for HWPs derived from timber harvesting in tropical and subtropical forests have been poorly studied, even though tropical countries by 2050 projected to contribute to 12% of the global timber production.(23)

More than 40 % of the world's 4 billion hectares of forests are in tropical regions, covering 1.73 billion hectares, corresponding to nearly half of the tropical land area. However, since 1990 the world has lost 420 million ha of forest due to land-use change and other non-sustainable land-use practices. Most of the forest area loss occurred in tropical forests of Africa, followed by South America. As a result, the global forest carbon stock decreased from 668 Gt C in 1990 to 662 Gt C in 2020 (24). Between 2005 to 2010 an estimated area of 2.2 billion hectares of tropical forest are subject to forest degradation with an estimated emission of 2.1 billion tons of carbon, of which 53% are due to timber harvests (25). In sustainably managed boreal and temperate forests, emissions from timber harvests are offset by the storage and mitigation capacity of wood products. Here we investigate to what extent this also applies to tropical and subtropical forests and what conclusions can be drawn for forest management from the perspective of reducing atmospheric CO₂ concentrations.

Results

The trend in the production of the three commodities under the study.

The carbon content of HWP was calculated on the annual basis production of three primary HWP commodities of Sawnwood, wood-based panels, and paper and paperboard products. Sawnwood dominated HWP production in early 1961 with an 87.73 % share. It continuously increased until the year 1990 when the production of Sawnwood reached approximately 65 million m³. After 1990, the production of Sawnwood was decreased, and only in 2006 did it get its peak temporarily. By 2018, the production of Sawnwood production is substantially reduced to about 49 million m³, i.e., approximately 12 % of global Sawnwood production.

The Wood-based Panel production has continuously increased until 2004, and the increasing rate has slightly slowed down after the year 2004. The rising trend was substantial until 1985. The production, however, expanded from 1 million m³ in 1961 to 34 million m³ in 2018. By 2018, Wood-based Panel shares 25% of the total output of 3 primary HWP semi-finished products.

Figure 1 shows a steady increase in the production of Paper and Paperboard in the last twenty years. Only produced as much as 1,7 million tons in 1961, the annual production reached 57,6 million in 2018. Representing a minor proportion of the total production of the three commodities in 1961, the yearly production of Paper and Paperboard took over the dominance of Sawnwood with a share of 40 percent of the total production of the three by the year 2004 until 2018.

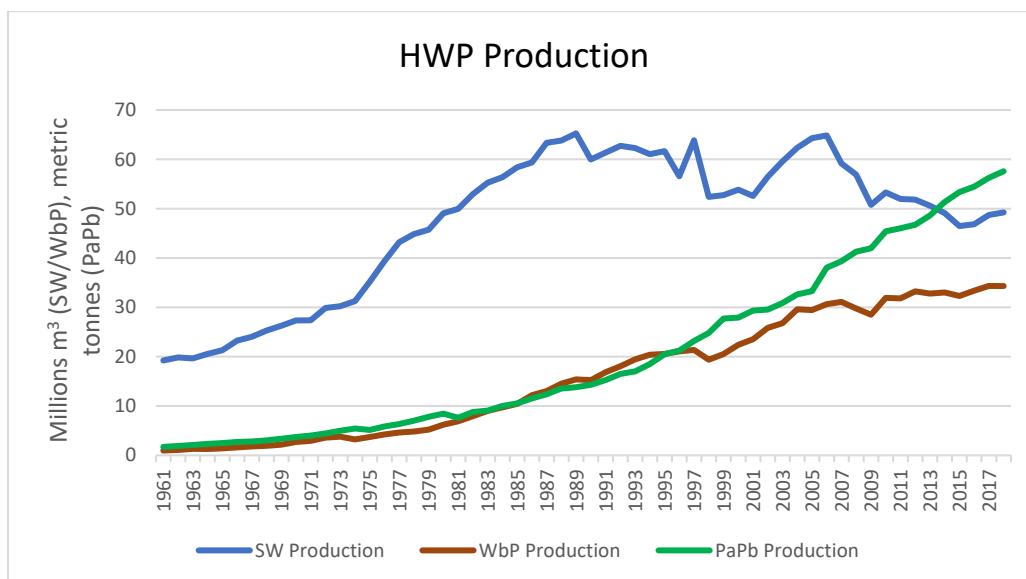


Figure 1. The Historical trend production of (i)Sawnwood, (ii) Wood-based Panel, and (iii)Paper and Paperboard in the continents- Southeast Asia and Pacific Islands (SEAP), Latin America (LAM), and Africa (AFR). The data are taken from the FAOSTAT-Forestry database.

Southeast Asia and Pacific Island share 61,6 % of total HWP production in 2018, followed by Latin America (34,6%) and Africa (3,7%). The dominance of Southeast Asia and Pacific Island started in 1980, and though there was a sharp decline in 1988, SEAP continued to lead the production share until 2018. Africa steadily share the lowest production for all those three products over time. The production history of the three commodities in three continents is presented in Figure 2.

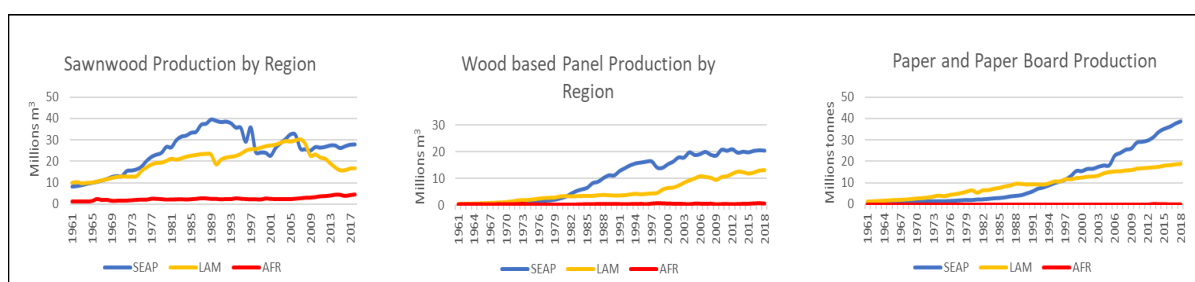


Figure 2. The Historical production of Sawnwood, Wood-based Panel, and Paper and Paper Board by three different continents- Southeast Asia and Pacific Islands (SEAP), Latin America (LAM), and Africa (AFR)

Carbon dynamic of Harvested Wood Products

The carbon inflow shows additional carbon to the HWP pool. Figure 4 depicts the carbon inflow to the HWP pool. Overall, the carbon inflow to the HWP pool via sawn wood decreased between 1980 and 2018, though periodic variations are noticeable. For example, the inflow of the Sawnwood pool was reduced by 1980, and it increased back in 1997 and 2006. The Sawnwood inflow started to decline steeply after the year 2006. The inflows of Wood-based Panels and Paper and Paperboard, on the other hand, have been steadily increased for the entire period. Compared to the wood-based Panel, Paper and Paperboard flow increased remarkably and profoundly rise in stock in 2017. After taking over the inflow

of Wood-based Panels in 1997, Paper and Paperboard continuously increased and overtook the dominance of Sawwood from 2012 onward.

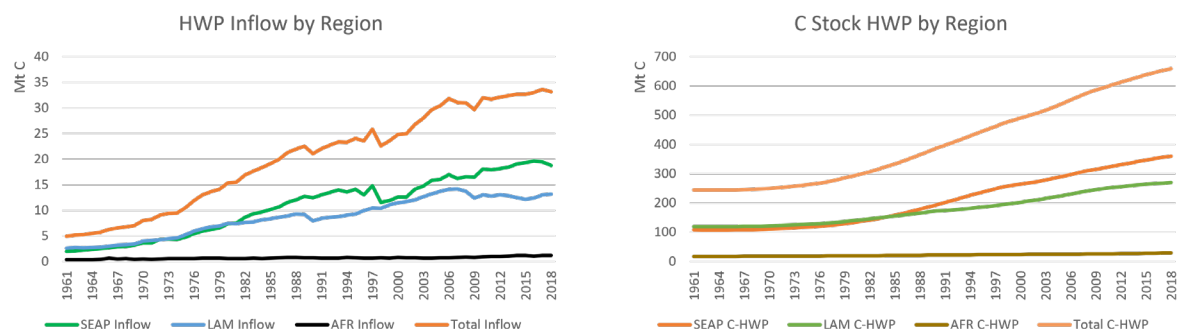


Figure 3. Inflow, HWP C-Stock, by region and in total.

Following the production approach, the total annual carbon inflow by 2017 is 33,6 Mt, consisting of 10.85 Mt of Sawwood (32 %), 8.98 Mt of Wood-based Panel (27%), and 13.77 Mt of Paper and Paperboard (41%). Southeast Asia dominates HWP production and carbon inflow by 58%, followed by Latin America 38.6% and Africa 3.46%. The annual inflow over from 1961 to 2018 is 20 Mt.

The carbon inflow influences the HWP stock. Early production from 1961 until 1981 contributed to an adverse change in stock and, from that point, started to contribute positively. By commodities, Wood-based Panel contributes mainly to this positive trend followed by Paper and Paperboard. Sawwood inflow provides a positive impact in the period of 1982-1998 and 2001-2006, and in the recent year continues the negative direction.

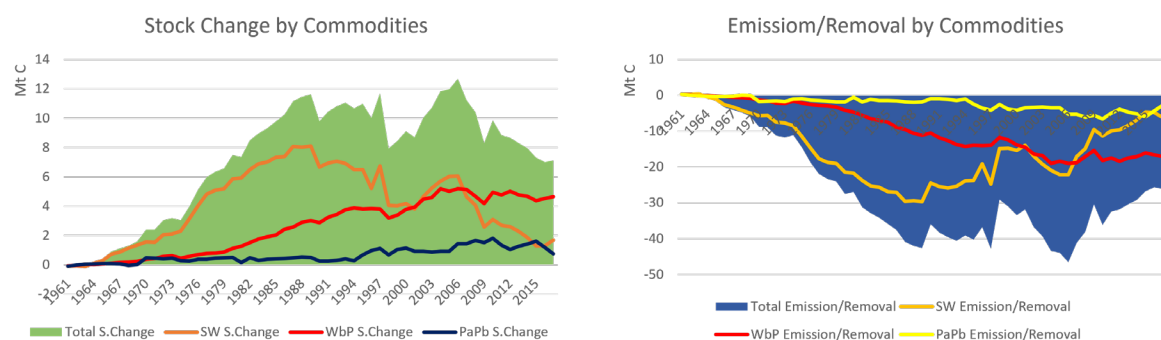


Figure 4. Stock change and carbon removal by commodities

We calculate the CO₂ emission or removal resulting from HWP production for individual HWP. From 1961 until 2017, HWP produced from those 33 tropical countries contributed to the total of 1521 Mt CO₂ eq sink/removal, which equals 26.7 Mt CO₂ eq year⁻¹. The above zero lines in emission/removal are emission, and below the line is removal/sink. HWP production emitted the atmosphere in 1961 until 1963. From 1964 until 2017, HWP contributes to carbon sink an average of 28.21 Mt CO₂ year⁻¹. Wood-based Panel mainly contributes to this increase. In 2017, the wood-based Panel contributed to 18 Mt CO₂ eq. (see Figure 4. Stock change and carbon removal by commodities)

Southeast Asia contributed mainly to the emission by 1961 with around 19 Mt of CO₂ and started to contribute to removal by 1980. Latin America contributed to the removal/sink of about 2.4 Mt CO₂ in 1961 and continued until 2017. While for Africa, the removal was as high as 0.06 Mt in early 1961. Indonesia, India, and Malaysia are the three biggest emitter countries, while, Mexico, Brazil, and Thailand are among the three most significant contributors to removal/sink (see Figure 5 and Figure 7)

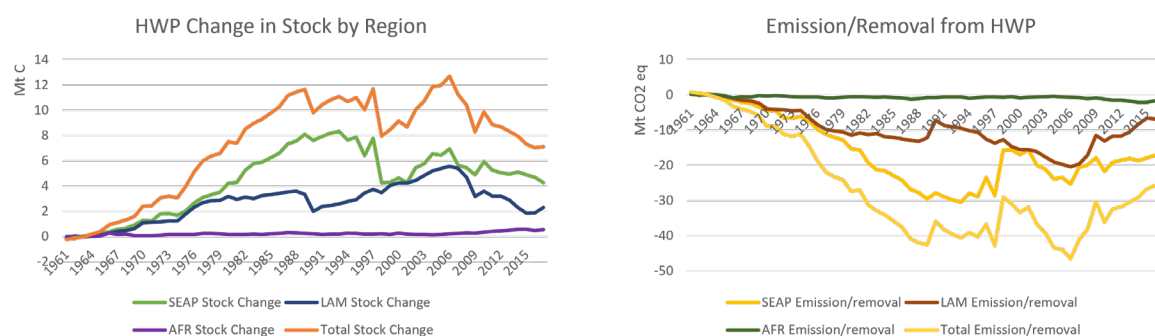


Figure 5. Emission or removal from different continents

Substitution Effect

The volume of annual carbon emissions reduction due to material substitution is presented in Figure 8, while Figure 9 shows more detail of countries and continents.

Assuming that wood's substitution is mainly material substitution for cement, concrete, or steel for construction, we exclude the HWP of Paper and Paper-based in this calculation. For the three scenarios with displacement factor of 0.7, 2.0, and 4.4 we assess the potential emission reduction by HWP produced. The average potential yearly impact of HWP substitution from 1961 to 2017 is ranges from 998.60 Mt to 6276.93 Mt with the middle range of 2,853 Mt CO₂ eq year⁻¹. Figure 8 present the potential carbon of substitution effect with 3 scenario levels and net CO₂ sink potential for substitution. For example, in 2017, the net sink from the substitution effect ranges from 1,579 Mt CO₂ eq (DF= 0.7) to 9927 Mt CO₂eq (DF=4.4), with the middle range of 4,512 Mt CO₂eq (DF=2.0).

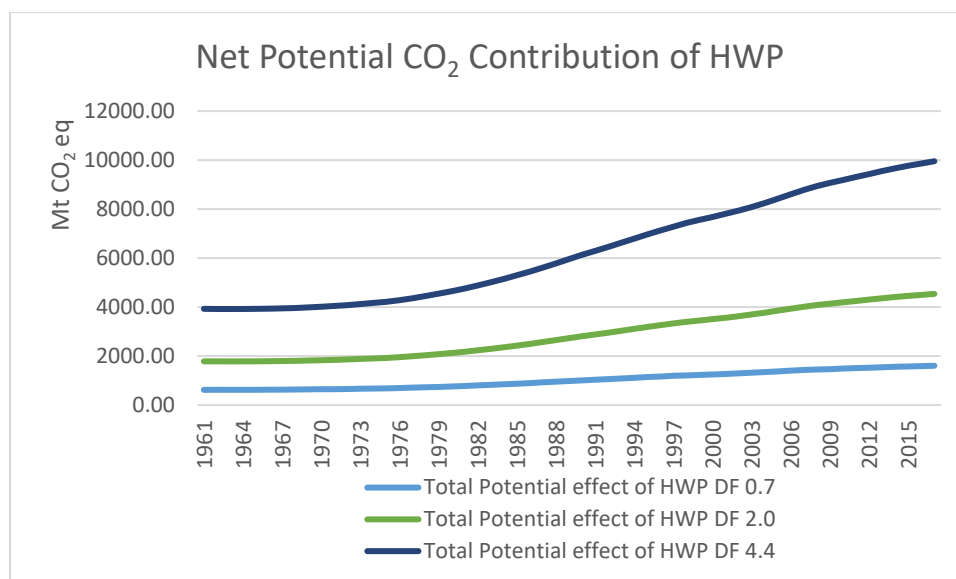


Figure 6. Potential and net CO₂ effect of Substitution in Mt CO₂ eq.

