Ecological, social and economic effects of timber exploitation in tropical forests, and the role of forest certification: a review

Authors: Lennart Flavio Meyer-Sand MSc, Prof. Dr. Douglas Sheil, Prof. Dr. Pieter Zuidema, Prof. Dr. Marielos Peña-Claros, Dr. Ute Sass-Klaassen

Forest Ecology and Forest Management Group (FEM)

Wageningen University and Research (WUR)

Commissioned by Forest Stewardship Council™ Denmark

October 2022

WAGENINGEN
UNIVERSITY & RESEARCH

Table of content

1. Introduction

1.1. Context

Tropical forests are of high importance for climate, biodiversity, carbon and people. These forests are altered by fragmentation, exploitation, natural disturbances and climate change. Scientists increasingly understand the processes that determine the responses of tropical forests to such disturbances, including those resulting from the extraction of timber. This knowledge helps to generate and evaluate practices of forest management for timber extraction.

Scientists, conservationists and international policy makers have formulated various guidelines for the sustainable management of tropical forests. The term "sustainable forest management" encompasses a wide range of aims, including maintaining the ecological values and processes of managed forests, the economic viability of forest management and the social acceptance of that management [1]. In general terms ecological sustainability means not to remove more resources, than can be recovered over a long period of time such that yields are not compromised [2]. In terms for sustainable forest management this means to sustain timber yields over time [1]. Development and testing of techniques such as "Reduced-impact logging" helped to reach goals of sustaining ecological and economic values by reducing damage to residual stand and increase future yields through directional felling and planned extraction [3]. During the 1990s and later, various forest management certification schemes have been developed, among others FSC, which formalized responsible and sustainable forest management in criteria and indicators. Since then, RIL techniques, planning of harvest operations and road building have been widely adopted by certified forest enterprises to achieve a reduction of damaged caused by logging and maximise future yields. The environmental impact of such improved management increases the ability of natural timber production forests to retain most of their biodiversity and associated ecosystem functions as well as their carbon, climatic and soil-hydrological ecosystem services [4].

In spite of the long period since the creation of forest management guidelines and certification schemes, there is still uncertainty about the long-term impact of timber production and management on tropical forests. Specifically, the long-term impact of environmental, economic and social values in managed forests is still poorly known. This is not entirely surprising, given the long logging cycles and scarcity of forest management research in tropical forests, as compared to other temperate and boreal forests [5]. Another issue of concern is that proportion of managed tropical forests that are certified has remained rather low.

There are several concerns about the long-term sustainability of tropical forest management. (1) There is concern that the current combination of logging cycles and logging intensity does not sustain timber yields for the next and further logging cycles. (2) Related to this, there are concerns that forest management will not be economically viable anymore within several decades. (3) There are concerns that new and less familiar timber species (a.k.a., lesser-known timber species, LKTS) gain access to market at a slow pace, thus limiting their contribution to bolster future timber volumes and recovery. (4) There are uncertainties about the extent to which biodiversity can best be sustained in tropical forests managed for timber. (5) There are concerns whether and under what conditions carbon stocks recover.

In addition, there are also uncertainties about the extent to which forest certification is (1) beneficial in terms of (1) environmental values of managed forests, (2) economic gains and viability of forest management, and (3) social conditions of people living in or near managed forests.

1.2 Aim of the study

This study aims to evaluate the environmental, social and economic effects of natural tropical forest management, and the extent to which FSC certification reduces negative implications or creates positive impacts. In addition, we specifically evaluated recent developments on the application and contribution of lesser-known timber species (LKTS).

Below we show where the items mentioned in the Terms of Reference of the assignment can be found in this report:

- Verify findings of the Putz et al. 2012 with recent literature — Chapter 3.
- Evaluate effects of current logging cycles — Section 3.1.
- Evaluate recent evidence for “primary forest premium” — Section 3.2.
- Evaluate importance of very large and old trees — Section 3.3.
- Impact of FSC on environmental, social and economic values — Chapter 4.
- Evaluate effects of timber diversification (LKTS) — Chapter 5.
- A summary for policy makers — Chapter 6.
- Recommendations for FSC stakeholders — Chapter 7.

2. Methods

We applied mixed methods for this study. First, we performed various literature searches to gather relevant scientific articles on the topics included in the report. Second, when literature searches yielded a small number of studies, we reached out to international colleagues, to obtain reports and information from interviews. Below we describe the approach for each of the chapters.

The basis for the contents of Chapter 3 was a literature search on studies that cited the meta-analysis of Putz et al 2012 on the effects of selective logging on biodiversity, carbon and timber stocks in tropical forests [6]. We searched for publications citing the Putz et al 2012 meta-analysis using Google Scholar, which resulted in 592 references (as found on July 11th 2022). Then we checked which of those studies in English contained relevant primary data and met the study scope, i.e. focus on the impact of certified tropical forest management. Publications on plantations, reforested areas or effects of enrichment planting were not included in this study. In this way, we reduced the number of publications to 233.

For all chapters, we conducted extensive literature searches in two scientific literature search engines, "Web of Science" (www.webofscience.com/wos) and "Scopus" (www.scopus.com) to ensure that as many relevant publications as possible were located prior to screening and selection [7]. The search strings used are listed in Supplementary Table 1.

in the annex. Certain topics were less well represented, i.e. certification, social impact, economic impact, lesser-known timber species (LKTS) and logging intensity. For these topics additional searches were performed. The same search strings were applied in both search engines including publication from 2012 onwards. This resulted in 212 unique, relevant publications (see Table 1 for number of publications per topic and scientific search engine).

Finally, we also obtained recommendations of relevant publications on less studied topics from 14 scientists identified through our personal networks (CIFOR [1], CIRAD[2], CATIE[3], SCU[4], SHR[5], UU[6], WUR). Our analysis is not a systematic literature review or meta-analysis and does thus not follow the formal methods required for such a study [8] but uses a more adaptive and targeted searching strategy to find studies on the topics of interest to FSC. Below we describe our literature search in detail.

Table 1. Number of unique publications per topic in Scopus and Web of Science. LTKS = lesser-known timber species.

Topic	Unique number of publications		Total number
	Scopus	Web of Science	
Certification	40	16	56
Social impact	30	9	39
Economic impact	13	1	14
Logging intensity	81	27	108
LKTS	10	2	12
Total			**212**

[1] Center for International Forestry Research (CIFOR)
[2] Centre de coopération internationale en recherche agronomique pour le développement (CIRAD)
[3] Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)
[4] Southern Cross University (SCU)
[5] Stichting Hout Research (SHR)
[6] Universiteit Utrecht (UU)

The preliminary search on lesser-known timber species found few studies and thus it was decided to enlarge the scope of the search. Therefore, the time interval of publications on this topic was expanded from ten to thirty years. Additionally, international scientists from CIFOR in Cameroon, Indonesia and Peru, CIRAD in Guatemala, CATIE in Costa Rica, SCU in Australia, as well as SHR, UU and WUR in the Netherlands were consulted to obtain further information on LKTS and their expertise on tropical forest certification. This approach yielded another 18 publications on LKTS, which were analysed for this study.