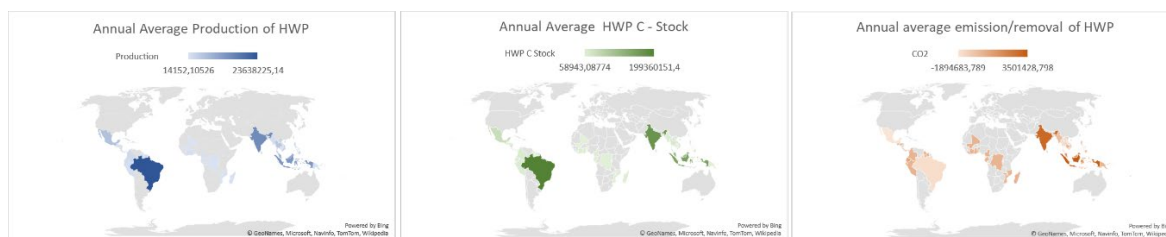


Figure 7. Average annual of Harvested wood Production, C-Stock and Emission/removal (DF=1.0) in Tropical Timber Producer Countries from 1961-2017

Total Potential Contribution of HWP

Combining the potential removal/emission from the harvested wood product with the potential substitution in different scenario, we find the net potential effect of harvested wood product in year 1961 is range between 624 Mt CO₂eq with low displacement factor to 3928 Mt CO₂eq in the high displacement factor scenario and 1605 Mt CO₂eq with low displacement factor to 9953 Mt CO₂eq in the high displacement factor in year 2017 as shown in the **Error! Reference source not found..** The total potential net contribution of HWP as a combination of carbon emission/removal from harvested wood carbon pool and potential contribution of substitution.

Discussion

The results show that the use of wood from tropical and temperate forests, as well as wood from managed boreal and temperate forests, can have a significant carbon effect. Nevertheless, some methodological aspects have to be considered when interpreting the results.

The estimations of carbon effects provided in this study are based on the HWP production data available at the FAOSTAT-Forestry database. The quality and reliability of individual country data may vary depending on the completeness and temporal actuality. In some cases, the data are also not based on comprehensive timber market statistics but are more in the nature of expert estimates. Nevertheless, the FAO data represent the most comprehensive collection of data on timber production in Asia, Africa and South America.

The tropical regions of Africa, Southeast Asia, and Latin America contribute almost 20 percent to the global harvested wood production (FAO, 2005). Since the 1960's the demand and production of harvested wood products from the tropical producer countries increased. The increase was mainly led by the substantial rise in the Paper and Paper board production and the steady growth of the Wood Panel production in Southeast Asia, and Latin America. In contrast, sawn timber production was more volatile. Compared to other regions, harvested wood production plays a minor role in Africa. In the period 1961 to 2017 Brazil, India, Indonesia, and Mexico are on average the largest producer countries. The change in production rates can be attributed to various factors. At the national level, economic development and the associated demand play a role, as do restrictions on timber harvesting in natural forests, the increasing proportion of forests in protected areas, and the expansion of plantation forestry. As wood products are also internationally traded commodities, events such as the global economic crisis between 2007 and 2009, the collapse of the Soviet Union, or timber trade regulations in Europe, the US or Australia have an impact as well.

The FAO figures used in this study do not indicate the sources of the wood used for harvested wood production. These can be tropical hardwoods (typically from natural forests), plantation hardwoods (e.g. Eucalyptus, Acacia, Teak, Gmelina and sandalwood), and plantation softwoods (e.g. pines, cypress). While saw logs are mostly from tropical hardwoods, wood panels and paper and paper board are increasingly produced from plantations (23). Globally, the area of planted forests has increased from 172 million ha to 295 million ha, with 50% of this increase in Asia and 11% in South America, and

only 2% in Africa (24). A direct comparison of the production figures with the depletion of natural tropical forests is therefore possible with caution at most for sawlogs.

In the absence of data on the carbon stock of the initial HWP pool, the starting points for the three commodity classes had to be estimated. For this purpose, the Tier 1 approach of IPCC was used, which is based on the average inflows of the first five years. This approach builds up the HWP-pool in the first three decades, so that the selected decay factor does not yet result in a regular outflow from the HWP-pool. It is not until the end of the 1980s that a realistic carbon content of the HWP pool can be assumed. This effect affects the Paper and Paperboard commodity class less, since the half-life here is only 2.5 years.

In contrast to North America and Europe, no reliable decay factors are available for HWPs from the tropics and subtropics. Differences are to be expected because, on the one hand, the durability of tropical timber is higher compared to temperate and boreal timber, and, on the other hand, differences in humidity and biotically induced decomposition agents influence the decay processes (26–28).

Table 1. Inflow, HWP Stock, Stock change, and Emission/removal of HWP from 1990-2017

Year	Inflow (Mt C)	Harvested Wood Stock (Mt C)	Stock change (Mt C)	Emission/removal (Mt CO ₂)
1990	21,07	387,67	9,80	-35,93
1991	22,02	397,47	10,44	-38,27
1992	22,73	407,91	10,81	-39,65
1993	23,34	418,72	11,07	-40,59
1994	23,30	429,79	10,68	-39,14
1995	24,02	440,47	10,98	-40,27
1996	23,57	451,45	10,02	-36,74
1997	25,82	461,47	11,69	-42,86
1998	22,59	473,16	7,94	-29,11
1999	23,58	481,10	8,45	-30,99
2000	24,80	489,55	9,12	-33,42
2001	24,92	498,67	8,69	-31,86
2002	26,79	507,36	10,03	-36,78
2003	28,00	517,39	10,71	-39,28
2004	29,70	528,10	11,85	-43,43
2005	30,41	539,94	11,98	-43,91
2006	31,80	551,92	12,69	-46,52
2007	31,10	564,61	11,24	-41,20
2008	31,02	575,84	10,40	-38,13
2009	29,66	586,24	8,29	-30,41
2010	31,98	594,54	9,85	-36,12
2011	31,69	604,39	8,83	-32,39
2012	32,13	613,22	8,67	-31,78
2013	32,35	621,89	8,30	-30,45
2014	32,64	630,19	7,96	-29,18
2015	32,67	638,15	7,30	-26,77
2016	33,01	645,45	7,01	-25,70
2017	33,61	652,46	7,11	-26,08
Average	27,87	525,33	9,71	-35,61

Table 1 shows the cut-off Figure from 1990-2017. As shown in Table 1 and Figure 8, the inflow is relatively increased, with 33.61 MtC in 2017 added to the HWP stock of 652 MtC and contributing to the sink of 26MtCO₂ eq. The average stock of HWP for this period is around 525.33 MtC with an annual inflow of 27.87 MtC, contributing to the annual sink/removal of 35 Mt CO₂eq y⁻¹. Using the year 1990-2017 as a reference, Southeast Asia and the Pacific dominated the average carbon stock in HWP with 281 Mt C y⁻¹ (53.43 %), followed by Latin America with 219 Mt C y⁻¹ (41.86%) and Africa with 24 Mt C y⁻¹ (4.71 %). On an annual basis, in the reference time, Southeast Asia contributes to the sink of 21.76 MtCO₂, followed by Latin America at 12.82 MtCO₂ and Africa at 1.01 MtCO₂. For 2000-2012 an annual HWP sink of 44.0 Mt CO₂ yr⁻¹ was estimated for European Union countries (11) , while an annual global HWP sink of 335 Mt CO₂eq y⁻¹ is reported for 2015 (4).

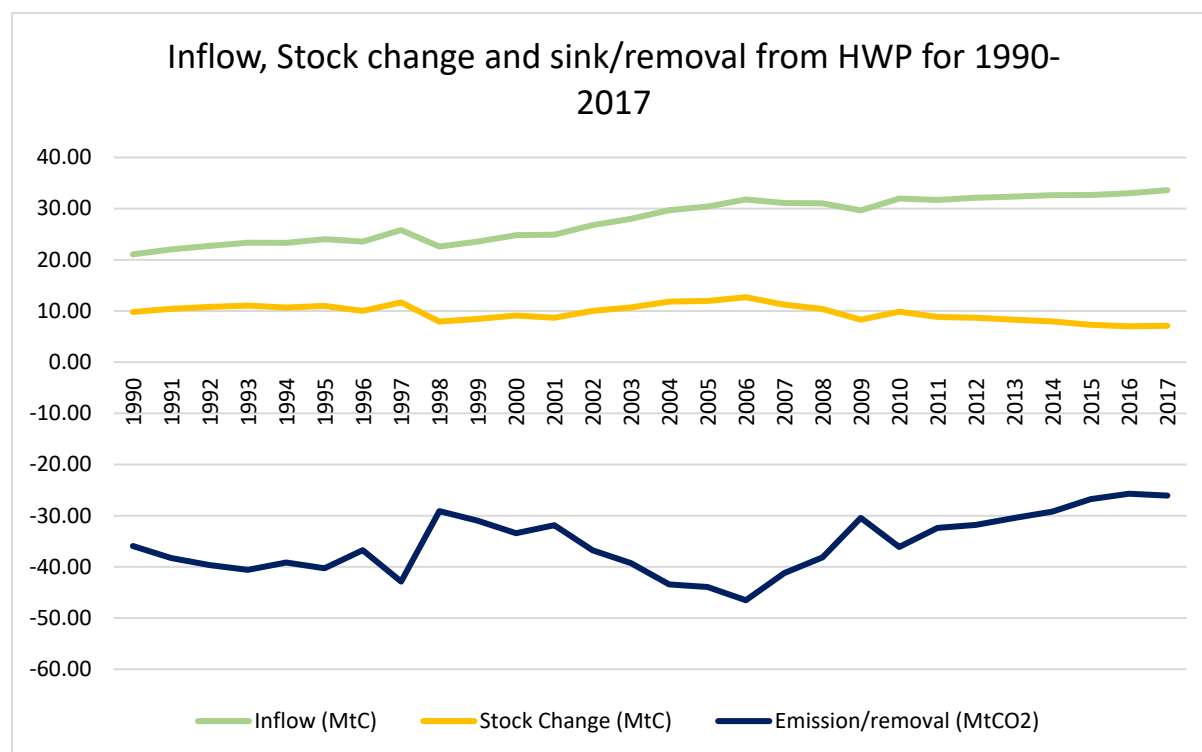


Figure 8. Inflow, Stock Change and Sink/Removal of HWP from 1990-2017

Displacement factors are determined by comprehensive life-cycle assessments. A decisive factor for the substitution effects are the emissions of the assumed energy mix. Since it is beyond the scope of the present study to establish the displacement factors corrected for the specific energy mix in the selected countries, we applied a scenario analysis to estimate the substitution effects. The displacement factors used were 0.7, 2.0 and 4.4. They provide a corridor within which the real substitution effects are likely to be located. For the three anticipated displacement factor we found an average annual emission reduction by HWPs between 998 Mt CO₂ eq y⁻¹ and 6278 Mt CO₂ eq y⁻¹. These emission reductions are mainly due to using HWPs for construction purposes. The results support the findings of other studies, which also show a significantly higher carbon effect due to substitution effects than to the increase in the HWP pool (8,29–32)

Conclusions

The role of tropical forests in climate change mitigation is complex. Carbon sequestration and emissions occur in different stages of forest stand development and beyond. Forests sequester atmospheric CO₂ by growth or regrowth and emit CO₂ to the atmosphere due to deforestation and the reduction of carbon density within standing forest. Recovery of the carbon by regrowth and ingrowth contribute considerably to carbon enhancement. Depending on the management of forest production regimes, such

as intensity of logging intervention or the use of reduced-impact logging in the tropics, studies show the ability of the logging area to recover within the management cycle (33–35).

The study suggests that timber harvesting can be seen as a transition of carbon from the forest carbon pool to the harvested wood products pool. The increasing wood production in use potentially contributes to a net reduction of CO₂ emissions. Domestic consumption will be more appropriate for this strategy when considering the emission from life cycle products. However, the increase in consumption will be only possible with the sustainability of forest management as HWP substitution is determined by the whole life cycle of the wood (Butarbutar et al., 2019). The holistic approach is required in quantifying carbon pools and flows in the forest sector, including the substitution effect. Therefore, it needs to be integrated into other forest-based accounting systems for a more integrative approach.

The contribution of HWP to the annual global carbon storage is relatively low. However, the HWP's potential to substitute energy-intensive materials and emissions-intensive energy sources, such as fossil fuel, exceeds the pooled effect of HWPs by orders of magnitude and is relatively untapped. Wood has been both a common and a historical choice for building construction. Hence, the need for just transition, as we move to a green economy-calling businesses to be leaders. At the same time, the rapid global urbanization trends, growing population, and consumer awareness yield many opportunities for implementing a low carbon economy. Cities and industries are at the forefront of climate action. We need to transform how we generate our energy, design our cities, and manage our lands, including forest lands. The world communities and the emerging actors have opportunities to use biodegradable, renewable, and recyclable organic products, i.e., wood, which presents numerous other “built-in” advantages; and to reduce the hard-to-abate emissions, such as emissions from cement and steel production. In tandem with other renewable energy sources such as solar and wind, the energy-substitution effects presented by the harvested wood products provide opportunities for the energy transition.

We do not argue for considering the substitution effects of wood use in national GHG accounting. Instead, the energy sector implicitly accounts for the mitigation effects of wood use. Our results show, however, that the mitigation effect of the use of wood must not be ignored when making policy decisions and looking for trade-offs between different interests in the optimal treatment of our forests. A better understanding of potential carbon stock changes in the Harvested Wood Products pool and the substitution effect is essential to support an effective mitigation strategy. However, a more comprehensive approach is required that considers the entire forest-wood chain. A decrease of forest carbon stocks by timber harvesting has to be balanced by substitution and storage effects resulting from timber utilization. There are still many unknowns in this impact chain. To name just a few: Re-growth of forests after use interventions, share of durable products in wood use, decay rates, change in displacement factors due to changes in energy mix towards renewables, recovery rates in mill processing. In addition to the consideration of the carbon balance, factors such as biodiversity, economic development and social welfare must not be neglected. Finally, the CO₂-benefits of HWPs do not offset the emissions caused by tropical deforestation.

Methods

Data

This study uses harvested wood data from the FAOSTAT-Forestry database (Food and Agriculture Organization of the United Nations, 2020). The data base includes statistics on the production, import, and export of different categories of harvested wood products. Following the 2019 IPCC refinement (6), three commodity classes of semi-finished wood products were used for calculations: (i) Sawnwood, (ii) wood-based Panel, and (iii) paper and paperboard. To compute the fraction of wood products, we use the FAOSTAT data of industrial roundwood, wood-pulp, and recovered-paper. Table 2 shows the tropical timber producer countries included in the study.

Table 2. List of Countries involved in the study by region.

Africa	Southeast Asia and Pacific	Latin America
Benin	Cambodia	Brazil
Cameroon	Fiji	Colombia
The Central African Republic	India	Costa Rica
Congo	Indonesia	Ecuador
Côte d'Ivoire	Malaysia	Guatemala
The Democratic Republic of the Congo	Myanmar	Guyana
Gabon	Papua New Guinea	Honduras
Ghana	Philippines	Mexico
Liberia	Thailand	Panama
Madagascar	Vietnam	Peru
Mali		Suriname
Mozambique		Trinidad and Tobago
Togo		Venezuela (the Bolivian Republic of)

Estimating the HWP carbon content

The FAO database includes annual values for raw wood and wood products beginning in 1961. The wood products are divided into different classes, which were combined for the calculation to commodity classes. Following the IPCC guidelines Tier 1 approach (6), we use the three commodity classes (1) Sawnwood, (2) wood-based panels, and (3) paper and paperboard. The definitions of these commodities are as follows:

Sawnwood: Wood that has been produced from both domestic and imported roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness.

Wood-based panels: an aggregate comprising veneer sheets, plywood, particle board, and fiberboard.

Paper and paperboard: an aggregate category that represents the sum of graphic papers; sanitary and household papers; packaging materials and other paper and paperboard. It excludes manufactured paper products such as boxes, cartons, books and magazines, etc.

For further details on the definitions of the three categories we refer to <https://www.fao.org/forestry/statistics/80572/en/>. In the FAO database, the production data on sawlogs and wood-based panels produced is expressed in volume units (m³) and on paper products in weight units (t). To calculate the carbon content, these units must be converted. IPCC (2019) presents uniform carbon conversion factors (cf) of the three aggregated commodity classes for the estimation of the carbon stock of the HWP pool in use (IPCC 2014, Table 21.1). The three commodity classes have different retention times in the HWP pool. A constant decay rate (k) is assumed under Tier 1 for the rate at which a commodity class is removed from the HWP pool and is expressed as a half-life in years. The default half-lives of the three commodity classes are given by IPCC (2014, Table 12.3) and are shown in Table 3.

Table 3. Half-life values and emission factor of commodities (after IPCC, 2014)

Commodity	Half-live (years)	Conversion factor (Mg C/m ³)
Sawnwood (aggregate)	35	0.229
Wood-based panels (aggregate)	25	0.269
Paper and Paperboard (aggregate)	2	0.386

Following a circular economy approach a substantial amount of paper and paperboard is recovered after its original purpose. According to IPCC (2019) recovered paper includes in addition residues from paper and paperboard production. As only limited country data is available from FAOSTAT on recovered (37,38), we use the generic regional data following Holik, (2013). The respective recovered paper utilization rates are 69% for Asia, 51% for Europe, and 35% for North America.

Displacement Factor.

Substituting wood for energy intensive materials reduces GHG emissions (40–43) Displacement factors (DFs) relate the emission reduction when substituting a functionally equivalent non-wood product by a wood product to the carbon mass contained in the wood used. DFs are calculated as

$$DF = \frac{f_{NW} - f_W}{C_W}$$

where f_{NW} are GHG emissions from the use of non-wood and f_W those from the use of wood, both expressed in mass units of carbon equivalent, and C_W is the carbon mass content of the wood product. According to Sathre & Gustavsson (2009) DFs range from as low as -2.3 to as high as 15.0. The calculation of for the substitution effect requires detailed information on wood utilization which is not available for most selected countries. Therefore we use a scenario approach, which is based on the average DFs from existing studies (42) We use three scenarios applying values of DF=0.7 for a conservative scenario, DF= 4.4 for an optimistic scenario, and DF= 2.0 representing an intermediate scenario (Sathre & Gustavsson, 2009). As Paper and Paper Board commodities generally are not used for replacing non-wood materials, we restrict the calculation of substitution effects on sawnwood and wood-based panels.

Carbon stock change in HWP

The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) – hereafter referred to as 2019 IPCC refinement - provides different approaches for estimating CO₂ emissions and removals from HWPs. The different methods are related to the processes (i.e. changes of carbon stocks within defined HWP pools or quantifying CO₂ fluxes from and to the atmosphere from HWPs) and the system boundaries (i.e. consuming or producing countries) applied in the calculation. The resulting approaches are shown in Table 4.

Table 4. Approaches to estimating CO₂ emissions and removals arising from HWPs (after (43))

Approaches	Processes and boundaries
Stock change	Change in the HWP pool accounted for the consuming country
Production	Change in the HWP pool based on domestically produced stocks.
Stock change for HWP of domestic origin (SCAD)	Change of HWP pool based on domestically produced and consumed stocks
Atmospheric flow	Fluxes of CO ₂ to the atmosphere from HWP accounted for in the country where they occur
Simple decay	Carbon transfer from forest carbon pools to HWP pool is counted as emissions from HWP pool at the time of end-of-life of HWP in the producing country

Since the analyses shown here aim at a global consideration of the corresponding substitution and storage effects, it is irrelevant in which country the harvested wood is converted into HWPs and where the HWPs are consumed. Taking into account import and export commodities would unnecessarily complicate the calculations and would not result in different emissions and removals in the aggregate compared to a direct comparison of national production data. Therefore, a modified production approach is used. According to Sato & Nojiri (2019) the production approach is a trade neutral approach

and thus best suited for the current study. We extend the production approach by considering only the production of HWPs in a country, regardless of whether the timber is domestic origin or not.

Estimating emissions and removals

According to 2019 IPCC refinement (IPCC, 2019) the net change of the carbon stock in year i is calculated for each in commodity class l , $\Delta C_l(i)$. The total CO₂ emissions and removal from net changes of the carbon stock in HWP in use during the year i , $\Delta CO_{2TOTAL}(i)$, is obtained by the sum of the l individual $\Delta C_l(i)$. Since the unit of the $\Delta C_l(i)$ is C, a factor of 44/12 needs to be applied to obtain CO₂ values. $\Delta C_l(i)$ is calculated by reducing the HWP pool at the beginning of year $i+1$, $C_l(i+1)$, by the HWP pool at the beginning of year i , $C_l(i)$.

$$\Delta C_l(i) = C_l(i+1) - C_l(i).$$

Therefore, a positive value represents an increase in the HWP pool during the year under consideration, i.e. a removal. Since, according to the IPCC conventions, removals are designated with a negative sign, the calculated difference must be denoted with a negative sign. Intuitively, it would be simpler to calculate $\Delta C_l(i)$ as $\Delta C_l(i) = C_l(i) - C_l(i+1)$, since this would directly result in the IPCC-compliant negative sign for removals. IPCC (2017), Equation 12.1 presents the respective calculations:

$$\Delta CO_{2TOTAL}(i) = -\frac{44}{12} * \sum_{l=1}^n \Delta C_l(i) \quad \text{IPCC (2019), equation 12.1.}$$

where l is an index number of a semi-finished HWP commodity class and n is the number of selected commodity classes of the semi-finished HWP commodities. Here $n=3$, as the three aggregated commodity classes sawnwood, wood-based panels, and paper and paperboard are considered.

The carbon stock in the particular HWP commodity class l at the beginning of the year $i+1$, $C_l(i+1)$, is based on the respective carbon stock at the beginning of year i , $C_l(i)$, the first order decay (FOD) and the carbon inflow to commodity class l in year i , $Inflow_l(i)$.

$$C_l(i+1) = e^{-k} * C_l(i) + \left[\frac{(1-e^{-k})}{k} \right] * Inflow_l(i) \quad \text{IPCC (2019), equation 12.2}$$

Some authors suggest that a Chi-square distribution is more accurate than the exponential distribution to describe decay (44–46)). To be consistent with the IPCC guidelines, we use the decay function following an exponential distribution function (IPCC, 2019, eq. 12.2). IPCC (2019) omits in equation 12.2 an index for commodity classes for the decay constant k . However, k must still be determined separately for each respective commodity class l .

According to IPCC (2019), equation 12.3 $Inflow_l(i)$ depends on the approach chosen for system boundaries, i.e. carbon inflow from domestic consumption or carbon inflow from the production from domestic harvests. Here inflow is the total domestic production of HWPs, regardless of the origin of the timber. The FOD for HWP commodity class l is taken into account by calculating a decay constant, k_l , for each commodity class l over the corresponding half-life, H_l .

$$k_l = \frac{\ln(2)}{H_l} \quad \text{after IPCC (2019)}$$

Following IPCC 2019, eq. 12.7, the annual carbon inflow from the production to the carbon stock of each HWP commodity class l , $Inflow_l(i)$, is calculated by

$$Inflow_{PAI}(i) = HWP_{DP_l}(i) * cf_l \quad \text{IPCC equation 12.7}$$

$$HWP_{DP_l}(i) = HWP_{P_l}(i) * f_R(i) \quad \text{IPCC equation 12.7}$$

where

cf_l = carbon conversion factor of commodity class l

$f_R(i)$ = Share of woody feedstock commodity class R (IRW, PULP or RecP) to produce the particular semi-finished HWP commodity class originating from domestic harvest in the year i

The FAO-statistics provide data on HWP for most countries since 1961. No data are available for the initial HWP-pool. The initial HWP-pool was estimated following the Tier 1 approach of IPCC (2019). As a proxy it is assumed that the HWP-pool at time 1 is in a steady state, i.e. $\Delta C(t_0)$ is 0. For each commodity class l the steady state HWP-carbon stock at time 0 is estimated by

$$C_l(t_0) = \frac{Inflow_{l_{average}}}{k} \quad \text{IPCC equation 12.4}$$

where the average inflow is calculated as the mean of the inflows of the first 5 years.

$$Inflow_{l_{average}} = \frac{\sum_{i=t_0}^{t_4} Inflow_l(i)}{5}$$

List of abbreviations

- HWP** - Harvested Wood Products
- GHG** - Greenhouse Gas
- CO₂** - Carbon Dioxide
- CSS** - Carbon Capture and Storage
- FAO** - Food and Agriculture Organization
- IPCC** - Intergovernmental Panel on Climate Change
- MtC** - Million Tons of Carbon
- MtCO₂** - Million Tons of Carbon Dioxide
- CO₂eq** - Carbon Dioxide Equivalent
- SCAD** - Stock Change for HWP of Domestic Origin

Declarations

Availability of data and materials

The data used for this study generated from FAOSTAT database

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TB carried out the study design and conduct data preparation and analysis. TB wrote and MK revised the manuscript. All authors have read and approved the final manuscript.

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Table 5. HWP carbon emission/removal, substitution effect and potential total contribution to the emission reduction

Year	Emission/Removal from HWP (Mt CO ₂ eq) (a)	Substitution effect of different scenario (Mt CO ₂ eq) (b)			Total Potential Net Contribution of HWP (Mt CO ₂ eq) (a+b)		
		DF 0.7	DF 2.0	DF 4.4	DF 0.7	DF 2.0	DF 4.4
1961	0,84	625,09	1785,98	3929,17	624,25	1785,14	3928,32
1962	0,41	624,41	1784,03	3924,86	624,00	1783,62	3924,45
1963	0,12	624,16	1783,31	3923,27	624,03	1783,18	3923,15
1964	-0,68	623,97	1782,78	3922,12	624,65	1783,46	3922,80
1965	-1,51	624,31	1783,75	3924,26	625,82	1785,26	3925,77
1966	-3,34	625,17	1786,20	3929,64	628,51	1789,54	3932,98
1967	-4,08	627,28	1792,22	3942,88	631,35	1796,30	3946,96
1968	-4,77	629,94	1799,83	3959,62	634,71	1804,60	3964,39
1969	-5,83	633,36	1809,59	3981,09	639,19	1815,42	3986,93
1970	-8,86	637,42	1821,20	4006,64	646,28	1830,06	4015,49
1971	-8,86	642,38	1835,37	4037,81	651,24	1844,23	4046,67
1972	-11,20	647,41	1849,74	4069,42	658,61	1860,94	4080,62
1973	-11,71	654,17	1869,06	4111,93	665,88	1880,77	4123,64
1974	-11,17	661,17	1889,05	4155,91	672,34	1900,22	4167,08
1975	-14,60	668,27	1909,35	4200,57	682,87	1923,95	4215,17
1976	-18,77	677,81	1936,60	4260,52	696,58	1955,37	4279,29
1977	-21,95	689,98	1971,37	4337,01	711,93	1993,31	4358,96
1978	-23,33	704,37	2012,48	4427,45	727,69	2035,81	4450,78
1979	-24,09	719,53	2055,79	4522,74	743,61	2079,88	4546,82
1980	-27,47	735,13	2100,37	4620,81	762,60	2127,84	4648,28
1981	-27,03	753,06	2151,60	4733,52	780,09	2178,63	4760,55
1982	-31,19	771,57	2204,50	4849,90	802,76	2235,69	4881,09
1983	-32,88	792,15	2263,28	4979,21	825,03	2296,16	5012,09
1984	-34,12	814,35	2326,71	5118,76	848,47	2360,83	5152,88
1985	-35,83	837,22	2392,07	5262,55	873,05	2427,89	5298,38
1986	-37,59	861,28	2460,81	5413,78	898,87	2498,39	5451,36
1987	-40,94	886,48	2532,80	5572,16	927,42	2573,74	5613,10
1988	-41,98	913,87	2611,06	5744,34	955,86	2653,05	5786,32
1989	-42,64	941,88	2691,09	5920,39	984,52	2733,72	5963,03
1990	-35,93	970,45	2772,72	6099,98	1006,38	2808,65	6135,91
1991	-38,27	994,95	2842,70	6253,94	1033,21	2880,97	6292,21
1992	-39,65	1021,06	2917,31	6418,08	1060,71	2956,96	6457,73
1993	-40,59	1048,03	2994,38	6587,63	1088,62	3034,97	6628,22
1994	-39,14	1075,42	3072,62	6759,75	1114,56	3111,76	6798,90
1995	-40,27	1102,06	3148,76	6927,26	1142,34	3189,03	6967,53
1996	-36,74	1128,52	3224,34	7093,56	1165,26	3261,09	7130,30
1997	-42,86	1151,76	3290,75	7239,65	1194,62	3333,61	7282,50
1998	-29,11	1178,86	3368,18	7410,00	1207,97	3397,29	7439,11
1999	-30,99	1197,49	3421,40	7527,07	1228,48	3452,39	7558,06
2000	-33,42	1216,49	3475,67	7646,48	1249,91	3509,10	7679,91
2001	-31,86	1236,94	3534,10	7775,02	1268,80	3565,96	7806,88

2002	-36,78	1256,83	3590,94	7900,07	1293,61	3627,72	7936,85
2003	-39,28	1280,21	3657,74	8047,02	1319,48	3697,01	8086,30
2004	-43,43	1305,44	3729,83	8205,62	1348,87	3773,26	8249,05
2005	-43,91	1333,43	3809,81	8381,58	1377,35	3853,72	8425,50
2006	-46,52	1361,78	3890,79	8559,74	1408,30	3937,31	8606,26
2007	-41,20	1390,63	3973,22	8741,08	1431,82	4014,42	8782,28
2008	-38,13	1415,77	4045,05	8899,11	1453,90	4083,18	8937,24
2009	-30,41	1438,17	4109,05	9039,90	1468,57	4139,45	9070,31
2010	-36,12	1455,57	4158,76	9149,28	1491,69	4194,89	9185,40
2011	-32,39	1476,22	4217,78	9279,11	1508,61	4250,17	9311,50
2012	-31,78	1495,42	4272,63	9399,78	1527,20	4304,41	9431,56
2013	-30,45	1514,99	4328,54	9522,78	1545,44	4358,99	9553,23
2014	-29,18	1533,06	4380,17	9636,38	1562,24	4409,36	9665,57
2015	-26,77	1549,84	4428,13	9741,88	1576,61	4454,89	9768,64
2016	-25,70	1564,41	4469,73	9833,42	1590,11	4495,44	9859,12
2017	-26,08	1579,35	4512,42	9927,33	1605,43	4538,50	9953,41

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How REDD+ and FLEGT-VPA processes are contributing towards SFM in Indonesia – the specialists' viewpoint

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SUMMARY

In an effort to reverse the trend of deforestation and forest degradation, several international initiatives have been attempted. Though promoted in different political arenas, Forest Law Enforcement, Governance and Trade (FLEGT) – Voluntary Partnership Agreement (VPA), and Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) share overlapping objectives of conservation of tropical forests. We explore specialists' viewpoint on FLEGT-VPA and REDD+ processes in Indonesia with reference to their contribution towards Sustainable Forest Management (SFM). The study shows that FLEGT-VPA and REDD+ regimes contribute towards SFM. While FLEGT-VPA improves enabling condition for SFM through governance reform, improved harvesting practices, and timber legality assurance system, REDD+ supports SFM through institutional strengthening, reforming policies and frameworks, mobilizing new and additional financial resources and increasing social and ecological resilience. We identified opportunities to achieve synergies between REDD+ and FLEGT-VPA by harmonizing their processes, tools, methodologies, technical assistance, capacity-building and funding mechanisms.

Keywords: sustainable forest management, REDD+, FLEGT-VPA, Indonesia, specialists' viewpoint

Comment les processus de la REDD+ et du FLEGT-VPA contribuent à la SFM en Indonésie-point de vue des spécialistes

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Dans un effort de pallier au courant de déforestation et de dégradation forestière, plusieurs initiatives internationales ont été tentées. Bien qu'étant promues dans différentes arènes politiques, la mise en action de la loi forestière, sa gestion et son commerce (FLEGT), l'accord de partenariat volontaire (VPA) et la réduction des émissions provenant de la déforestation et de la dégradation forestière dans les pays en voie de développement (REDD+) partagent tous des objectifs de conservation de la forêt tropicale qui se chevauchent. Nous explorons le point de vue des spécialistes sur les processus du FLEGT-VPA et de la REDD+ en Indonésie, en se référant à leur contribution à la gestion forestière durable (SFM). L'étude montre que les régimes du FLEGT-VPA et de la REDD+ contribuent à la SMF. Alors que le FLEGT-VPA améliore les conditions permettant la SMF, avec une réforme de la gestion, des pratiques de récolte améliorées et un système d'assurance de la légalité du bois ; la REDD+ soutient la SMF avec une fortification institutionnelle, des réformes de politique et de cadres, une mobilisation de ressources financières nouvelles et additionnelles, et un accroissement de la résilience sociale et écologique. Nous identifions des opportunités pour parvenir à une synergie entre la REDD+ et le FLEGT-VPA, en harmonisant leur processus, outils, méthodologies et leur assistance technique, ainsi que des mécanismes pour financer et construire leur capacité.