Information from the publications were extracted by capturing the key results of the specific publication. Chapter 3 focusses on the latest development of natural forest management in the tropics based on scientific findings from recent meta-analysis, reviews and other most relevant publications on this topic. The studies retained were selected from the pool of the 233 citations of the Putz et al 2012 publication with preference to summaries from meta-analysis and reviews to verify the findings.

From the literature search, which yielded 212 publications plus 18 additional indicated on LKTS, we reviewed in total 63 publications. For chapter 4 on the impact of certification, the initial search yielded 56 unique publications, and after a screening 33 were retained and reviewed. These publications contain results on the effect of FSC logging in natural tropical forests on environmental, economic, and social values. Chapter 5 presents the studies about diversification of timber species. Here we analyse alternative timber species, their potential impact on sustaining timber yields and on maintaining ecosystem functions.

3. Recent findings on the effect of tropical forest management on three key ecosystem services

In this chapter, we verify whether the findings reported in the Putz et al 2012 meta-analysis are still valid using more recent publications (Figure 1). The meta-analysis had revealed that on average 54% of the timber volume removed in the first cut is available for the second and third cycle. Yet, if only the same species are harvested, just 35% of the volume is available. In addition, once logged forests retain on average of 76% of their carbon stocks. Furthermore, it was found that the species richness is very similar to an old-growth forest with 85 to 100% of original species richness (i.e. total counts of taxa regardless of their status) of birds, mammals, invertebrates and plants after a first selective logging intervention [6].

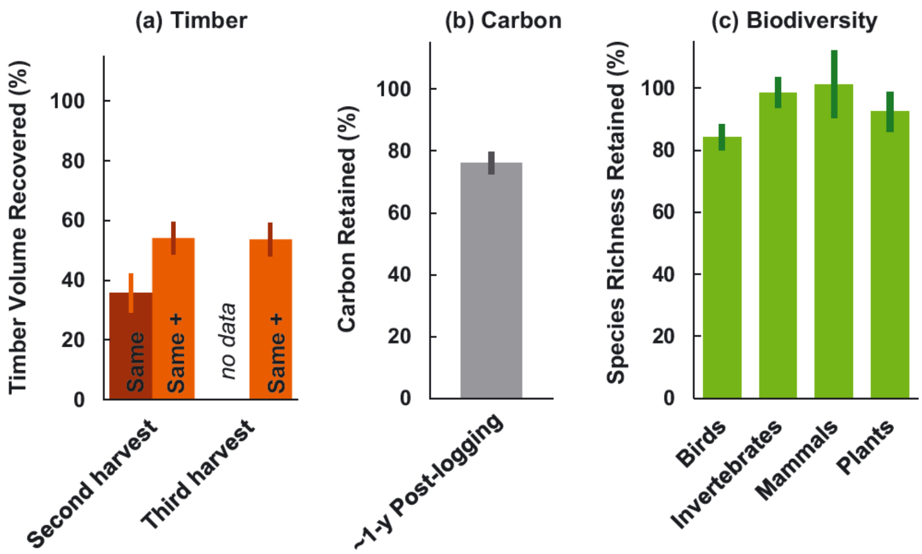

Figure 1. Retention and recovery of ecological values in tropical forests managed for timber extraction, showing mean values from a literature review. (a) Recovery of timber volume at the second or third harvest, as percentage of volume extracted at the first or second harvest. Bars indicated with „Same" include studies in which volume recovery was calculated for per species. Bars indicated with „Same +", include studies in which the same or a modified set of species is exploited during the second and third harvest compared to the first harvest. (b) Retention of forest carbon in first years after logging. (c) Retention of species richness for different species groups, comparing logged and unlogged forests, or forest after vs before logging. Figure taken from Putz et al 2012 [1].

Our review has also assessed the timber productivity, carbon stock retention and species richness (of various selected taxa) for selectively logged forests. Overall, the findings of Putz et al. 2012 are confirmed. Evidence indicates that current harvesting intensities and rotation intervals will typically not sustain timber yields. Selective logged forests recover their carbon stocks faster than conventional logging [4]. But only low logging disturbance up to 10m³/ha seems to have no or little impact of species richness, this is site dependent and according to the taxonomic group [9]. Consequently, if timber volumes are to be maintained, carbon stocks and species composition to return to pre-logging state, then operational specifications on sustained timber yields are needed. Otherwise, the industry would need to adjust to lower timber volumes and lower profits [1].

In the following subsections we provide more details on the effect of logging on the abovementioned ecosystem services, using the most comprehensive studies done on the subject.

3.1. Timber volume

Using long-term permanent plot data from 15 sites distributed across the Amazon, simulation models showed that harvest intensity of 20m³/ha does not allow to recover the extracted timber volume when using a cutting cycle of 30 years. Longer cutting cycles (up to 65 years) and lower harvesting intensities (10 m³/ha) resulted in higher recovery of timber volume, but with larger variation across the Amazon basin. These results support the finding of Putz et al 2012, that timber yield are not sustained on the long term through selective logging [10]. The authors suggested to expand the pool of commercially used timber to maintain the timber stock over time. But even with the inclusion of 348 lesser-known timber species and a 20m³/ha logging intensity, only 70% of harvestable timber stock recovered after a 30 year cycle [10]. The results indicate a decline of timber stocks as natural regrowth cannot compete with the current extraction volume and rotation lengths [10]. Improvements could result from lengthening the cutting cycle and reducing harvest volumes combined with silvicultural interventions to improve growth [10]. Alternatively, the application of extensive low-intensity land-sharing strategy throughout the Amazon could sustain support long-term timber provision, however high logistical costs could make this option financially unattractive [11]. The choice of the land-use strategy is conflictive between carbon and biodiversity retention vs. sustaining timber yields. It was found incompatible to optimise both timber stocks recovery and forest conservation (carbon and biodiversity) at the same time, signifying a trade-off in maximising timber production with those for carbon and biodiversity [11].

Another analysis on the sustainability of Brazilian concessions revealed that consistent timber production can only be maintained for one cutting cycle (35 years) with a volume removal of 15 to 20 m³/ha and an initial 20% proportion of commercial species (usual scenario). Or in other words, under current conditions long-term timber yields are unsustainable [12]. The only scenario that could be classified as sustainable from a timber production perspective is based on 60 years cutting cycle, with a low logging intensity (10m³/ha) and a 90% initial proportion of commercial species. However, that scenario would only provide 2% of current annual timber production in Brazil, if limited to the current area covered by forestry concessions. The authors thus urge for substantial reforms both in the forest management and timber industry sectors in order to be sustain yields in the long-term without jeopardizing the conservation and natural regeneration of remaining natural forests [12].