Cómo están contribuyendo los procesos REDD+ y AVA-FLEGT a la GFS en Indonesia – el punto de vista de los especialistas

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Son varias las iniciativas internacionales que se han probado en un esfuerzo por invertir la tendencia de la deforestación y la degradación de los bosques. Aunque se promueven en diferentes ámbitos políticos, los Acuerdos Voluntarios de Asociación (AVA) del plan de acción de la UE llamado Aplicación de Leyes, Gobernanza y Comercio Forestales (FLEGT, por sus siglas en inglés) y el programa de Reducción de las

Emisiones de la Deforestación y la Degradación de Bosques (REDD+) en los países en desarrollo comparten objetivos superpuestos de conservación de los bosques tropicales. El artículo explora el punto de vista de los especialistas sobre los procesos AVA-FLEGT y REDD+ en Indonesia en relación a su contribución a la Gestión Forestal Sostenible (GFS). El estudio muestra que los regímenes AVA-FLEGT y REDD+ contribuyen a la GFS. Mientras que el AVA-FLEGT mejora las condiciones propicias para la GFS mediante la reforma de la gobernanza, la mejora de las prácticas de aprovechamiento y el sistema de garantía de la legalidad de la madera, REDD+ apoya la GFS mediante el fortalecimiento institucional, la reforma de las políticas y los marcos, la movilización de recursos financieros nuevos y adicionales y el aumento de la resiliencia social y ecológica. En el artículo se identifican oportunidades para lograr sinergias entre REDD+ y AVA-FLEGT mediante la armonización de sus procesos, herramientas, metodologías y mecanismos de asistencia técnica, fomento de capacidades y financiación.

INTRODUCTION

Deforestation and forest degradation have been major issues in the international arena related to climate change. Between 2005 and 2010, deforestation accounted for up to 10% of the global man-made carbon dioxide (CO₂) emissions and annual forest degradation emissions of 2.1 billion tons of CO₂ across 74 developing countries (Pearson *et al.* 2017). Therefore, conserving forests and improving forest management practices can contribute significantly to climate change mitigation. In an effort to reverse the trend or to minimize the forest loss, concept of Sustainable Forest Management (SFM) has been put forward. SFM has been accepted by the international community as a framework for global forest management efforts under the Non-Legally Binding Instrument on all Types of Forests (NLBI) which was adopted at the seventh session of the United Nations Forum on Forests (UNFF) in 2007. The 11th session of the UNFF renamed the NLBI as 'UN Forest Instrument'.

Despite the significant policy outputs and progress in implementing SFM, the persisting high rate of deforestation and forest degradation shows that the central goal of the SFM has still not been achieved (Cosslett 2013). Approximately 250 million hectares of tropical forests have been cleared and converted, mostly for agricultural use, since the 1992 Rio Summit (ISU 2015, Neupane 2015). Every two seconds, across the world, an area of forest equivalent to size of a football field is clear-cut by illegal loggers (Goncalves *et al.* 2012). According to FAO's Forest Resource Assessment, annually 7.6 million hectares (ha) of forests are deforested and 12 million ha forests are degraded in the period of 2010–2015 (FAO 2015). Most of the deforestation and forest degradation are still occurring in tropical forests (FAO 2016), often in the most biodiverse regions of the world, such as Indonesia and Brazil (Vijay *et al.* 2016). Although recent data suggest a slightly declining trend, deforestation still continues in Indonesia at a steep pace (Korhonen-Kurki *et al.* 2017). In Sumatra and Kalimantan, the annual deforestation rates have been 2.7% and 1.3% respectively during the period 2000–2010 (Indrarto *et al.* 2012); and the country is the world's second-largest emitter of carbon from gross deforestation, peaking in 2012 at 0.362 Gt CO₂ per year before declining to 0.205 Gt CO₂ per year in 2013.

Since 2001, several initiatives have been attempted to address the deforestation and forest degradation. These initiatives include forest certification, Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan leading towards

a Voluntary Partnership Agreement (VPA) with the European Union (EU), Integrated Conservation and Development Projects, and Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) (Tacconi *et al.* 2004, Setiono and Husein 2005, Luttrell *et al.* 2011, Redford *et al.* 2013).

The EU's FLEGT Action Plan is a forest conservation and development intervention that aims to reduce illegal logging by improving forest governance and law enforcement, and promoting trade in legally produced timber (EC 2003). A central component of the initiatives is the bilateral VPA between the EU and a country exporting timber to the EU. Key elements of the VPA include (1) a Timber Legality Assurance System (TLAS) which verifies legality throughout the value chain- from tree felling to export of the finished products and issues verified legal timber products with 'FLEGT' licenses, (2) commitments to public disclosure of information and other improvements to forest governance, and (3) a framework for overseeing, monitoring and evaluating implementation of the VPA and its economic, social and environmental impacts (Overdevest and Zeitlin 2018).

During the 2007 United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties in Bali (COP13), the Parties confirmed the urgent need to take further action to reduce emissions from deforestation and forest degradation and adopted a work program. REDD+ has evolved as an important emissions reduction mechanism within the UNFCCC, especially in countries rich in tropical forest (Korhonen-Kurki *et al.* 2018). The program focuses on reducing greenhouse gas (GHG) emissions through financial incentives and other benefits to developing countries for carbon storage and reduced emissions from forest lands via different eligible activities.

FLEGT-VPA in Indonesia

In 2001 during Bali declaration, Indonesia and the United Kingdom signed a bilateral Memorandum of Understanding (MoU) to combat illegal logging (Overdevest and Zeitlin 2018). The multi-stakeholder review process initiated by the MoU produced the form of an auditable forest certification standard called *Sistem Verifikasi Legalitas Kayu* (SVLK). SVLK is a system assuring the sustainable management of forests and timber legality through SFM and timber legality certification and self-declaration of conformity. The SVLK later served as a basis for FLEGT-VPA negotiations with the EU (Overdevest and Zeitlin 2018).

In 2007, negotiations on VPA started between Indonesia and the EU. In 2011, the EU approved SVLK as the TLAS of Indonesia to be applied to prove the legality of Indonesian timber. In 2013, the negotiations on VPA were completed. The following year, Indonesia became the first Asian country to ratify a VPA. On November 2016, Indonesia began issuing FLEGT licenses. FLEGT-licensed products are considered to comply with the European Union Timber Regulation (EUTR) requirements. Indonesia supplies approximately a third of the EU's tropical timber imports by value (EU-Commission 2016).

Since the FLEGT licensing began, all Indonesian timber products need to be verified as being legal by the SVLK to export to EU and V-Legal document for any other market. The third party auditors called Conformity Assessment Bodies (CABs) accredited by the Indonesian national accreditation board (*Komite Akreditasi Nasional*, KAN) have been established to assess legal compliance. All forest operators are required to hire CABs to access the legality of their operations. The Licensing Authorities (LAs) are well-established for issuing FLEGT licenses. By the end of 2016, SVLK had certified more than 2700 companies operating as a timber industry and more than 22 million hectares of forests (JIC 2016). There are increasing numbers of large companies upstream and downstream of the supply chain that have obtained SVLK certification (Sucofindo 2018).

A Joint Implementation Committee (JIC) has been established which includes the representatives from government, civil society, the private sector and officials from the EU delegation. The JIC endorses and oversees implementation of the VPA and the FLEGT licensing scheme. The impact monitoring (IM) by civil society actors is recognized as an integral component of VPA to assess the compliance with SVLK's requirements. IM can submit complaints to CABs concerning irregularities in legality verification of the operators and to KAN concerning the operations of the CABs. In Indonesia, *Jaringan Pemantau Independen Kehutanan* (JPIK) is the main national network. In addition, three more IM networks have been established namely *Aliansi Pemantau Independen Kehutanan Sumatera*, *Alliance Against Forest Mafia*, and *Eyes of the Forests* (Sucofindo 2018).

The Ministry of Environment and Forestry (MoEF) has an operational online system (i.e., SIPUHH) in place for monitoring the pre-harvest inventories and movement of logs from the natural forests and plantations located in the forest zone up to the primary industries. However, there is no particular monitoring mechanism established for monitoring primary industries onwards. Therefore, Indonesia has committed to develop online integrated information management system (SI PHPL), which will enable data synchronization and controlling the timber movement throughout the supply chain from forest via timber depots and primary processing to the secondary/tertiary processing (Overdevest and Zeitlin 2018).

REDD+ in Indonesia

Since 2008, Indonesia has been engaged and committed to REDD+, with demonstration sites and numerous institutional

and regulatory changes (Korhonen-Kurki *et al.* 2017). In 2008, Indonesia published a Yellow Book - the multi-sectoral guide for Indonesian governmental agencies in integrating climate change into its overall National Development Plan. In 2009 at the Copenhagen Climate Change Conference, President Susilo Bambang Yudhoyono announced a target of 26% overall emissions reduction from business as usual independently by 2020, and by 41% with international assistance (Luttrell *et al.* 2014, Korhonen-Kurki *et al.* 2017). REDD+ is envisaged as a key component in realizing the commitment.

By 2009, Indonesia was the country with the largest number of REDD+ pilot activities globally (Wertz-Kanounnikoff and Kongphan-Apirak 2009). In May 2010, Indonesia and Norway signed a Letter of Intent (LoI) in relation to one billion USD pledge based on performance (Korhonen-Kurki *et al.* 2017). Several activities identified in the LoI are underway or have been completed. These include consultations concerning the design of a REDD+ National Strategy, the establishment of an independent agency for measurement, reporting and verification (MRV), a presidential decree for a moratorium on issuing new licenses for concessions on forestland, and the selection of a province for pilot implementation.

Since the inception of REDD+, several milestones have been achieved, for instance, establishment of a Forest Reference Emission Level (FREL), development of National Forest Monitoring System (NFMS) including MRV system, development and implementation of Indonesia Principal, Criteria, and Indicator of Safeguards (PRISAI) and Safeguards Information System (SIS), and accomplishment of Strategic Environment and Social Assessment (SESA) in several regions. A national registry system linking REDD+ financing, safeguards/benefit sharing mechanisms (BSMs), and REDD+ implementation is under preparation. The target of GHG emission reduction has been increased from 26% (Copenhagen pledge) to 29% (Nationally Determined Contribution (NDC) goal, unconditional) with the increase in the time frame from 2020 to 2030 (MoEF 2018). The NDC includes land use and forestry as one of the mitigation focus areas. REDD+ is considered as one of the mechanisms for technical capacity development, a source of mitigation finance and a tool to contribute to land tenure and forest governance in the NDC. A legal umbrella for climate financing, including for REDD+, is recently enacted through Government Regulation No. 46/2017 on Economic Instrument for Environment which has been elaborated with Presidential Regulation No 77/2018 on the Environmental Fund Management (MoEF 2018).

Rationale for the study

FLEGT-VPA and REDD+ have been developed on different political platforms. They are currently co-evolving. They share a multitude of similar objectives. A major objective of both processes is to approach their respective issues holistically, taking into account social, economic and ecological aspects of SFM. Many components of FLEGT-VPA and REDD+ can be linked to the concepts of SFM. However, the understanding of how FLEGT-VPA and REDD+ can interlink

with SFM is limited (Tegegne *et al.* 2018). To enhance the understanding, this paper analyses the contributions of REDD+ and FLEGT-VPA towards SFM through the seven thematic elements of SFM enshrined in the 'Non-legally Binding Instruments on all types of forests' which was adopted in the seventh session of the United Nations Forum on Forests in 2007. These elements comprise several indicators by which achievements of SFM, and the contributions and potential roles of FLEGT-VPA and REDD+ therein, can be measured. REDD+, FLEGT and SFM, all three are concerned with countries' forest resources and ultimately they should reinforce each other. Hence, it is widely acknowledged that their implementation needs to be coordinated at national, sub-national and local levels. Nevertheless, the complexities lie in understanding the interactions between different policy processes operating at the same space but in a different scale and vary in response to policy and other processes. In this paper, we assess specialists' viewpoint on how the FLEGT-VPA and REDD+ regimes are contributing towards SFM in Indonesia and explore the opportunities for synergy among the SFM, REDD+ and FLEGT-VPA.

METHODOLOGY

We draw from several informal discussions and formal semi structure interviews with specialists involved in FLEGT-VPA and REDD+ processes. Specialists here refer to the persons who have working experience in the context of REDD+ or FLEGT-VPA or both in the government, private or academic sectors. In order to represent a broad cross-section of forest stakeholders, the respondent selection process utilized already existed forestry specialists (the chambers) categories formed by the National Council of Forestry, i.e.: Government, Academia, Private Sector, Community, and Civil Society Organization (CSOs) and are grouped under six categories (Table 1). The interviews were conducted in two stages.

Stage I consisted of semi-structured interviews involving two sets of questionnaires with 110 specialists from different

categories. The interviews were conducted during March to July 2018. Specialists were selected using the snowball respondent selection method. The first set consisted of a questionnaire designed to explore the contributions of REDD+ towards SFM, and the second set was designed to explore FLEGT-VPA's contributions towards the SFM. Each set of the questionnaire consisted of 58 indicators for SFM grouped under 19 indicator groups and 7 criteria (ITTO 2016). The respondents were asked to specify the level of contribution of the given regime in terms of individual indicators using the traffic light approach (weigh the contribution of REDD+ and FLEGT-VPA towards SFM). Hence, contribution was ranked into three categories (0 = no contribution, 1= minor contribution, 2= high contribution). Mostly, face to face interviews were carried out. The questionnaire was sent by emails, where face to face interview was not possible. Once the questionnaires were collected and analysed, indicators were ranked in such a way that the indicator that received the highest positive response (response was based on the contribution towards the SFM) was ranked as one. Since two separate questionnaires were used for FLEGT-VPA and REDD+, indicators were ranked separately for each regime.

During stage II, in-depth interviews with 43 specialists were carried out (Table 1). The interviews were conducted during October to November 2018. We used our own experience and judgements in selecting specialists who may provide insights into each regime based on their involvement in the regime. A semi- structured interview questionnaire was designed for each regime (FLEGT-VPA and REDD+) based on the top 20 indicators selected from stage I study (Table 2, for details see Supplementary material: Table 1, 2, 3, and 4, and Figure 1). The interview began with broad questions aimed at getting specialists' perception on the development of each regime in Indonesia, followed by a questionnaire. Interviews were undertaken on Indonesian Language, recorded and transcribed later to English.

The major part of the analysis was based on the interview and discussion with the 43 respondents. Qualitative analysis was performed according to the ITTO sustainable forest

TABLE 1 Breakdown of specialists interviewed according to their categories

Specialists categories	Stage I	Stage II	
	Interviewed specialists	Interviewed specialists	
	REDD+ and FLEGT-VPA	REDD+	FLEGT-VPA
Government	31	9	4
Private sector including forest Entrepreneurs and independent experts	33	-	8
Academia / research institutions	14	5	1
International Organizations including Donor and INGOs	20	6	3
Civil Society Organizations	10	4	3
Media	2	-	-
Total	110	24	19

management objectives (ITTO 2015), namely i) providing the enabling conditions for SFM, ii) ensuring forest ecosystem health and vitality, iii) maintaining the multiple functions of forests to deliver products and environmental services, and iv) integrating social, cultural and economic aspects to implement SFM. These four objectives include seven criteria which are similar to the seven thematic elements of SFM endorsed by UNFF (CPF 2004). In addition, specialists' opinion on the interaction between FLEGT-VPA and REDD+ was noted during interviews. The study was complemented by the analysis of the documents.

RESULTS

Contribution towards providing the enabling conditions for SFM

FLEGT-VPA

Respondents indicated that the FLEGT-VPA has contributed towards the progress of SFM through improved governance, policies reinforcement and enhanced capacity for the SFM. One of the significant contributions to the forest governance reform is the engagement of stakeholders from different sectors, including civil society and private sectors and independent observers in planning, policy dialog and implementation. This is considered as a revolutionary approach in forest governance as prior to FLEGT-VPA, trade agreements did not involve the public participation. Lately, FLEGT-VPA has also been lauded for its focus on reinforcing, rather than undermining, state power and the rule of law to addressing forest loss. With the adoption and reinforcement of reduced impact logging (RIL), VPA addresses some of the drivers of deforestation and forest degradation.