A study from Ghana analysing data from12 permanent plots highlighted the importance of use of light machinery. The timber regrowth was negatively influenced by the damage and compaction caused by the use of heavy machinery. The scientists also concluded that the country’s 40 year felling cycle is not sustained in the next rotation [13].

3.2. Primary forest premium

An important cause of the low timber recovery rates reported in the previous section is that in all calculations, the timber volume obtained during the second cutting cycle is compared to the volume extracted during the first cutting cycle. When comparing to the first cut, low recovery rates are to be expected because in previously unlogged natural tropical forests, trees that are harvested are large as they have grown for a (very) long period of time since reaching the minimum cutting diameter. Studies on tree ages have confirmed that >50% of the volume extracted during the first cut is obtained from trees that have grown >50 years since reaching the minimum cutting diameter [14]. This ‘additional’ timber volume of timber has been coined the “primary forest premium” as it can only be obtained at the first cutting cycle. This premium has been described by foresters more than a century ago but has not gained wider recognition.

The implications of the primary forest premium have been discussed quite extensively in the 2012 Putz et al meta-analysis. Since then, there has not been any opposition to this notion in the scientific literature. Yet, on the other hand, empirical studies on timber recovery in tropical forests have not explicitly discussed the implications of this premium for their results on sustaining timber yields. A very recent theoretical account on accommodating the primary forest premium suggests to estimate a premium of 50% (among others) and adjust timber recovery rates accordingly [1]. Estimating the proportion of timber volume attributed to the primary forest premium is not trivial and empirical estimates are lacking so far, even though this concept and its consequences is extremely important for assessing the sustainability of forest management in the long-term.

3.3. The importance of protecting larger trees

Many studies have highlighted the importance of maintaining large trees within a forest subjected to timber harvesting. Such trees are often of low value for timber, being difficult to fell and skid and often impacted by rot and other defects [15]. Nonetheless these trees play an important role in carbon storage [16]–[19], are providers of habitat for specialised biodiversity including pollinators [18], [20], as well as important sources of fruit and seed and as reservoirs of genetic diversity [15], [21], [22]. In addition, studies of functional diversity among forest stands with different histories also indicate that many important forest properties disproportionally reflect the characteristics of these larger stature stems and species [23]–[25].

Explicit recommendations are few. For example, some scientists recommend that trees over one meter diameter are protected and this has been repeated in more recent appraisals [15], [21] We did not find any explicit studies of the differences arising in production forests in which larger trees were protected versus those where they were cut. Nonetheless, the general principles and observations underpinning the value of larger trees appear sound and have withstood the last decade of research.

3.4. Carbon stock

The above ground biomass recovered to 100% 16 years after selective logging and to 77% in the case of conventional logging. However, the rotation interval of selective logged forest is too short for the giant emergent trees to grow from sizes below the cutting limit, resulting in overall lower biomass levels compared to old growth forests if these larger trees are removed [4]. A wide adoption of land-sparing, meaning a high intensity logging in distinct areas such as the fringes of the Amazon, could improve the carbon retention [11]. The authors emphasize that this approach would reduce carbon emissions and biodiversity loss, but the land-sparing strategy also results in lower timber recovery compared to land-sharing [11].

A systematic review on selective logging concluded that Reduced Impact Logging (RIL) causes lower residual tree damage compared to Conventional Logging (CL). The above ground biomass was negatively correlated with logging intensity and the hypothesis that RIL reduces the loss of above ground biomass was not supported. The scientists of this review also stated that there are currently too few studies that compare the biomass recovery between CL and RIL logged sites to reliably test differences in impact [26]. The results of a study across the 10 Amazon permanent plots showed that the above ground carbon stock (ACS) loss increases with volume extracted. The recovery time increases with initial ACS loss [27]. See Figure 2 for detailed results.

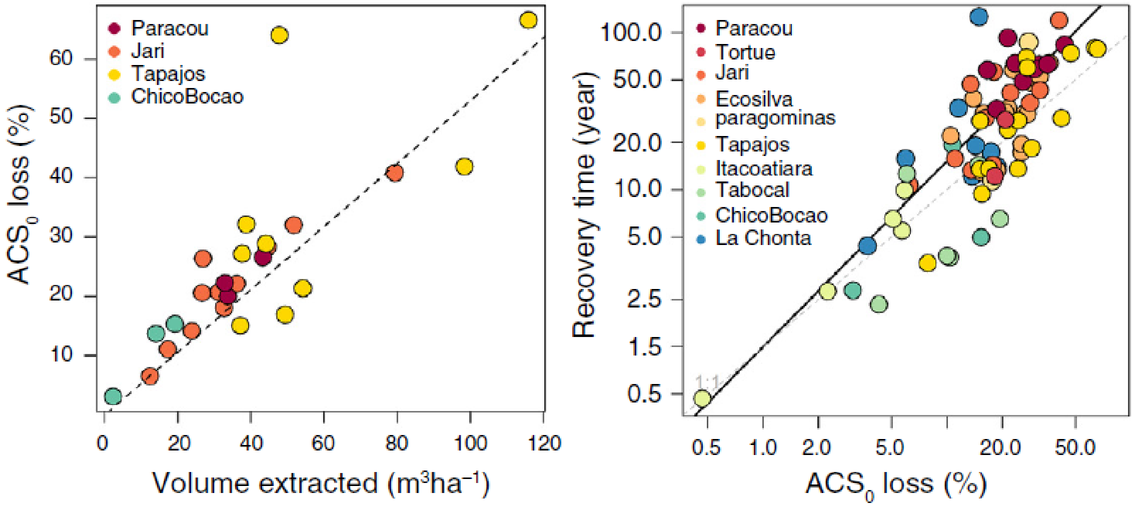

Figure 2. The percentage of initial aboveground carbon stock loss (ACS_0 loss) due to selective logging and damage-induced mortality increases with timber volume extracted (left). Relation between time of recovery and ACS_0 loss for 10 sites across the Amazon basin. The recovery time increases with ACS_0 loss (right), so that losses of 10, 25 or 50% of pre-logging ACS would require 12, 43 or 75 years, respectively, to recover regardless of location in the Amazon region. Figure taken and modified from Rutishauser et al. 2015 [27].

3.5. Biodiversity

Logged forests retain most of their ecosystem functions and services as well as biodiversity. Although logging results in shifts of species composition from disturbance sensitive to edge-tolerant species, they present a much higher biological value than other disturbed habitats [4]. A pantropical analysis reported that lightly logged forests often support more animals and species than primary forests [9]. For birds, the species richness increases with more intense logging due to an influx of habitat generalists. However, for some other groups there is a decrease after an initial increase: the logging thresholds are 10 m^3/ha for mammals, 23 m^3/ha for amphibians and 41 m^3/ha for invertebrates. Neotropical fauna was found to be more sensitive to logging than from Central Africa or Asia [9]. The results are presented in Figure 3 below per taxonomic group and bird generalists and forest specialists' species.

A recent meta-analysis, reviewing 287 published studies, did not find any impact differences amongst the continents, but confirms a positive response of light logging through RIL on bird species richness [28]. A review on logging impact concluded that low logging intensity led to an increase of tree richness but noted a decline in tree richness decrease with greater removals. Overall RIL did not reduce the loss of tree richness. Yet low intensity is the best way to reduce the biodiversity loss and enhance number of tree species [26].

A meta-analysis of various types of forest management on species richness concludes that RIL is less detrimental than CL, even with similar logging intensities [4]. It is important to underline the that an increase in tree alpha diversity does not imply an enhanced biodiversity value as the additions are typically generalists including weedy species that like disturbed forests and may be replacing rarer, more disturbance sensitive, species only found inside the forest interior [4][28]. Another study from the

Amazon found that land-sparing strategy, so the intense land exploitation in dedicated areas, could increase species richness compared to extensive low intensity land use through a land-sharing strategy [11]. A review comparing the effectiveness of four conservation strategies in terms of environmental, economic and social outcome found that certification and RIL had in most cases a positive effect for each of the three values [29]. **Error! Reference source not found.** shows the results for that section of the review. The findings of the were gathered in interactive platform to find evidence per country, thematic group of outcome and evidence type (https://www.conservationeffectiveness.org).

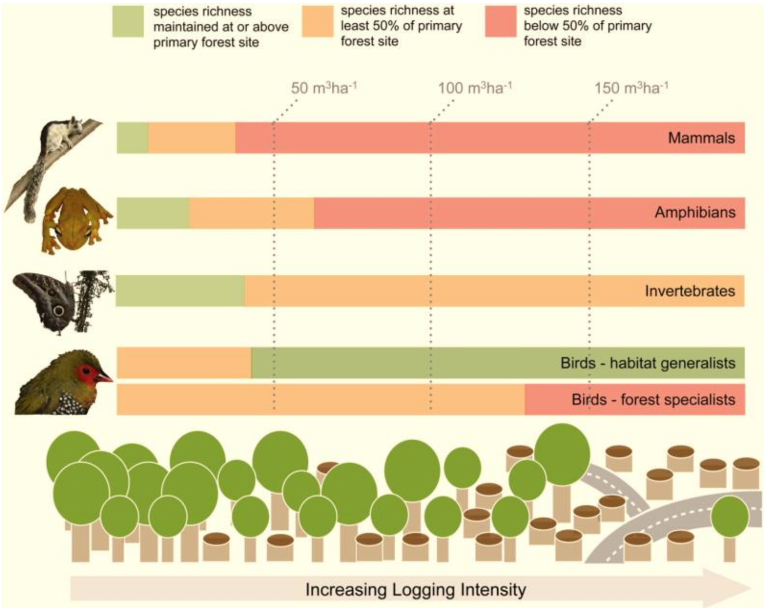

Figure 3. The effect of logging intensity on the species richness of several groups of organisms. Species richness of mammals, amphibians and invertebrates decreases as logging intensity increases, with mammals and amphibians losing half of their species at logging intensities of 38 m^3 ha^{-1} and 63 m^3 ha^{-1}, respectively. The response of birds varies with the group of birds considered: generalist birds increase in density in heavily logged areas while forest specialist birds decline. Figure taken from Burivalova et al. 2014 [9] (Graphical Summary in Supplementary Material).

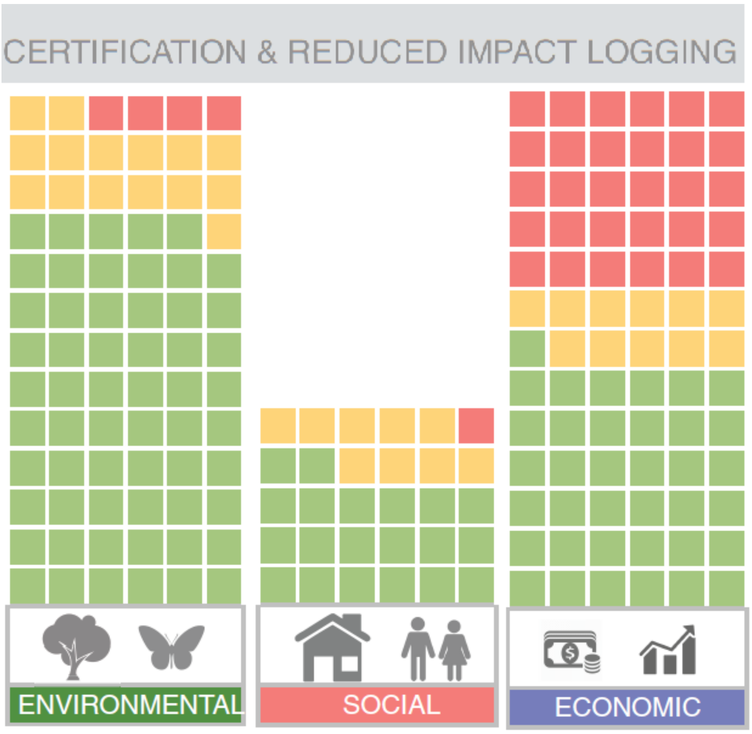

Figure 4. Overview and outcome of certification and RIL conservation strategy in terms of environmental, social and economic outcome. Red squares represent negative outcomes (i.e. worse than control sites), yellow corresponds to neutral outcomes and green to positive outcomes. Individual squares do not have equal value, cannot be cancelled out, and summarised into overall effect sizes. Figure taken and adapted from Burivalova et al 2019 [29].

4. Impact of FSC certification on managed tropical forest

We evaluated the impact of FSC certified concessions of natural tropical forest management on the environment, financial viability as well as social cohesion. This should be put in contrast to conventional logging activities in the tropics and gather evidence on the positive and negative effects of these values.

The literature search of publications focussing on the impact of certification brought up 56 publications. After the first selection, 33 publications were retained as they contained primary data concerning the environmental, economic, or social impact of FSC concessions. Additionally, one unpublished study was included. The broader range of publications on tropical forest management, help place these limited results into context.