Specialists stated that SVLK provides guidance on harvesting, processing and trading of timber. In addition to legality assurance, SVLK also includes Indonesia's SFM (*Pengelolaan Hutan Produksi Lestari* PHPL) certification. The Government agencies and other bodies are tasked with controlling and verifying legal compliance of operations, and ensure SVLK functions are credible. The JIC endorses and oversees the implementation of the VPA and the FLEGT licensing scheme. CABs have established procedures and resources in place to implement audit, certification and surveillance. These activities are subject to systematic external checks that build confidence in their integrity. The MoEF and the KAN pay continuous attention to the performance of CABs and LAs.

Indonesia has prepared the legality matrix that outlines the framework for the TLAS and VPA. It includes a list of relevant forest practice regulations, requirements for timber transport and taxes and royalties. Indonesia has also prepared the responsibility matrix indicating which ministries and departments are responsible for making relevant legal documentation accessible to the public. The clear outlined roles and responsibilities enable transparency and accountability and help in the monitoring process.

Respondents agree that stakeholders' involvement in VPA process has built the capacity of the civil society, forest concessioners, forestry practitioners and government staff on the implementation of SFM. Training on RIL, forest inventory and database management to local people, government officials and CSO's enhanced their technical competency, for example, in forest monitoring.

REDD+

Respondents indicated that REDD+ implementation has brought many positive improvements towards improving the enabling condition for SFM. This is especially true in case of institutional strengthening, reinforcing policies and regulations, appropriate governance and bringing additional funding. At the sub-national level, REDD+ institutions (taking the form as Working Group, commission, or task force) are established at 11 provinces. REDD+ program supports in establishment and strengthening of Forest Management Units (FMUs). The FMUs are managing forest resources at the local level and provide the basis for improved forest governance, planning, monitoring forest resources and stakeholder engagement. REDD+ encourages and supports forest concessionaires in obtaining forest certification.

Reinforcement of RIL, higher commitments to conserve High Conservation Value (HCV), higher commitments to conserve High Carbon Stock (HCS) forests, the establishment of essential ecosystem zone (*Zona Ekosistem Esensial*), and reinforcement of safeguards and BSMs have positively contributed to create enabling conditions for SFM. Conflict resolution desk is enforced through the social forestry task force. Several regional customary laws as a requirement for customary land right have been recognized/developed. Until November 12, 2018, in those provinces where regional customary law has been developed as pre requirement, around 33 customary forest/land right has been issued by government covering an area of 27,950 hectare, which are distributed in different provinces, such as Jambi, South Sulawesi, Central Sulawesi, West Kalimantan, East Kalimantan, and West Java.

REDD+ program has brought scientists, governments, I/NGOs and private sectors to work collaboratively for reducing GHG emissions. As a result, coordination between ministries at the national level and agencies at the provincial and local levels and other stakeholders to tackle deforestation and forest degradation and to utilize the forest and land resources has improved. The unilateral, bilateral and multilateral supports for REDD+ readiness have influenced the national and provincial governments to adopt appropriate policies and measures (PAMs) to address the drivers of deforestation and forest degradation in their middle and long-term agendas.

REDD+ initiatives appreciate the role of the private sector in mitigation actions. Improved forest management practices such as Reduced Impact Logging-Carbon (RIL-C) to reduce emission from natural production forests, and certification are listed as mitigation actions in private sectors. The production forest concessions in East Kalimantan (Berau District) have contributed towards the reduced carbon emissions compared to traditional selective/conventional logging by adopting RIL practice, supported by REDD+ pilot initiatives.

TABLE 2 Specialists' viewpoint on level of contribution of REDD+ and FLEGT-VPA towards SFM. Out of 58 ITTO indicators for SFM, 20 indicators for which REDD+ and FLEGT-VPA contributed the most are shown in the table. Contributions are given in per cent of the total respondents (REDD+, n = 110; FLEGT, n = 106). Indicators were ranked in such a way that the indicator that received the highest positive response was ranked as one. Among the top 20 indicators, 12 indicators (from SN 1 to SN 12) are common in both regimes. Respondents evaluated indicators from SN 13-20 to the list of top 20 for REDD+, and indicators from SN 21-28 to the list of top 20 for FLEGT-VPA

SN	ITTO criteria	Indicator group	Indicator	REDD+		FLEGT	
				Rank	Respondent (%)	Rank	Respondent (%)
1	Criterion 1	1. Policy, legal and governance framework	Forest governance	1	48	6	46
2	Criterion 1	1. Policy, legal and governance framework	Policies, laws and regulations for governing forests	3	44	3	56
3	Criterion 1	1. Policy, legal and governance framework	Forest tenure and ownership	17	31	16	30
4	Criterion 1	2. Institutional framework	Institutions responsible for, and supportive of, forest management	4	39	8	42
5	Criterion 1	3. Planning and monitoring framework	Long-term projections, strategies and plans for production PFE and protection PFE	13	34	17	28
6	Criterion 2	5. Extent and condition of forests	Forest area in compliance schemes	14	33	4	52
7	Criterion 2	5. Extent and condition of forests	Multiyear forest management plans in FMUs	8	36	9	40
8	Criterion 2	5. Extent and condition of forests	Forest condition	18	31	18	28
9	Criterion 3	6. Addressing threats to, and vulnerabilities of, forests	Threats to forests caused directly by human activities	2	47	5	50
10	Criterion 4	10. Silviculture in natural and planted forests	Reduced impact harvesting and silvicultural operations	5	38	15	34
11	Criterion 4	8. Resource assessment	Natural production forest inventories, by product	9	36	7	45
12	Criterion 4	9. Harvesting planning and control procedures	Timber harvesting arrangements in natural production forests	19	31	1	59
13	Criterion 1	3. Planning and monitoring framework	Integration of forests in national and subnational land-use planning	10	35		
14	Criterion 1	3. Planning and monitoring framework	Capacity and mechanisms for management planning and the periodic monitoring of implementation	15	33		
15	Criterion 2	5. Extent and condition of forests	Extent and percentage of total land area under comprehensive land-use plans	11	34		
16	Criterion 2	5. Extent and condition of forests	Forest carbon stock	12	34		
17	Criterion 4	8. Resource assessment	Forest carbon stock	7	37		
18	Criterion 7	18. Social and cultural aspects	Mechanisms for resolving disputes between forest stakeholders	16	32		

TABLE 2 *Continued*

SN	ITTO crite- ria	Indicator group	Indicator	REDD+		FLEGT	
				Rank	Respondent (%)	Rank	Respondent (%)
19	Criterion 7	19. Community and indigenous peoples' rights and participation in forest management	Tenure and user rights of indigenous peoples and local communities over publicly owned forests	6	38		
20	Criterion 7	19. Community and indigenous peoples' rights and participation in forest management	Involvement of indigenous peoples and local communities in forest management	20	31		
21	Criterion 1	2. Institutional framework	Availability of professional and technical personnel to perform and support forest management			10	39
22	Criterion 4	8. Resource assessment	Actual and allowable harvest of wood and non-wood products in natural forests			12	38
23	Criterion 4	8. Resource assessment	Actual harvest of wood and non-wood products in planted forests			13	37
24	Criterion 4	9. Harvesting planning and control procedures	Forest product tracking systems or similar control mechanisms			2	58
25	Criterion 4	9. Harvesting planning and control procedures	Historical records on the extent, nature and management of forests			14	36
26	Criterion 7	17. Economic aspects	Wood and non-wood forest product processing capacities and efficiency			20	26
27	Criterion 7	18. Social and cultural aspects	Capacity building of the workforce in forest management and forest industry			11	39
28	Criterion 7	18. Social and cultural aspects	Procedures to ensure the health and safety of forest workers			19	28

Note: The Table shows the ranking up to top 20, for the rest of the ranking, please see Table 1 and Table 2 provided in 'Supplementary Materials'.

Continuous attention from many international and national actors drawn by the REDD+ program, have improved the transparency and law enforcement in the government administration. In addition, REDD+ has been able to bring additional funding. Though, so far funding has come mainly through development aid, there is also the potential of funding from the voluntary market. REDD+ funds could be used to finance for SFM activities. One Map Policy is regarded as one of the significant policy interventions and efforts on conflict resolution on spatial planning and land utilization. The policy intends to achieve common and authoritative maps through one reference, one database, one standard, and one geoportal.

Despite the contributions towards SFM, respondents still perceive REDD+ as a highly centralized policy and criticize its top-down approaches of implementation. Because of limited and slow guidance from the central government resulting from the weak vertical coordination, integrating REDD+ to the regional/local development plan and sectoral agenda is challenging.

Knowledge of international UNFCCC decisions, of national REDD+ implementation strategy and understanding of IPCC Land Use, Land-Use Change and Forestry estimation and reporting requirements is limited at the local level. In addition, there is no uniformity in REDD+ development processes between the provinces. REDD+ implementation is limited only in a small number of provinces. Only few provinces, such as East Kalimantan and Jambi, have developed adequate REDD+ relevant institutions and structures. A few are developing REDD+ safeguards and BSMs (e.g. East Kalimantan). This may jeopardize the nationwide implementation of REDD+ by 2020.

In 2015, President Mr. Joko Widodo has disbanded BP REDD+ Agency (Presidential Decree No. 16/2015; 23 Jan. 2015), which was established in 2013 preceding the REDD+ Task Force 2010; and integrated REDD+ Agency and National Council of Climate Change into the MoEF. The Directorate General of Climate Change (DG PPI) was established in MoEF in 2015 and is now the government entity responsible for REDD+. The tasks of the BP REDD+ are now integrated as the MoEF's tasks (Article 59). Some respondents expressed that the abolishing of the REDD+ agency and assigning the REDD+ tasks back to into the ministerial bureaucracy is a deviation from the LoI between the Indonesia and the Norway and may raise several issues. In the LoI, there is a term specifically indicating the role of REDD+: "Establish a special agency reporting directly to the President to coordinate the efforts...." (LoI, VI, b). The head of REDD+ agency was equivalent to a minister and directly reporting to the president. In the new set-up, REDD+ tasks are managed at the sub-directorate of the Directorate General for Climate Change, as a relatively small part of the overall MoEF operations.

Contribution towards ensuring forest ecosystem health and vitality

FLEGT-VPA

Specialists believe FLEGT-VPA contributes indirectly towards forest ecosystem health and vitality through

enhanced legality, capacity building and multi layered monitoring mechanism. In Indonesia, adherence to the forest management plan and regular comprehensive inventory are important part of the TLAS of FLEGT-VPA. As part of FLEGT-VPA, a technical unit of forestry offices are required to have risk analysis and prepare fire risk map. Fire prevention squads are trained. Concessions are responsible for the health, security and protection of their concession area.

An operational SIPUHH online system allows monitoring of the pre-harvest inventories and real time tracking of timber movement from the natural forests and plantations located in the forest zone up to the primary industries. However, at the field level, due to limited resources and technical competency, use of online reporting system is still a challenge. Inconsistency of different online reporting system (e.g. SIPUHH: online application used for timber registration, SIMPONI: online application used by Ministry of Finance, SIMPEL: electronic environmental reporting system) may further creates confusion. Integrated timber information system (SI PHPL) is slated for the nationwide implementation in 2018, will enable data synchronization throughout the supply chain from forest via timber depots and primary processing to the secondary/tertiary processing.

A key component of the Indonesian VPAs is a multi-layered monitoring mechanism. Firstly, it involves independent monitoring system that tasks CSOs and individuals with responsibility to raise concerns regarding irregularities in legality verification of the operators. JPIK (*Jaringan Pemantau Independen Kehutanan*) is the main national IM network, though there are other three types of IM exist in Indonesia. Secondly, it includes the measures to assess its overall effectiveness in the form of Comprehensive Monitoring. The MoEF appoints a multi-stakeholder Joint Working Group to monitor and review the SVLK. Thirdly, it includes Periodic Evaluation. This is a periodic formal third party audit to review the functioning of TLAS performance commissioned by JIC. Fourthly, multi-layered monitoring mechanism involves impact monitoring, which evaluates the impacts of SVLK on the domestic market, including how local people and other potentially vulnerable communities are affected by the activities of the VPAs. Finally, an Independent Market Monitor is foreseen to evaluate the acceptance of FLEGT-licensed timber in the EU market.

REDD+

Interviewees stated that the Indonesia has taken a significant step towards protection and improved management of forest through REDD+ policy and program such as through its moratorium. For example, Peat land moratorium on the Granting of New Licenses and Improvement of Natural Primary Forest and Peatland Governance is believed to have created opportunities to undertake critical forest governance reform. Other forest moratoriums include Peat Land Restoration, and Palm Oil Moratorium. The domestic PAMs include National Action Plan for Greenhouse Gas Emission Reduction (Presidential Instruction Inpres No 61/ 2011), and National Strategy on Corruption Prevention (Presidential Instruction Inpres No

8/2018) which is designed to facilitate cooperation among MoEF, Corruption Eradication Commission (KPK), other law enforcement agencies, civil society and the media.

Specialists suggested that due to bold regulatory reforms and mobilizing actions to reduce deforestation under REDD+ mechanism, there is a significant reduction in deforestation in natural forests, forest degradation and forest fires in the current years. Forest fire in Indonesia is the significant source of GHG emissions and huge clouds of toxic smog. According to the respondents, from the beginning of 2017 and to middle of 2018, Indonesia managed to prevent deforestation considerably and to abate forest fire significantly compared to the forest fires in 2015. However, they cautioned that it is difficult to attribute such improvements only to REDD+ mechanism. They expressed that President Widodo's strong political will and commitments to protect natural forest ecosystems and to address the illegal logging issues have driven tremendous efforts nationwide to curb deforestation and forest fires.

Contribution towards maintaining the multiple functions of forests to deliver products and environmental services

FLEGT-VPA

Respondents mentioned that the FLEGT-VPA implementation has resulted in the low impact timber harvesting plans, reinforcement of RIL, and improved forest product tracking system, which consequently have reduced the negative impacts on ecosystem functions and services. Concessioners are required to follow the harvesting standards. Regular comprehensive forest inventory (*Inventarisasi Hutan Menyeluruh Berkala*, IHMB) is now a pre-requisite for the planning. Enrichment planting is highly encouraged. Concessionaires are required to provide data of forest regeneration and forest condition to ensure SFM is practiced. As discussed above SIPUHH online system allows tracing timber movement from the natural forests and plantations, so as to distinguish legal and illegal timber. The consideration that FLEGT pays to logging practice is also relevant to the protective functions of forests for soil and water.

REDD+

Under the REDD+ implementation, specialists argued that the reinforcement of RIL has increased long-term financial gain and environmental benefits. Since RIL/RIL-C is tailored to local condition, it could bring significant improvement in production planning so that the company can optimize the business profitability and timber yield sustainability with reduced adverse impacts to the remaining forest stands from harvesting activities. However, the majority of the respondents acknowledge that investment in RIL/RIL-C is expensive to start with and generally referred to as 'Reduced Income Logging' in the beginning. In addition, there is deficient of skilled human resources. RIL/RIL-C requires specialized knowledge in timber harvesting process; thus capacity building (through advanced training and research) for logging

concessioners and KPH staffs in implementing RIL/ RIL-C practice is urgently needed.

Indonesia has established a functioning REDD+ SIS. Addressing and respecting REDD+ safeguards ensures the enhancement of broader social and environmental benefits including incentivizing non-carbon benefits.

Contribution towards integrating social, cultural and economic aspects to implement SFM

FLEGT-VPA

The study obtained mixed opinions in this issue area. Implementation of SVLK has ensured that the concessionaire contributes financial incentives for community development. The proportion of the benefit sharing depends on the negotiation between concessionaire and the local government and thus varies among provinces. For instance, concessionaires are allowed to allocate up to 20 % of the plantation forest area for the livelihood activities (MoEF 2015). Concessionaires employ local residents in various forest management activities including harvesting operations.