Most published studies focused on environmental impacts, followed by social and economic impacts. Some studies combined two categories, e.g. socio-economic. In these cases, each impact category was evaluated separately. As in each impact category, several aspects could be evaluated at the same time, we classified the outcome of the study inconclusive if both positive and negative outcomes were recorded, but without clear indication of the studied effect. In cases where no significant differences were found, the study was rated as neutral. Studies categorised either positive or negative showed significant different results to the reference site (e.g. conventional logging concession or old-growth forest) and were judged by the respective authors to have overall a good or bad effect on the specific impact type (environmental, financial, social). Although, the here presented publications look into case study on a local, national, regional or global level, we do not differentiate by the publication's scope of investigation, also because the number of publications is rather limited. However, we acknowledge that local studies are not always comparable to another setting. The weighing of the importance is, therefore, not carried out. Meaning that each study has the same weight and Table 2 shows the percentage of positive and negative impact per value type.

In general, the majority of the publications find FSC certification to be beneficial for forest management in the tropics. In the following subsections, we summarized the effect of FSC on environmental, economic and social values.

Table 2. Overview of publications on environmental, economic and social impacts of certification. Conclusions are shown per impact type.

Type of certification impacts	Positive	Neutral	Negative	Incon-clusive	Total	% Positive	% Negative
Environmental impacts	12	4	6	1	23	52 %	26 %
Economic impacts	0	1	4	1	6	0 %	67 %
Social impacts	4	0	2	1	7	57 %	29 %
Total	**16**	**5**	**12**	**3**	**36**	**44 %**	**33 %**

4.1. Environmental impacts

Out of the 23 studies assessing the environmental impacts of certification, 12 found a positive, four a neutral, six a negative effect and one study was inconclusive. Most of these publications focused on biodiversity and species abundance (10), some on carbon storage or CO2 emissions and a few on forest disturbance, deforestation or conservation.

4.1.1. Biodiversity and species abundance

The conservation responsibility of certified forest concessions becomes evident when looking into the distribution of birds. A pantropical study in nine countries analysed the presence of 537 bird species in managed and unmanaged tropical forests. The abundance of 104 tropical forest birds declined over time in selectively logged forests, of which 55 species occurred in concessions of the study countries became less abundant. It was found that on average 26% of a species' in-country forested range overlapped with a logging concession, with 32 species having >50% and 5 species >75% of their national range within a logging concession. From all sites, Borneo showed the highest concentration of bird species vulnerable to selective logging (25 in total) [30]. Another study in Peru determining the acoustic space used, soundscapes composition and bird richness did not find significant differences in species richness and composition between FSC concessions, non-FSC concessions and control sites. However, the mean acoustic space used was higher in the FSC sites than in non-FSC and control sites, indicating a greater richness of acoustically active birds [31].

Several other studies on animal abundance focused on mammals. RIL in Brazil had a negative impact on bat species due to increased canopy openings after logging compared to a control site (unlogged forest plots) [32]. The response of the bat assembly was fast reflects the short-term impacts of RIL. Furthermore, the general composition of understorey bat species and phytophagous bats changed. Yet, the bat composition in the control site also altered in the observation period, indicating that other factors may have influenced the bat assemblages [32]. Two studies carried out in the Republic of Congo found that ape density differed between certified (1.05 and 2.1 individuals/km²) and unlogged forest (1.43 and 1.47 individuals/km²) [33]. This was explained by the increase of mean herbaceous stem density in the concession [33] on which chimpanzees feed on [34]. However, chimpanzees are more sensitive to logging as they nest significantly closer to the ground in disturbed forests. The same was the case for gorillas, but not significantly [33]. Gorillas were associated with more heterogeneous habitats and were attracted to recently logged areas with abundant terrestrial herbaceous vegetation [34]. They also avoided active timber exploitation sites and roads, while chimpanzees nest encounter rates decreased with increasing intensity of human impact [34]. This underlines the importance of measures for the protection of ape in FSC concessions.

That landscape context and forest disturbance are important also holds true for jaguars [35]. In this Latin American study across Bolivia, French Guiana, Guatemala and Nicaragua jaguar prey was most abundant in remote areas or logged areas close to protected areas or with an overlap [35]. It was concluded that adequate logging management can maintain jaguar populations. Particular attention should be given to efficient access control in FSC managed forests, because hunting has a negative effect on jaguar frequency [35]. A case study from Guatemala and Peru also found that well-managed logging concessions can maintain important populations of large and medium-sized mammals. Especially large herbivores and large carnivores are present as long as hunting is controlled in combination with low timber volume removal (1.2 – 3 m^3/ha) [36]. Similarly, it was found that FSC - certification has a positive impact on the abundance of mammals over 10kg compared to non-FSC concessions in Central Africa. Overall, more animal observations through camera-trapping were made in the seven FSC concessions compared to seven non-FSC concessions. In many regions of the tropics the greatest threat to wildlife species in areas managed for timber arises through the intensification of hunting. This reflects improved access and the presence of forestry crews. We thus specifically mention recent studies (still unpublished) showing that, at least in Central Africa, the FSC regulations aimed to reduce the (hunting) pressure on large mammals, including high priority conservation species like forest elephants, large carnivores and primates and contributes to their conservation (Zwerts, 2022) The same has been observed for forest concessions in Bolivia (Peña Claros, pers. observation).

A correlation between road proximity to an intact forest landscape (IFL) and wilderness vulnerability was found in the Republic of Congo, highlighting the negative impact of road network and its expansion [33]. This is in particular relevant for FSC concessions, as the road network established is much more sophisticated and the roads tend to be larger than in non-certified forests [37].

A study carried out on Malaysian Borneo revealed that in one FSC concession (Deramakot) threatened animal species occupy larger areas than in non FSC concessions and account for higher level of species richness [38]. Camera-trapping in the same concession confirmed that certified managed forests did harbour endangered species compared to non-FSC certified forests [39]. The long-time certified concession showed species richness and functional diversity measures comparable to unlogged forest [39]. The application of RIL since 1995 in Deramakot seems to benefit the presence of certain IUCN-listed mammals in this particular FSC concession [38]. The camera-traps did not record any hunters throughout the study period, the presence of hunting pressure from nearby villages cannot be ruled out. Yet the certification status alone is not a sufficient to safeguard the biodiversity value of a forest, it needs continuous and periodic re-evaluation over time to assess the mammalian richness [38]. But logged forests in Sabah still retain unique assemblages that can be discussed through perspectives in beta, phylogenetic and functional diversity of vulnerable species, which are essential in conserving terrestrial mammalian biodiversity [39].

Studies that monitored the richness of fauna through camera traps or line transect observation mostly found positive or no impact of certification versus non-certified forest on the presence of animals. According to the presented studies, we can say that species richness and conservation values were mostly maintained in FSC concessions. RIL has clear advantages over CL in terms of animal abundance. This was also found by a recent meta-analysis revealing that RIL is less detrimental for birds, arthropods, mammals and especially bats [40]. When logging intensity is considered, this advantage become smaller [29]. In Central Africa, human pressure on wildlife through hunting was found to be lower in RIL harvested areas than in CL [41]. FSC certified forests harbour endangered species and through good management populations can be preserved.