Despite the social safeguards arrangement in FLEGT-VPA, majority of specialists indicated uncertainty whether SVLK protects the interests of local and indigenous communities (LICs) and recognize and respects their customary rights to traditional land, in particular. The traditional (customary) land, which was previously appropriated and reclassified by the government as state property, is now to be returned to the indigenous people (Indonesian constitutional court decision, 2013). The handover process is yet to be completed following certain criteria. In those areas which have been returned to the community under customary ownership, still lacks legal evidence (statutory ownership). Another concern raised by the respondents on the VPA process is about the legalising timber harvest in the social forests. Recognizing the collective rights of local communities to have access to the forest resources for livelihood needs, the patch of state forest area is handed over to a community as a different form of social forestry scheme (*Perhutanan Sosial / Social Forestry Scheme*). However, handing over the previously encroached areas as a social forest and thus legalizing timber harvested from these social forests may lead to the perception that encroachment is legalized by the government.

The interviewees are very concerned that timber industries might harness more economic benefits than the forest concessionaires. FLEGT-VPA process basically deals with the fulfilment of the standards. Specialists believe that it has no control over the market price of the timber, and thus, it discourages the management unit (concessions). They are skeptical that timber industries are benefited from premium price due to SVLK, while price paid to the concession remains the same. In contrast, some concessionaires consider that FLEGT-VPA adds an additional cost and bring no direct economic benefit to them. For instance, concessionaires need to verify their product by private auditing bodies accredited by KAN which adds additional economic burden. This

clearly puts small scale producer at a disadvantage in meeting this requirement. Hence the opening international market seems to bring direct benefit among the forest industries rather than the concessionaries.

Similarly, the respondents believe that support to small-scale forest activities provides opportunities for secured livelihood activities, however, it is yet to achieve in Indonesia. Issuance of SVLK certification requires certainty of concession area and utilization rights, proof of legitimate ownership of timber and concession area, permit documentation, etc. In reality, most of the small-scale forest based enterprises are operating informally and only a few of them have the permits necessary to meet the requirements for harvesting and transporting timber. The cost of compliance and surveillance is so high that the market cannot offset the cost incurred, so SVLK has been an additional burden. The FLEGT licensing system has further worsened the situation.

Additionally, respondents suggested that there are still loopholes for the entry of illegal logs into the supply chain through certified big companies. The interviewees cited permit issued to Registered Timber shelter/terminal (Tempat Penampungan Terdaftar Kayu Olahan (TPTKO)) as an example. Forestry service easily issues a permit to TPTKO, which still is prone to illegal logging activity. One of the respondents said, “*There are evidence that TPTKO sometimes obtains timber from IPK kebun (permit to use timber from plantation land clearing) and IPK tambang (permit to use timber from mining land clearing)*”.

REDD+

Interviewees revealed that with the REDD+ implementation, local people's interest is back to the development agenda. REDD+ National Strategy highlights the importance of local people's participation and land tenure reform for the success of forest conservation. With the Cancun agreement, Free Prior and Informed Consent (FPIC) and other social safeguards, REDD+ accelerates the recognition of indigenous/local people tenure right. They agree that the implementation of REDD+ accommodates and accelerates the decision of the Indonesian Constitutional Court (Mahkamah Konstitusi), number 35/PUU-X/2012, thereby removing customary forests from state control. During Susilo Bambang Yudhoyono (Indonesia President 2004–2014) administration, the Indonesia government opened an opportunity for indigenous people to make a participatory map of their area which is integrated within the OMP which is also part of REDD+ programme. In 2012, the total area of indigenous people estimated to be around 4.8 million acres and currently increased to around 9.3 million acres. This program is still continuing under Jokowi's regime (2014–2019), nevertheless, the progress of legal resignation (stipulated by the government) is still slow.

Furthermore, development and the implementation of REDD+ SIS acknowledge and clarify the right of local and indigenous people on land tenure, forest resources and benefit sharing. At the national and the local level, the conflict resolution desk is being established. For instance, in East Kalimantan, as guidance for addressing conflicts, the environmental and social management framework is being developed.

DISCUSSION

FLEGT-VPA contribution towards sustainable forest management

With decades of experience in promoting and implementing SFM, continued deforestation and forest degradation are still taking place in Indonesia. According to Lesniewska and McDermott (2014), illegal logging, industrial logging of the natural forests and unsustainable logging practices have played a significant role in this continuous forest loss. The creation of logging infrastructures such as logging roads, skid trails and logging decks as well as policies devaluing “degraded” forests have set the stage for the conversion of logged forests to palm oil and tree plantations (Rudel *et al.* 2009). There is a great potential to scale up SFM for wood production and environmental and socioeconomic benefits, as long as the barriers to SFM could be removed. Hindrances widely discussed are mainly related to policies, regulations, governance and finance (Cosslett 2013). Policies and measures to support FLEGT strategies are supposed to deliver improved governance and enhanced capacity for SFM.

Based on the specialists' opinion, our study shows FLEGT-VPA contribute (directly or indirectly) towards SFM especially through forest governance reform, enhanced transparency, improved harvesting practices, and TLAS. The significant contribution of FLEGT-VPA to the forest governance reform is the engagement of diverse national stakeholders in planning, negotiation, policy dialog and implementation. In addition, involvement of different stakeholders in the VPA process has enhanced their capacity for the SFM, for instance enhanced technical competency in forest monitoring. The multi-stakeholder nature of Indonesian VPA is often referred to have improved contribution towards the recognition of stakeholder's right in forest governance (Overdevest and Zeitlin 2016, Overdevest and Zeitlin 2018).

Respondents praised the development of SIPUHH (*Sistem informasi Penatausahaan Hasil Hutan*) online system, which allows real time tracking of timber movement from the forest zone to the primary industries. The completion of the SI PHPL will further enable data synchronization throughout the entire timber supply chain. Establishment of the independent verification system, multi-layered monitoring system, and preparation of legality matrix are the basis of the VPA implementation in Indonesia. As discussed, the multi layered monitoring system and the integrated online system are expected to control and prevent the “3Cs”: forest Crime, Conflicts and Corruption. However, interviewees could not deny the fact that there are still loopholes for the entry of illegal logs into the supply chain.

Major contributors of forest degradation are conventional logging and poor forest management practices (Hosonuma *et al.* 2012, MoEF 2018). Illegal logging has been a topic of serious national, regional and global concern for several decades, due to its serious impacts on forest biodiversity, wildlife habitat, and soil quality, access to water, poverty, GHG emissions and governance. Application of rigorous

planning and management practices, adoption of best practices (such as RIL), enhancement of the productive function of the forest resource through enhanced legality indirectly contribute to forest biodiversity conservation and to some extent can maintain and enhance ecosystem functions (Tegegne *et al.* 2018). Most of the respondents envision FLEGT-VPA and the SVLK (a mandatory timber legality assurance system) as policy instruments to reduce illegal logging and other forest crimes. Though biodiversity conservation and the enhancement of protective function of the forests are not the primary focus of FLEGT-VPA, specialists agree that through low impact timber harvesting plans and reinforcement of RIL, FLEGT-VPA have contributed towards SFM objectives in Indonesia ensuring forest ecosystem health and vitality, and maintaining the multiple functions of forests to deliver products and environmental services.

The European Commission (2007) identifies the need to consider social safeguards in order to minimize adverse impacts on indigenous and local communities while designing and implementing VPAs. This is reflected in the VPA concluded between Indonesia and EU. Article 12 of the agreement states “*in order to minimize possible adverse impacts of this Agreement, the Parties agree to develop a better understanding of the impacts on the timber industry as well as on the livelihoods of potentially affected indigenous and local communities as described in their respective national laws and regulations*” (EU FLEGT Facility 2016). The statement clearly conveys that while formulating agreement precautionary principles with respect to adverse social effects should be taken into account in addition to the principles of legality. In line to the agreement, specialists confirmed that implementation of SVLK has ensured that the concessionaire contributes financial incentives for community development either through providing employment to local people or through sharing benefits.

By fulfilling the Indonesian SFM standard, where the indicator for local/indigenous interest has been accommodated, it is assumed that SVLK contribute to protect the interest of LICs. However, our study shows the uncertainties remains regarding whether SVLK protects the interests of LICs and recognize and respects their customary rights to traditional land. In addition respondents revealed that FLEGT-VPA is perceived as an additional economic burden to the small and medium forest enterprises (SMFEs). According to the National Statistics Agency (BPS), there could be up to 753,000 small-scale enterprises, employing up to 1.5 million people (BPS 2011). Among them, only about 4000 are registered as timber exporters (Obidzinski *et al.* 2014). SMFEs (and secondary timber processing in general) still face challenges in meeting SVLK requirements due to limited technical knowledge and financial constraints (Obidzinski *et al.* 2014, Sucofindo 2018). Many authors agree that Indonesia is adopting an approach driven by technical verification requirements which create new market barriers for small-scale producers (Lesniewska and McDermott 2014, Rutt *et al.* 2018). Along similar line, Maryudi and Myers (2018) refer to the emergence of FLEGT license renting and describe as a new mode of elite resource capture and the production of new

vulnerabilities. Similarly, various markets related barriers for small and medium-scale forest producers were identified in the VPA in Cameroon (Carodenuto and Ramcilovic-Suominen 2014) and in Ghana (Hajjar 2015, Hansen *et al.* 2018, Hirons *et al.* 2018).

REDD+ contribution towards sustainable forest management

The study shows the REDD+ implementation has brought many positive improvements towards the progress of SFM through embarking on bold reforms in national legislations and frameworks, institutional strengthening, reinforcing policies and regulations, and increasing social and ecological resilience. Establishment of working group, commission and task force (e.g. social forestry task force) at different provinces, facilitate horizontal and vertical coordination between the actors involve in the REDD+ implementation. One Map Policy is considered as one of the remarkable policy interventions of REDD+ implementation on conflict resolution and information accessibility. Information (data and knowledge, and their construction and use) is one of the elements needed for transformational change from business as usual deforestation and forest degradation. Information is a currency and a source of power in the REDD+ world (Angelsen *et al.* 2012) and in entire forest management arena in the context of SFM as a climate change mitigation tool.

Major drivers of deforestation and forest degradation in Indonesia are palm oil plantations, mining, infrastructures, slash and burn, illegal logging, forest fire and legal selective logging (Rudel *et al.* 2009, Wicke *et al.* 2011, Hosonuma *et al.* 2012, MoEF 2018). The REDD+ mechanism has been able to bring ministries associated with these drivers together to cope with issues related to mining, agriculture and palm oil plantation and forest land conversion. Transformational change beyond the forestry is required to fully harness the mitigation potential of REDD+ (Angelsen *et al.* 2012), by doing so the REDD+ Agency is successful to some extent to break ministerial silos and solving sectoral difficulties (Indrarto *et al.* 2012, Korhonen-Kurki *et al.* 2017).

REDD+ implementation has ensured the reinforcement/adoption of RIL. Selective logging emits 6% of tropical greenhouse gases annually (Ellis *et al.* 2019). Studies evaluating RIL performance have indicated potentials emission reductions and speedy biomass/carbon recovery from RIL in selectively logged forests across the tropics.

Studies in Southeast Asia, Africa, and South and Central America have clearly documented that the undesired impacts of selective/conventional logging (CL) on residual stands and soils (Putz *et al.* 2008, Martin *et al.* 2015) and logging emissions (Sist *et al.* 2003, Ellis *et al.* 2019, Umunay *et al.* 2019) can be substantially reduced through implementation of RIL technique. Employment of RIL practices resulted in fewer damaged trees and lower carbon emissions even in ejidos (communities) in Yucatan Peninsula in Mexico with high logging intensities (Ellis *et al.* 2019). Sist *et al.* (2003) compared RIL and conventional techniques in 24 one-hactare sample plots established in a mixed dipterocarp hill forest in East

Kalimantan. They revealed that RIL techniques nearly halved the number of trees destroyed, i.e., 36 trees/ha in RIL vs 60 in conventional. In this case, the reduction is dominated by the reduction in logging infrastructure, i.e., skidding trails. Ellis *et al.* (2019) synthesize data from 61 coordinated field-based surveys of logging impacts in countries across tropics: Mexico, Peru, Suriname, Gabon, Republic of Congo (RoC), Democratic Republic of Congo (DRC); and Indonesia (East and North Kalimantan). They estimated that implementation of RIL would reduce logging emissions by 44% of the total tropical GHG emissions while maintaining timber production. Umunay *et al.* (2019) estimated the carbon emissions from selective logging using reduced-impact logging for carbon emissions reductions (RIL-C) protocol in 23 forest concessions in DRC (8), Gabon (9) and RoC (6). In an overall average, the committed logging emissions per cubic meter of timber harvest was found to be 2.1 tC (ranged from 0.63 tC m⁻³ in a forest concession in RoC to 4.8 tC m⁻³ in a concession in Gabon) which was mostly dominated by damaged caused by logging infrastructure development. They suggested that the implementation of RIL-C would reduce emissions by 34%, 45% and 62% in RoC, DRC and Gabon, respectively.

Similarly, several researches revealed that practices of RIL is reported to show a positive impact on biomass/C-recovery (Gourlet-Fleury *et al.* 2013, de Graaf *et al.* 1999, Peña-Claros *et al.* 2008, Priyadi *et al.* 2005, Villegas *et al.* 2009). By 16 years post-logging, the RIL plot recovered 100% of its original above-ground biomass. Average annual increment in above-ground biomass was 6-times higher in the RIL than CL (West *et al.* 2014). The findings of the studies highlighted the potential from the implementation of RIL-C to reduce damage on residual stands by reducing the logging damage and logging infrastructure damage, and consequently to cut half of logging emissions without reducing timber yields. This suggests that adaptation of best RIL-C practices would contribute substantially to the Indonesian forest sector's efforts to mitigate climate change, and to meet its emission reduction target pledged in its nationally determined contribution (NDC). Transformation from destructive selective logging or conventional logging to RIL would represent an efficient forest-based strategy to mitigate climate change under REDD+ and would be an important step towards sustainable forest management (West *et al.* 2014).

REDD+ implementation has also ensured a higher commitments to conserve HCV forests, higher commitments to conserve HCS forests, the establishment of essential ecosystem zone and reinforcement of safeguards and BSM, which have positively contributed towards creating enabling conditions for SFM by ensuring the forest ecosystem health and vitality and maintaining the forests functions and services. The REDD+ process has contributed substantially to the assessment of threats to forest ecosystems by identifying and quantifying drivers of deforestation and forest degradation. As set out in the REDD+ National Strategy (Indonesian REDD+ Task Force 2012), REDD+ programs include activities such as the rehabilitation and restoration of degraded areas. In addition REDD+ partnership between Indonesia and

Norway has resulted in issuance of different moratoriums (e.g. peatland moratorium, palm oil moratorium). Such policies and programs aim to protect the forest ecosystems from the direct and underlying drivers of deforestation and forest degradation and hence increase ecosystem resilience. These periodic moratoriums have allowed for better planning for forest governance, data collection and revision of policies and regulations (Murdiyarso *et al.* 2011, Austin *et al.* 2014).

The data released on Global Forest Watch by the University of Maryland shows a 60% drop in tree cover loss in primary forests in 2017 compared to 2016. The loss of primary forest significantly went down by 88% in protected peat areas between 2016 and 2017. Partly the national peat drainage moratorium, which is in effect since 2016, contributed to the achievements (Hamzah *et al.* 2018).

REDD+ promotes carbon sequestration and storage, reduce GHG emissions, and enhance ecological and social resilience to environmental change. SFM activities under REDD+ ensure the sustained supply of low-carbon intensive forest products and services; protect biodiversity, water supplies and soils; and provide green jobs and support the livelihoods of forest dependent/local people. In periods of 2013–2017, Indonesia has reduced 358 MtCO₂e emissions in total or 71.6 MtCO₂e annually against the 1990–2012 baseline emissions only from deforestation and forest degradation (MoEF 2018). In 2017, Indonesia reduced 200 MtCO₂e emissions by reducing tree cover loss in primary forests compared with 2016 (Hamzah *et al.* 2018). From June to October 2015, forest fires burned more than 2.6 million hectares in Indonesia (Jong 2019) and cost Indonesia an estimated USD 16.1 billion (World Bank 2016). A substantial proportion of the cost constitutes the loss of biodiversity and reduced capacity of forest carbon storage of the forests. Beside the 2015 fires, Indonesia has been able to keep the annual emissions from the deforestation and forest degradation well below the reference emission level (MoEF 2018). After 2015, the problem is largely abated, the area burned in 2017 was just 6% of the 2015 total (Jong 2019). The substantial reduction in the forest area burnt has contributed considerably to forest health and vitality. However, fires in peat forests are still a huge challenge for the country. Indonesia hosts the world's third-largest span of tropical rainforests and several biodiversity hotspots. Protecting Indonesian rainforests is pivotal for achieving long-term temperature goal of Paris Agreement, meeting the Indonesian NDC target of emissions reduction and critical for survival of the rich biodiversity.

REDD+ SIS is an important mechanism for providing guidance on monitoring and evaluating the potential social and environmental impacts of REDD+ implementation. Indonesia's REDD+ National Strategy and SIS respect the knowledge and rights of LICs and emphasize the recognition of tenure and property right for the success of forest conservation. The need to clarify tenure rights is already under discussion in the context of REDD+: doing so in a socially acceptable manner facilitates the involvement of all stakeholders in integrated and participative land-use planning processes (Duchelle *et al.* 2014, Gregersen *et al.* 2010,

Karsenty and Ongolo 2012) as a basis for sustainable low-carbon and climate resilient development.

As finance is considered as one of the barriers of SFM, REDD+ can contribute to overcome this hurdle by bringing additional funding. Both REDD+ and forest landscape restoration (FLR) aim to reduce and reverse forest degradation, and promote and upscale sustainable management of forests. An adequate, long-term and predictable financial resource is a key challenge for the FLR at a large scale (Neupane *et al.* 2017). In addition, FLR activities face a number of barriers including unclear tenure rights and lack of implementation and monitoring capacity (FAO and Global Mechanism of the UNCCD 2015). REDD+ funds could be used to finance FLR activities (Maraseni *et al.* 2014, Neupane 2015, Sanz and Penman 2016, Neupane *et al.* 2017), for example, to finance capacity building and reward emission reductions in FLR initiatives (FAO and Global Mechanism of the UNCCD 2015). REDD+ and other long-term financing schemes could revolutionize funding (Mansourian *et al.* 2017) and REDD+ projects can be aligned to FLR activities. However, synergies between the initiatives need to be improved through interaction management. The cooperation and harmonization between the national institutions implementing REDD+ and FLR, and coordination among the major financing institutions related to FLR and REDD+ should be ensured (Carrapatoso and Geck 2018). REDD+ can promote restoration of degraded natural forests, however, the carbon price would need to be higher (Ranjan 2019) than the USD 5 for a REDD+ credit, for example, paid by the Carbon Fund of the Forest Carbon Partnership Facility of the World Bank. Moreover, governments need to integrate FLR into their planning budget at the national and sub-national levels (FAO and Global Mechanism of the UNCCD 2015).

Roughly EUR 19.4 billion of public funding have been committed to direct and indirect REDD+ activities between 2008 and 2015, provided by EU, non-EU and multilateral organizations, and EUR 17.2 billion (89%) were disbursed in the same period (COWI 2018). Indonesia is one of the countries receiving a significant amount of allocated REDD+ funding (Norman and Nakhooa 2014). The recipient countries have been investing significant amount on forestry development, forest policy reform, capacity development, biodiversity and safeguards; and to prepare the REDD+ elements related to the areas. Investment in the areas and development of forest monitoring, REDD+ MRV and national safeguards systems contribute towards sustainable management of the forest resources.

On February 16 of this year, Norway and Indonesia have agreed on a first payment from a \$1 billion pact which was signed in 2010 between the countries under the REDD+ mechanism. Indonesia demonstrated that it reduced 4.8 million tCO₂e emissions through reducing rates of deforestation in natural forests in 2017. Currently, independent verification of the emissions reduction is taking place. The amount of the first payment still needs to be negotiated by both countries. Since the Financing REDD+ in Indonesia is abolished along with the BP REDD+, the payment is expected to be channelled to the Badan Layanan Umum.

Political commitment is a key to promote policy development and implementation of the policy. Political commitment to tackle deforestation and forest degradation has been established at the national, provincial and local levels. Indonesia has demonstrated a strong political will that clearly support effective and efficient REDD+ at the highest level of government. The commitment has been shown beyond the forestry sectors such as agriculture and mining sectors. However the recent policy event, the establishment of DG PPI within the MoEF, had not been considered thoroughly in terms of its local, national and international effects. Members of the defunct BP REDD+ have enormous knowledge and institutional memory which are crucial for further REDD+ development. In a way, the REDD+ institution is scaled down from Cabinet-level to directorate level under the MoEF. In such scenario, interviewees concern about the visibility of the REDD+ which may fade and question about the capability of the DG PPI to coordinate other ministries (Korhonen-Kurki *et al.* 2017).

The road ahead for REDD+ depends on many factors including the carbon price and market for the emissions reductions and removals. For example, Indonesia is expecting a higher valuation than \$5 per tCO₂e for the payment under the \$1 billion deal with Norway. In Indonesia, changes in policy and political leadership have been affecting REDD+ processes. In general, specialists see the favourable direction for REDD+ implementation, as there is a strong political commitment at the national level. High political will also have been observed in several provinces.

REDD+ has been streamlined within national policies and measures at the national level in Indonesia. The government considered REDD+ as an integral component of domestic PAMs to accomplish its proposed climate action to Paris Agreement, i.e. NDC. This demonstrates the governments' strong commitment to implement REDD+ effectively to reach its stringent target as specified in the NDC.

Specialists' opinion on the interaction between FLEGT-VPA and REDD+ in Indonesia

Specialists believe that REDD+ and FLEGT-VPA share synergistic relationship rather than conflicting. Though initialized with a slightly different objective, i.e. REDD+ is considered as a climate change mitigation strategy while FLEGT-VPA is more about legality and promoting trade in legal timber, both shares the same global objective of conservation and sustainable management of global forests. While FLEGT-VPA is emphasized on reducing illegal logging through forest law enforcement and improved forest governance, and REDD+ is focused on reducing carbon emissions; both are concerned with the forestry sector. Implementing the specific elements of one regime, therefore automatically affect another as mostly the similar actors are involved. However, the interest and idea/ideology of the actors and information possession among them might vary. While REDD+ is popular among the public, FLEGT-VPA is popular directly with forest management units.

This study shows that both regimes contribute towards each of the four objectives of the SFM. Both regimes contributed strongly towards *providing the enabling conditions for SFM*. While REDD+ contributed directly towards *the forest ecosystem health and vitality* and *maintaining multiple functions of the forest* through reducing deforestation, reducing unsustainable logging, increasing forest areas under sustainable management and forest conservation, supporting long-term management commitments, and conducting afforestation and reforestation activities, FLEGT-VPA contributed indirectly through enhanced legality, capacity building and multi layered monitoring mechanism. Addressing and respecting REDD+ safeguards promote different aspects of social forestry through enhancement of social benefits and equitable BSM. FLEGT-VPA contributes to economic aspect of SFM through promoting trade in legal timber.

The respondents suggested that FLEGT-VPA supports the REDD+ implementation by improved forest governance and law enforcement. FLEGT-VPA strengthens the legal aspects of the company and its area which needs to implement REDD+. With the adoption of sound planning and the management practices including RIL, FLEGT-VPA addresses some of the drivers of forest degradation and thus contributes to reduce carbon emissions due to conventional logging. Involvement of the multi-stakeholder approach in VPAs agreement and process, it creates enabling conditions by contributing to a transparent and inclusive national process for policy making in the land use sector. In addition, numbers of the SVLK certified companies have also signed an agreement on to increase in carbon stock and biodiversity values in the concessions. For example, several concessions have signed the agreement for further promoting biodiversity and carbon conservation in their area with international NGO/CSO. REDD+ helps companies to get in FLEGT-VPA, the certification ensures sustainable management of forest.

FLEGT-VPA development activities involve capacity building of the stakeholders. In addition to the technical assistance, the support includes capacity building of the communities. Training on RIL, the global positioning system handling, forest inventory and record keeping have been conducted for the communities involved in logging. Database development training and training on proposal writing to the involved officials contribute to their competence. Training on negotiation techniques contributed significantly to the human assets of the logging/local communities. The community capacity building not only empowers the local/logging communities to implement the FLEGT-VPA, but also enhances their knowledge of sustainable forest management, forest assessment and REDD+.

Since FLEGT-VPA and REDD+ target essentially the same sector, deal mostly with the similar stakeholders and use fairly similar institutional structure, there are opportunities to achieve synergy between REDD+ and FLEGT-VPA by harmonizing their procedures and instruments. Harmonization in data collection, processing and analysis, information derivation and sharing, and capacity building will benefit both of the processes significantly. The harmonization might reduce the

costs for the MRV system of both regimes and increase the economic efficiency of the monitoring systems of the regimes.

CONCLUSIONS

Both FLEGT-VPA and REDD+ feature forests high on the environmental agenda in Indonesia. Implementation of FLEGT-VPA has resulted in progress towards SFM mainly providing the enabling conditions for SFM through forest law enforcement, improved forest governance and increased transparency. Participation of diverse stakeholders including civil society in the VPA negotiation process and their capacity building has ensured people's voice in decision making and policy process. While the respondents praised FLEGT-VPA for creating enabling conditions for the legal trade, various markets related barriers for small-scale forest producers such as excessively expensive legality verification process are identified. Likewise, FLEGT-VPA's contribution to the indigenous people/ local people regarding benefit sharing mechanism and the forest land tenure is unclear. This implies that FLEGT-VPA still undermines the 'people's choice'.

REDD+ contributes towards SFM through strengthening institutional set-up, capacity building, improving forest governance, and by providing financial incentives. Reinforcement of reduced impact logging, attention to high conservation value, and the establishment of essential ecosystem areas through REDD+ implementation have positively contributed to create enabling condition for SFM in Indonesia. REDD+ implementation has improved the coordination between different sectors. REDD+ has brought new and additional forest-related financing resources from public, private and philanthropic sources to incentivize to mobilize actions to reduce deforestation and forest fires, and for the implementation of sustainable forest management. REDD+ has contributed significantly in the involvement of local communities and indigenous peoples in the national processes of low carbon pathways and climate resilient development agenda. REDD+ promoted forest-based economic, social and environmental benefits, including improving the livelihoods of forest-dependent people and promoted equitable benefit sharing through the BSM. However, REDD+ has been often criticized by specialists as a 'top-down' and/or 'donor driven national processes'.

There are opportunities for synergies between REDD+ and FLEGT-VPA by harmonizing their processes, procedures and instruments. Harmonization in data collection, processing and analysis, information derivation and sharing will benefit both of the processes significantly. The harmonization might reduce the costs for the MRV system of both regimes and increase the economic efficiency of the monitoring systems of the regimes. The capacity and infrastructure that have been developed for SFM can be applied for the efficient implementation of REDD+, and FLEGT-VPA while the resources that REDD+ and FLEGT-VPA bring will encourage greater uptake of SFM. REDD+ can benefit from on-going forest governance reform. As both REDD+ and FLEGT-VPA

are in the initial stage and are co-evolving, the long-term contribution of each regime is yet to see; however, the early insights help in understanding the progress towards the synergies between different regimes.

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List of acronyms

BSMs	Benefit Sharing Mechanisms	NDC	Nationally Determined Contribution
C&I	Criteria and Indicators	NGOs	Non-Governmental Organizations
CABs	Conformity Assessment Bodies	NFMS	National Forest Monitoring System
CL	Conventional Logging	NLBI	Non-Legally Binding Instrument on all Types of Forests
COP	Conference of Parties	PAMs	Policies and Measures
CSOs	Civil Society Organizations	PHPL	<i>Pengelolaan Hutan Produksi Lestari</i> (Sustainable forest management)
DNPI	National Council of Climate Change	PRISAI	Indonesia Safeguard System / Principal, Criteria, and Indicator of Safeguards
EU	European Union	REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries
EUTR	European Union Timber Regulation	RIL	Reduced Impact Logging
FCPF	Forest Carbon Partnership Facility of the World Bank	RIL-C	Reduced Impact Logging Carbon
FLEGT	Forest Law Enforcement, Governance and Trade Action Plan	SESA	Strategic Environment and Social Assessment
FLR	Forest Landscape Restoration	SFM	Sustainable Forest Management
FMUs	Forest Management Units	SI PHPL	Integrated Timber Information System
FREL	Forest Reference Emission Level	SIPUHH	<i>Sistem informasi Penatausahaan Hasil Hutan</i> (online application used for timber registration)
GHGs	Greenhouse Gas Emissions	SIS	Safeguards Information System
HCS	High Carbon Stock	SMFEs	Small and Medium-sized Enterprises
HCV	High Conservation Value	SVLK	<i>Sistem Verifikasi Legalitas Kayu</i> (acronym of Indonesia's national timber legality assurance system)
IM	Impact Monitoring	TLAS	Timber Legality Assurance System
INGOs	International Non-Governmental Organizations	TPTKO	Registered Timber shelter/terminal (Tempat Penampungan Terdaftar Kayu Olahan)
ITTO	International Tropical Timber Organization	UN	United Nations
JIC	Joint Implementation Committee	UNFCCC	United Nations Framework Convention on Climate Change
JPIK	<i>Jaringan Pemantu Independen Kehutanan</i>	UNFF	United Nations Forum on Forests
KAN	Indonesian National Accreditation Board	VPA	Voluntary Partnership Agreement
LICs	Local and Indigenous Communities		
LoI	Letter of Intent		
MoEF	Ministry of Environment and Forestry		
MoU	Memoranda of Understanding		
MRV	Measurement, Reporting and Verification system		

SUPPLEMENTARY MATERIALS

TABLE 1 Specialists' viewpoint (overall) on level of contribution of REDD+ towards SFM. Contribution of REDD+ are shown as no contribution, minor contribution and major contribution in reference to ITTO Criteria, Indicator group and Indicators. Contributions (last three columns) are shown in the number of the respondents (n=110)

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
Criterion 1: Enabling conditions for sustainable forest management	1. Policy, legal and governance framework	Policies, laws and regulations for governing forests	IND_1	17	45	48
		Forest tenure and ownership	IND_2	33	43	34
		Forest governance	IND_3	13	44	53
	2. Institutional frame-work	Institutions responsible for, and supportive of, forest management	IND_4	25	42	43
		Availability of professional and technical personnel to perform and support forest management	IND_5	28	53	29
	3. Planning and monitoring framework	Integration of forests in national and subnational land-use planning	IND_6	26	46	38
		Capacity and mechanisms for management planning and the periodic monitoring of implementation	IND_7	15	59	36
		Long-term projections, strategies and plans for production and protection PFE	IND_8	16	57	37
	4. Economic framework	Stakeholder participation in land-use and forest management planning, monitoring and assessment	IND_9	21	61	28
		National and international public and private funding committed to SFM	IND_10	34	59	17
Criterion 2: Extent and condition of forests	5. Extent and condition of forests	Incentives to encourage SFM	IND_11	53	42	15
		Extent of total land area under comprehensive land-use plans	IND_12	32	41	37
		Extent of forests committed to production and protection	IND_13	32	46	32
		Extent and percentage of total land area under each forest type	IND_14	37	47	26
		Multiyear forest management plans in FMUs	IND_15	20	50	40
	6. Addressing threats to, and vulnerabilities of, forest ecosystem health and resilience	Forest area in compliance schemes	IND_16	21	53	36
		Change in forested area	IND_17	29	51	30
		Forest condition	IND_18	22	54	34
		Forest carbon stock	IND_19	18	55	37
		Threats to forests caused directly by human activities	IND_20	21	37	52
Criterion 3: Forest ecosystem health and resilience	7. Restoration of degraded forests and lands	Vulnerability of forests to natural disturbances	IND_21	44	52	14
		Forest resilience and climate-change adaptation	IND_22	47	45	18
		Degraded forests and landscapes restored	IND_23	35	48	27
		Area of formerly degraded forest or forest land restored	IND_24	36	47	27