4.1.2. Carbon storage and emissions

The two FSC concessions Deramakot and adjacent Tangkulap in Sabah, Malaysia had a greater carbon storage after five years, but forest intactness only increased in the less heavily logged stand, i.e. Deramakot. So, the logging history of a stand plays a key role on its recovery [42]. Certified concessions in Indonesia did not emit less carbon dioxide per unit area harvested from logging activities (felling, skidding, hauling) than non-certified concessions, except for skidding [43]. Similarly, no significant differences in carbon emissions were detected in Gabon, Democratic Republic of Congo and the

Republic of Congo between six FSC and 17 non-certified concessions [44]. Overall, skidding did account for the smallest portion of emissions (6%), followed by felling (44%) and hauling (50%). FSC concessions emitted less carbon through skidding, felling and hauling operations, but never significantly. The emissions from felling were mostly contributed by felled trees left in the stand (22%), and the felling damage (13%) as well as to a lesser extent by extracted wood (9%). Overall, the biggest carbon emission was recorded for the logging road construction (45%). While the establishment of log landing site contributed merely 5% of CO2 emissions [44] On the whole, due to wider road constructed in FSC-concession, the carbon emission was larger compared to uncertified forests, but not significantly [44]. In Peru, slightly lower emissions per unit timber (volume and carbon) were found in certified FMU, except for roads. Findings from Central Africa, that FSC concession have larger roads than in non-certified concessions were also reported [37]. On the contrary to the study in Central Africa, logging infrastructure (skid trails and log yards and roads) contributed little to emissions, whereas 65% of emissions originated from logging operations of crop trees (extracted log and crop tree residuals) [37]. Another study from Mexico did also not associate FSC certification with difference in carbon emissions from selective logging. Nonetheless the application of RIL-C did result in fewer damaged trees and lower carbon emissions in ejidos with high logging intensities, of which two are FSC certified. These two sites showed similar emissions, but performed better than most non-certified concessions [45]. A pan-tropical study showed that RIL-C adopation can potentially halve the carbon emissions, allthough it did also not find evidence that certified FMU have lower emission than uncertified FMU [46].

Two other studies investigated the effect on above-ground biomass (AGB) and forest disturbance. In Gabon volume harvested in a FSC concession was lower (5.7m³/ha) than in conventional logging site (11.4m³/ha) and AGB loss was also less (2.9% and 6.3% respectively). So, the authors concluded that despite differences in logging intensities, certification yielded environmental benefits in terms of carbon and reduced damage on residual stand [47]. In Brazil, four indicators of disturbance were compared amongst RIL, CL and not controlled (illegal) logged sites. Frequency of disturbance was similar between the 17 CL and 19 RIL plots, as they were only logged once in 15 years, while the 45 plots with illegal logging practices were logged three times. Overall, RIL showed the lowest impact on maximum intensity, mean and cumulative disturbance. RIL reduced the effect in terms of canopy openings too, but not in terms of AGB [48].

We can say that studies on carbon storage and emissions showed a positive environmental impact from FSC certification and well-planned forest operations. The carbon emissions were similar or lower in RIL sites than CL. Good Road construction as part of RIL, is to reduce skidding distances and thus damage to residual stand. Contradictory is the cause of carbon emissions. A study from Central Africa accounts road construction as main source of emissions, while in Peru the log extraction was the main source of emissions. We nevertheless conclude that RIL has advantages over CL in terms of carbon emissions and residual stand damage. [40]. Low intensity disturbance led to little loss of AGB [47]. The AGB loss determines the time needed to recover to the initial AGB values and it varies with volumes extracted [49]. We thus stretch the importance to further develop RIL techniques and continuously include them in the FSC indicators.

4.1.3. Conservation, forest fragmentation and deforestation

Studies of the influence of FSC certification and good forest management on forest cover loss, deforestation and conservation yielded mixed results. An analysis of data between 2000 and 2013 of intact forest landscape (IFL) in Central Africa indicated that FSC-certified concessions had a higher pace of fragmentation within their boundaries than in IFLs outside. This was explained by the establishment of roads and the selective logging practice [50]. The planning of forest operations through a forest management plan may have increased the deforestation in certified Congolese concessions. The timber production was higher and more stable compared to actively exploited forests without forest management plan [51]. The impact of certification on tree cover loss varied in sites in Brazil, Gabon and Indonesia compared to other FMU in the same landscape. The concession in Gabon showed no difference to a non-certified FMU, in Indonesia a small, insignificant and in Brazil a significant, but varying impact on tree cover loss [52].

A study carried out in Cameroon found that current logging practices do not allow the forest to regrow sufficiently to sustain yields. The projected volume available in the next cycle will be between 21 – 36%. Even the lengthening of the logging intervals will not be sufficient to obtain same yields over time. One suggestion was to opt for species-specific volume removal, which could yield up to 73% of the initial harvested amount [53].

Certified community forestry in Tanzania positively impacted the conservation effectiveness and improve the conservation effects with neighbouring national forest reserves [54]. FSC concessions in Kalimantan, Indonesia had an increased forest cover of nearly 5% in a time span of eight years. However, perforated area (fragmentation) was increased in FSC sites by 3.82 km² on average due to selective logging practices. In addition, the air pollution was reduced by 31%, even though fire incidence did not differ significantly with non-certified concessions [55].

The publications on forest cover loss, deforestation and conservation yielded mixed results. Increased fragmentation related to certified forests was reported. The planned operation written in a managed plan seemed to favour deforestation. The level of disturbance plays the central role of biodiversity change, this was also revealed by other scientists. Supported by the results above and a recent study [29], we concluded that the RIL showed better results than CL in terms of forest fragmentation and degradation.

4.2. Economic impacts

Few studies analysed the financial impact (6 out of 33 studies, Table 2) and when they did most of the outcomes were negative. In Mexico certified community forests had lower management costs per unit, but also had lower returns than non-certified forests. FSC concessions were smaller and had lower sales numbers [56]. Indigenous forest landowners in Papua New Guinea were unable to develop a financially viable business model for small-scale native forest management. Although the six organisations received training and funding, the operators of portable sawmills did not meet the quality and quantity required by the buyers. This led to ceasing of lumber purchases. Furthermore, the landowners struggled to adhere to FSC principles, eventually resulting in the loss of their certificate [57]. A similar story was reported from Indonesia, where community forestry did not provide the agreed annual timber volume to the industry agreed in the annual harvest plan. This made it difficult to maintain a business relation between the community and sawmills [58].

The number of FSC certificates provided to timber concessions in natural forest in Bolivia decreased in the early 2000s and 2010s. Interviews with various stakeholders identified three main reasons for the decline: Legal and land-tenure insecurity, lack of support from the government and economic downturn. Another aspect was the rise of domestic and regional demand for non-certified wood products [59].