TABLE 1 Continued

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
Criterion 4: Forest production	8. Resource assessment	Natural production forest inventories, by product	IND_25	35	35	40
		Actual and allowable harvest of wood and non-wood products in natural forests	IND_26	39	43	28
	9. Harvesting planning and control procedures	Actual harvest of wood and non-wood products in planted forests	IND_27	44	44	22
		Forest carbon stock	IND_28	17	52	41
	10. Silviculture in natural and planted forests	Timber harvesting arrangements in natural production forests	IND_29	24	52	34
		Forest product tracking systems or similar control mechanisms	IND_30	31	46	33
		Historical records on the extent, nature and management of forests	IND_31	42	48	20
		Reduced impact harvesting and silvicultural operations	IND_32	21	47	42
Criterion 5: Forest biological diversity	11. Ecosystem diversity	Silvicultural management in planted forests	IND_33	44	38	28
		Strategic monitoring of silvicultural systems in natural and planted forests	IND_34	40	42	28
		Forest extent in protected areas	IND_35	37	41	32
		Buffer zone management and connectivity of protected forest areas	IND_36	27	55	28
	12. Species diversity	Threatened forest-dependent species	IND_37	34	42	34
		Procedures for conserving tree species diversity in natural tropical forests	IND_38	36	47	26
		<i>In situ</i> conservation of genetic variation within specified forest tree species	IND_39	56	29	25
		Biodiversity conservation measures in natural production forests	IND_40	32	47	31
Criterion 6: Soil and water protection	13. Genetic diversity	Biodiversity conservation in planted forests	IND_41	36	51	23
		Forest area managed primarily for the protection of soil and water	IND_42	29	48	33
		Protection of downstream catchment values at the landscape level	IND_43	41	45	24
		Soil productivity and water retention capacity in production forests	IND_44	50	40	20
	14. Biodiversity conservation in production forests	Area of production PFE considered environmentally sensitive and protected	IND_45	45	34	31
		Forest engineering for soil and water protection	IND_46	53	43	14
		Contribution of the forest sector to gross domestic product	IND_47	60	32	18
		Value of domestically produced forest products and environmental services	IND_48	43	44	23
Criterion 7: Economic, social and cultural aspects		Wood and non-wood forest product processing capacities and efficiency	IND_49	36	44	30

TABLE 1 Continued

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
18. Social and cultural aspects		Capacity building of the workforce in forest management and forest industry	IND_50	23	57	30
		Procedures to ensure the health and safety of forest workers	IND_51	43	49	18
		Mechanisms for the equitable sharing of the costs and benefits of forest management	IND_52	41	44	25
		Mechanisms for resolving disputes between forest stakeholders	IND_53	28	47	35
		Local livelihoods and forest management	IND_54	44	42	24
19. Community and indigenous peoples' rights and participation in forest management		Forests reserved for specific cultural, research or educational purposes	IND_55	41	49	20
		Tenure and user rights of indigenous /local communities over publicly owned forests	IND_56	28	40	42
		Involvement of indigenous/local communities in forest management	IND_57	31	45	34
		Recognition and value of forest-management knowledge and skills of local people	IND_58	39	50	21

TABLE 2 Specialists' viewpoint (overall) on contribution of FLEGT-VPA towards SFM. Contribution of FLEGT-VPA is shown as no contribution, minor contribution and major contribution in reference to ITTO Criteria, Indicator group and Indicators. Contributions (last three columns) are shown in the number of the respondents (n= 106)

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
Criterion 1: Enabling conditions for sustainable forest management	Policy, legal and governance framework	Policies, laws and regulations for governing forests	IND_1	12	35	59
		Forest tenure and ownership	IND_2	20	54	32
		Forest governance	IND_3	7	50	49
	Institutional framework	Institutions responsible for, and supportive of, forest management	IND_4	10	51	45
		Availability of professional and technical personnel to perform and support forest management	IND_5	13	52	41
Planning and monitoring framework		Integration of forests in national and subnational land-use planning	IND_6	43	44	19
		Capacity and mechanisms for management planning and the periodic monitoring of implementation	IND_7	27	53	26
		Long-term projections, strategies and plans for production and protection PFE	IND_8	25	51	30
		Stakeholder participation in land-use and forest management planning, monitoring and assessment	IND_9	24	61	21

TABLE 2 *Continued*

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
Criterion 2: Extent and condition of forests	Economic framework	National and international public and private funding committed to SFM	IND_10	35	51	20
		Incentives to encourage SFM	IND_11	51	38	17
	Extent and condition of forests	Extent of total land area under comprehensive land-use plans	IND_12	55	31	20
		Extent of forests committed to production and protection	IND_13	53	30	23
		Extent and percentage of total land area under each forest type	IND_14	59	31	16
		Multiyear forest management plans in FMUs	IND_15	15	49	42
		Forest area in compliance schemes	IND_16	13	38	55
		Change in forested area	IND_17	38	44	24
		Forest condition	IND_18	21	55	30
		Forest carbon stock	IND_19	28	58	20
Criterion 3: Addressing threats to, and vulnerabilities of, forests ecosystem health and resilience	Restoration of degraded forests and lands	Threats to forests caused directly by human activities	IND_20	17	36	53
		Vulnerability of forests to natural disturbances	IND_21	37	51	18
		Forest resilience and climate-change adaptation	IND_22	55	34	17
		Degraded forests and landscapes restored	IND_23	70	26	10
	Resource assessment	Area of formerly degraded forest or forest land restored	IND_24	74	21	11
		Natural production forest inventories, by product	IND_25	21	37	48
		Actual and allowable harvest of wood and non-wood products in natural forests	IND_26	21	45	40
		Actual harvest of wood and non-wood products in planted forests	IND_27	18	49	39
		Forest carbon stock	IND_28	33	53	20
		Timber harvesting arrangements in natural production forests	IND_29	11	32	63
Criterion 4: Forest production	Harvesting planning and control procedures	Forest product tracking systems or similar control mechanisms	IND_30	9	36	61
		Historical records on the extent, nature and management of forests	IND_31	21	47	38
	Silviculture in natural and planted forests	Reduced impact harvesting and silvicultural operations	IND_32	31	39	36
		Silvicultural management in planted forests	IND_33	41	40	25
		Strategic monitoring of silvicultural systems in natural and planted forests	IND_34	40	40	26

TABLE 2 Continued

ITTO Criteria	Indicator group	Indicators	Indicator ID	No contribution	Minor contribution	Major contribution
Criterion 5: Forest biological diversity	Ecosystem diversity	Forest extent in protected areas	IND_35	42	43	21
		Buffer zone management and connectivity of protected forest areas	IND_36	36	50	20
	Species diversity	Threatened forest-dependent species	IND_37	41	48	17
		Procedures for conserving tree species diversity in natural tropical forests	IND_38	39	46	21
Criterion 6: Soil and water protection	Genetic diversity	<i>In situ</i> conservation of genetic variation within specified forest tree species	IND_39	60	28	18
		Biodiversity conservation measures in natural production forests	IND_40	30	53	23
	Extent of protection	Biodiversity conservation in planted forests	IND_41	35	60	11
		Forest area managed primarily for the protection of soil and water	IND_42	53	40	13
Criterion 7: Economic, social and cultural aspects	Protective functions in production forests	Protection of downstream catchment values at the landscape level	IND_43	56	35	15
		Soil productivity and water retention capacity in production forests	IND_44	56	40	10
	Economic aspects	Area of production PFE considered environmentally sensitive and protected	IND_45	36	55	15
		Forest engineering for soil and water protection	IND_46	48	52	6
Social and cultural aspects	Economic aspects	Contribution of the forest sector to gross domestic product	IND_47	37	47	22
		Value of domestically produced forest products and environmental services	IND_48	32	52	22
		Wood and non-wood forest product processing capacities and efficiency	IND_49	25	53	28
		Capacity building of the workforce in forest management and forest industry	IND_50	17	48	41
	Social and cultural aspects	Procedures to ensure the health and safety of forest workers	IND_51	23	53	30
		Mechanisms for the equitable sharing of the costs and benefits of forest management	IND_52	63	33	10
		Mechanisms for resolving disputes between forest stakeholders	IND_53	32	52	22
		Local livelihoods and forest management	IND_54	54	35	17
	Community and indigenous peoples' rights and participation in forest management	Forests reserved for specific cultural, research or educational purposes	IND_55	46	46	14
		Tenure and user rights of indigenous /local communities over publicly owned forests	IND_56	28	56	22
		Involvement of indigenous/local communities in forest management	IND_57	35	48	23
		Recognition and value of forest-management knowledge and skills of local people	IND_58	56	32	18

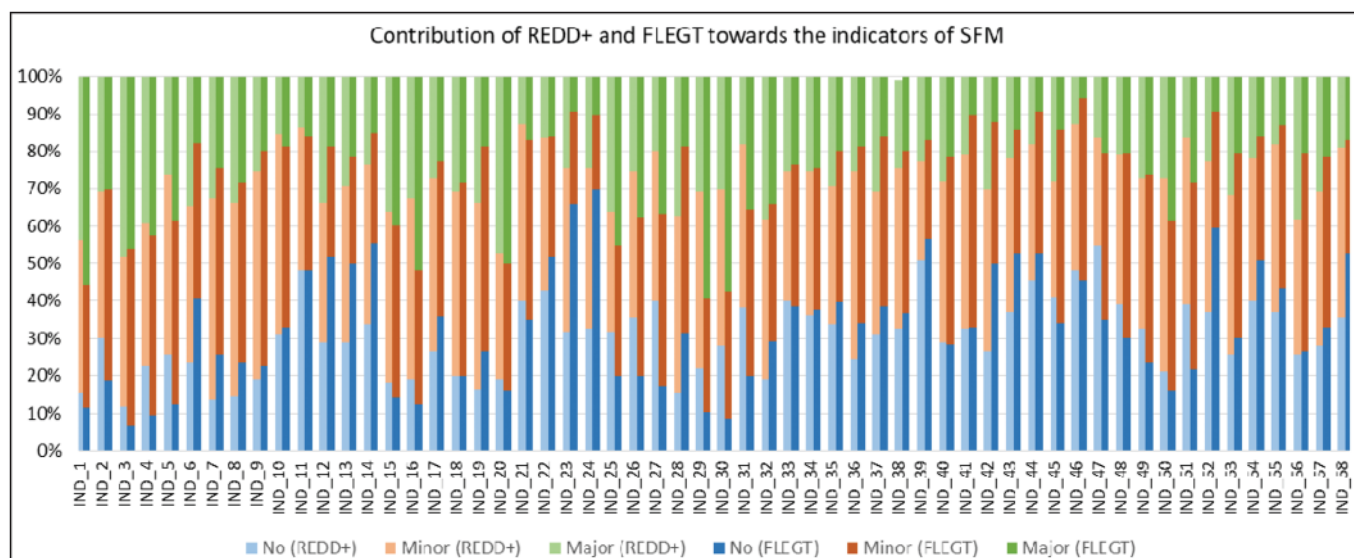
TABLE 3 Top 20 indicators of ITTO selected on the basis of level of contributed by REDD+. Contribution is shown in per cent of the total respondents ($n = 110$)

SN	ITTO Criteria	Indicator group ID	Indicator ID	Indicator ID abbreviation	High contribution
1	Criterion 1	1. Policy, legal and governance framework	Forest governance	IND_3	48%
2	Criterion 3	6. Addressing threats to, and vulnerabilities of, forests	Threats to forests caused directly by human activities	IND_20	47%
3	Criterion 1	1. Policy, legal and governance framework	Policies, laws and regulations for governing forests	IND_1	44%
4	Criterion 1	2. Institutional framework	Institutions responsible for, and supportive of, forest management	IND_4	39%
5	Criterion 4	10. Silviculture in natural and planted forests	Reduced impact harvesting and silvicultural operations	IND_32	38%
6	Criterion 7	19. Community and indigenous peoples' rights and participation in forest mgt.	Tenure and user rights of indigenous peoples and local communities over publicly owned forests	IND_56	38%
7	Criterion 4	8. Resource assessment	Forest carbon stock	IND_28	37%
8	Criterion 2	5. Extent and condition of forests	Multiyear forest management plans in FMUs	IND_15	36%
9	Criterion 4	8. Resource assessment	Natural production forest inventories, by product	IND_25	36%
10	Criterion 1	3. Planning and monitoring framework	Integration of forests in national and subnational land-use planning	IND_6	35%
11	Criterion 2	5. Extent and condition of forests	Extent and percentage of total land area under comprehensive land-use plans	IND_12	34%
12	Criterion 2	5. Extent and condition of forests	Forest carbon stock	IND_19	34%
13	Criterion 1	3. Planning and monitoring framework	Long-term projections, strategies and plans for production PFE and protection PFE	IND_8	34%
14	Criterion 2	5. Extent and condition of forests	Forest area in compliance schemes	IND_16	33%
15	Criterion 1	3. Planning and monitoring framework	Capacity and mechanisms for management planning and the periodic monitoring of implementation	IND_7	33%
16	Criterion 7	18. Social and cultural aspects	Mechanisms for resolving disputes between forest stakeholders	IND_53	32%
17	Criterion 1	1. Policy, legal and governance framework	Forest tenure and ownership	IND_2	31%
18	Criterion 2	5. Extent and condition of forests	Forest condition	IND_18	31%
19	Criterion 4	9. Harvesting planning and control procedures	Timber harvesting arrangements in natural production forests	IND_29	31%
20	Criterion 7	19. Community and indigenous peoples' rights and participation in forest mgt.	Involvement of indigenous peoples and local communities in forest management	IND_57	31%

TABLE 4 Top 20 indicators of ITTO SFM contributed by FLEGT. Contribution is shown in per cent of the total respondents ($n = 106$)

SN	ITTO Criteria ID	Indicator group ID	Indicator ID	Indicator ID abbreviation	High contribution
1	Criterion 4	9. Harvesting planning and control procedures	Timber harvesting arrangements in natural production forests	IND_29	59%
2	Criterion 4	9. Harvesting planning and control procedures	Forest product tracking systems or similar control mechanisms	IND_30	58%
3	Criterion 1	1. Policy, legal and governance framework	Policies, laws and regulations for governing forests	IND_1	56%
4	Criterion 2	5. Extent and condition of forests	Forest area in compliance schemes	IND_16	52%
5	Criterion 3	6. Addressing threats to, and vulnerabilities of, forests	Threats to forests caused directly by human activities	IND_20	50%
6	Criterion 1	1. Policy, legal and governance framework	Forest governance	IND_3	46%
7	Criterion 4	8. Resource assessment	Natural production forest inventories, by product	IND_25	45%
8	Criterion 1	2. Institutional framework	Institutions responsible for, and supportive of, forest management	IND_4	42%
9	Criterion 2	5. Extent and condition of forests	Multiyear forest management plans in FMUs	IND_15	40%
10	Criterion 1	2. Institutional framework	Availability of professional and technical personnel to perform and support forest mgt.	IND_5	39%
11	Criterion 7	18. Social and cultural aspects	Capacity building of the workforce in forest management and forest industry	IND_50	39%
12	Criterion 4	8. Resource assessment	Actual and allowable harvest of wood and non-wood products in natural forests	IND_26	38%
13	Criterion 4	8. Resource assessment	Actual harvest of wood and non-wood products in planted forests	IND_27	37%
14	Criterion 4	9. Harvesting planning and control procedures	Historical records on the extent, nature and management of forests	IND_31	36%
15	Criterion 4	10. Silviculture in natural and planted forests	Reduced impact harvesting and silvicultural operations	IND_32	34%
16	Criterion 1	1. Policy, legal and governance framework	Forest tenure and ownership	IND_2	30%
17	Criterion 1	3. Planning and monitoring framework	Long-term projections, strategies and plans for production PFE and protection PFE	IND_8	28%
18	Criterion 2	5. Extent and condition of forests	Forest condition	IND_18	28%
19	Criterion 7	18. Social and cultural aspects	Procedures to ensure the health and safety of forest workers	IND_51	28%
20	Criterion 7	17. Economic aspects	Wood and non-wood forest product processing capacities and efficiency	IND_49	26%

FIGURE 1 Specialist' viewpoint on the synergy between SFM, REDD+ and FLEGT-VPA (REDD+, $n = 110$, FLEGT-VPA, $n = 106$) respondents. No denotes no contribution of the related regime to the SFM. Minor and Major denote the minor and major contribution of REDD + and FLEGT- VPA towards each indicator of SFM. IND refers to indicator ID (Table 1)



I certify that the cumulative dissertation titled "*Sustainable Forest Management and Carbon Balance in Tropical Forests*," written by Tunggul Butarbutar from the University of Hamburg (Institute for World Forestry), has been proofread for English grammar, spelling, and punctuation by a native English speaker. The execution of recommended edits ultimately lies with the author.

The dissertation was reviewed by myself, Katherine Linscott, a native English speaker, currently studying at the Universität Hamburg.

A handwritten signature in black ink, reading "Katherine Linscott". The script is cursive and fluid, with the first name and last name clearly distinguishable.

Katherine Linscott

April 1, 2025