Meaning that the framework for companies to successfully run their business is important. A study from Brazil also indicates that insecure land tenure ship in combination with complex registration and permit obtainment impedes Amazonian smallholder and communities to do legal forest management. The hurdles seem too high for communities to continuously run a responsible forest operation. The market of the primary forest products are mostly domestic or for the growing South-South trade [60].

The current definition of intact forest landscapes (IFL) likely penalises FSC certified enterprises with regard on the establishment and maintenance of their road network. Nonetheless, the management standards are better than CL and non-certified concessions [61]. The land sharing approach with low intensity evenly spread throughout a forest stand is more profitable than different types of land sparing. In Brazil fragmented and block land sparing were compared with land sharing option. With increased logging intensity the profitability of land sharing decreased but was still higher than other forms of land sparing. It was suggested that other financial incentives like carbon-based payment schemes or timber certification are needed to cover the opportunity costs of land sparing and thus reduce the ecological damage to tropical forests [62].

Six studies were found on the economic value of FSC. These studies are sometimes compared to conventional and sometimes to illegal logging operations. These practices do not adhere to the same principles nor must meet these standards. A recent meta-analysis found that FSC-RIL is less profitable than CL [29]. Certification brought higher timber prices and improved market access, but also increased pre-logging costs from planning [29]. Only some studies reported on community forest management and that the communities struggled to run the operations due to structural challenges. The meta-analysis showed mixed results in terms of economic value of community forest management [29]. Financial difficulties of certified forest enterprises were reported from Central Africa. This led to the selling of the concessions to companies that seemed unwilling to continue the certificate. Today there is only one FSC concession left in Cameroon [63], indicating possible high competition with other logging concessions and challenging to operate profitable, but can be partially explained due to the high forest taxes in the country [63].

The studies appear too few and too mixed to fairly evaluate the economic value of FSC certification in general. Although there is little evidence on the positive economic impact of FSC, we cautiously draw the conclusion that favoured by higher timber sales prices and better market access in combination with better planned operations compared to CL, FSC has some financial advantages if the initial investments in training, planning and certification can be met. We suggest scrutinizing this further as well as to consider the revision of the definition of IFL mentioned above.

4.3. Social impacts

In total seven publication assessed the social impact of certified logging. Four reported a positive impact on social values, while two were negative and one was inconclusive. Interviews of rural forest community in Cameroon asked the type of the ecosystem services (ES) provided. Overall, respondents mentioned most frequently provisioning (93%) and cultural & amenity services (68%), whereas regulating services were less stated (16%). Most important types of provision were non-timber forest products (84%), meat provision (60%), cultural heritage (50%), fish (36%), wood (35%) and traditional medicine (30%) [64]. This underlines the dependency of forest populations on protein sources through hunting and subsistence livelihood. There were slight variations amongst forest land allocation type. In particular, the identification of at least one cultural & amenity ES was more often identified by interviewed persons from the protected area (93%) than community forestry (57%) and concession (53%) [64]. The perception on ES abundance of people living in or around a FSC concession only differed slightly with those living in a protected area and community forestry [64]. As described above certified community forest management in Papua New Guinea and Indonesia struggled to operate financially viable, despite being regarded as better for the environment [57], [58].

In Brazil a case of community forestry also describes that an association established a sustainable way of timber exploitation, after improving its technical, social and managerial skills. The association obtained environmental licences as well as forest certification, but eventually had to discontinue its activity due to changes in forest policies and lost its FSC certificate. The new legal requirements ended CFM-oriented regulations and hence the association's successful path, ultimately leading to failure [65]. In Guatemala scientists studied the migration characteristics of forest concession communities, i.e. people living in and around managed forests. They found that migration was not driven by the prospect of a potential CFM concession membership, although it offered opportunities [66]. It was also concluded that the Maya Biosphere Reserve with active FSC concessions can conserve the forest, while providing benefits to household members adjacent to the concession [66].

A study in Tanzania identified a positive impact on human wellbeing, a reduction on gender inequality and improved conservation and social interaction effects between nice certified CFM and national forest reserves [54]. FSC certified CFM in Indonesia reduced the fuelwood dependence by 33%, the incidence of acute respiratory illness by 32% and of malnutrition by 65%. In addition, the village funding was increased by 8% compared to non-certified settlements [55].

Social effect remains inconclusive as few studies were found with limited scope. However, the few publications report positively on people's well-being and livelihood conditions. This is in line with another meta-analysis, stating the living conditions improved or remained unchanged. Furthermore, FSC certification was associated with a higher compliance with existing labour laws and other regulations [29]. The case study on ES from Cameroon shows the importance of provision of forest products to people living in the forest. Especially in Central Africa, hunting plays a major role for these communities [41].

5. Diversification of timber species

We evaluated the effects of a more diverse utilisation of available timber species, the so called "lesser-known timber species (LKTS)" on environmental impacts of selective logging. A previous study commissioned by FSC Netherlands suggests a positive environmental and social effect of using LKTS [67]. So, we searched specifically for publications with information on their regeneration dynamic of LKTS in natural tropical forests. The initial search on lesser-known or lesser used timber species has brought up very few results. From the preliminary search, in total 12 publications were retrieved from the search on Scopus and Web of Science. Therefore, for this chapter, we contacted scientists from CIFOR, CIRAD, CATIE and SHR about other publications and their knowledge or experience regarding LKTS. The broadening of the search, including older studies, technical reports, reference guides on LKTS and personal communication, that gave more insights on the topic through 18 additional publications. This section of the report presents the findings and discusses the broader usage of timber species.

The detailed results of publications cited on 132 timber species are found in the annex in Supplementary Table 2. Figure 5 summaries the type of study and the outcome of the reports and publications on LKTS. Further information on publications on LKTS can also be found on the page of The European Sustainable Tropical Timber Coalition (https://www.europeansttc.com/species/). We highlight the reference guide published by WWF, showing alternatives for commonly traded timbers (http://awsassets.panda.org/downloads/wwf_gftn_lkts_guide_final_july_2013_1.pdf).

5.1. Definition of lesser-known timber species

The term "lesser-known timber species" has been getting more attention in recent decades and refers to species of low importance for the international market, though they might have domestic importance [68]. This classification can be misleading, as some information on some species properties is available e.g., on technological characteristics of 245 tropical timber species by CIRAD (Technical sheets available - Tropix 7 - CIRAD). Sometimes the terms "lesser-utilised timber species" and "lesser-used timber species" are utilised interchangeably but imprecisely as they may comprise different species [69]. For this report we included all publications on species that were referred to as LKTS, because it was not always clear if the authors make that distinction, and the naming varies. Most publications refer to LKTS species that play a minor role in forest management or timber industry today (or at the time of the publication) but are used nationally or are mentioned as alternatives for over-exploited species.

5.2. Importance of a diversified timber usage

The timber industry prefers the harvest of species, whose appearance (colour) and texture is desirable and wood qualities are proven, such as workability and durability, while at the same time are abundant [70]. Furthermore, the productivity and the range of application of the timber is also of importance [71]. Yet, the selective logging in tropical America of few commercialised species such as Mahogany (*Swietenia macrophylla, Swietenia humilis, Swietenia mahagoni*), Ipê (*Tabebuia impetiginosa*), Cedro (*Cedrela odorata*) and Jatobá (*Hymenaea courbaril*) amongst others, has led to a depletion of these species and subsequently, endangering their existence [72], [73]. From Australia, the case of red cedar

(*Toona ciliata*) is reported, which was once the main harvested tree species, till it became nearly extinct and local timber cutters diversified their use of species [71]. In Central African Republic currently, only eight timber species account for 80% of the total timber production [74]. All these examples show the need to diversify the logged species and explore further the potential of other species. Especially, as current yields cannot be sustained at the current level on the long term [6]. So, the utilisation of LKTS is one important key element to contribute to more flexible forest management [75]. However, not all species have been sufficiently studied in terms of wood properties, possible application and silvicultural management, knowledge remains somewhat scarce or at local level and there is a need to better understand their natural disturbance regime as a basis for sustainable forest management practices in tropical moist forests [76].

5.3. Mechanical and wood properties of lesser-known timber species

The majority of the studies found are investigating specific wood properties such as density, fibre length, wood anatomy, tangential shrinkage, ease of working, durability, resistance to rot, termites, and other mechanical properties of local lesser-used species, to determine their potential for different applications. The proposed usage of the species covers interior usage, such as door framing, furniture, wall panelling, flooring, plywood and veneer, outdoor use in window framing, but also pulp and paper production as well as heavy construction [77]–[90]. *Terminalia amazonia* from Honduras has better mechanical properties than Mahogany, indicating that it is a potential timber for structural applications, though further research on its physical, chemical and anatomical properties is needed, to verify if it could be used as alternative [89]. We want to add here that the appearance and workability are important to find substitutes of mahogany. One review reported on LKTS from Mozambique [91]. Other researchers performed thermo-mechanic tests on different timbers [92] or estimated the climate adaptability of *Eucalyptus* spp in its native range across Australia. [93]. The findings provide valuable information on the potential habitat conditions for *Eucalyptus* spp plantations, rather than natural managed forests.

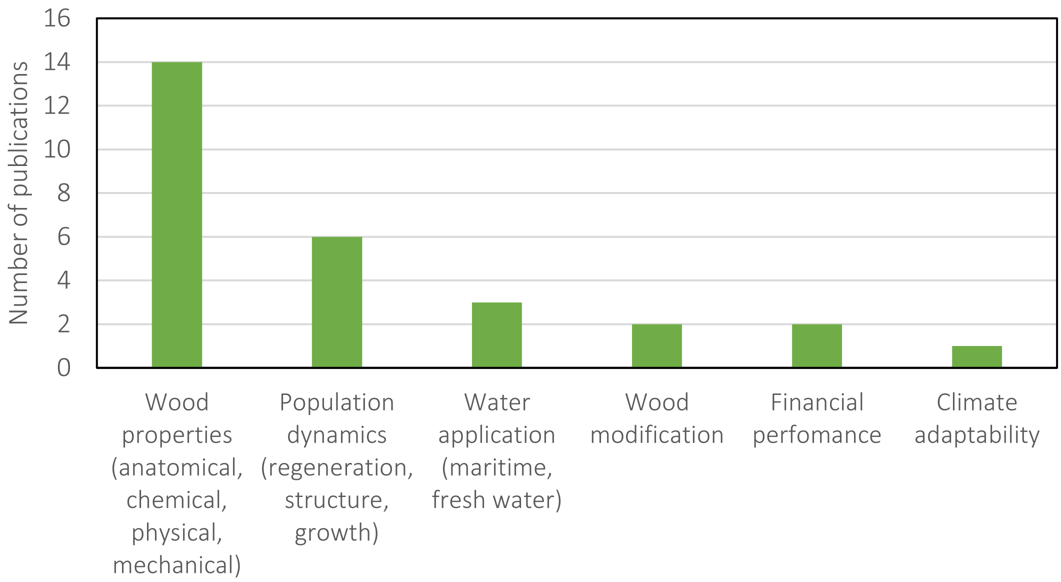

Figure 5. Number of studies per topic on lesser-known timer species (LKTS).

5.4. Species regeneration, population dynamics and seedling selection

One study evaluated the regeneration and management of 16 lesser-known timber species in Peru after three types of disturbance, but with varying results. For nine species conclusions could not be drawn for silvicultural species-specific characteristics due to limited regeneration. Six species showed better regeneration at the least disturbed site, while *Cariniana sp*. regrew best on the intermediately disturbed site [76]. Another study presented the volume of Bolivia's growing stock for numerous LKTS and stretches the importance of a more diverse timber use to achieve sustainable forest management [70]. Two studies in Central America studied the population structure and dynamics of the endangered species *Guaiacum sanctum* [94]–[96]. The genus of *Guaiacum* was indicated for high durability besides *Guazuma crinita* and *Callycophyllum spruceanum* (Guariguata, 2022). The two latter pioneer species were mentioned to have been more widely used by small scale farmers for income sources. Two studies evaluated their financial potential comparing early and late selection of seedlings and as option of livelihood improvement for rural population [97], [98]. One study analysed the population regrowth, the stem and crown shape and illumination availability of *Callycophyllum spruceanum* on a small forest patch in the Peruvian Amazon eight years after abandonment [99].

5.5. Alternative timber species in maritime application

With the enlarged scope of the search, three reports were found focussing on the effect of maritime and fresh water construction of several LKTS [100]–[102]. Greenheart (*Chlorocardium rodiei*) and Azobé (*Lophira alata*) are well known timber species valued for their use in marine applications. Alternatives are, according to their resistance to gribble shipworms and other woodboring invertebrates and rot, Niové (*Staudtia kamerunensis*), Sougé (*Parinari excelsa*), Supucaia (*Lecythis paraensis*), Tatajuba (*Bagassa guianensis*) or Timborana timber (*Enterolobium schomburgkii*) [100]. These results were confirmed in a later study, also comparing LKTS against the two benchmark marine species, with the exception for Niové, which was found to be less resistant to shipworms than the two reference species (Azobé and Greenhear) [101]. If attrition is not of major importance, other species like Basralocus (*Dicorynia guianensis*), Cloeziana (*Eucalyptus cloeziana*), Dabéma (*Piptadeniastrum africanum*), Garapa (*Apuleia leiocarpa*), Mora (*Mora excelsa*), Okan (*Cylicodiscus gabunensis*) and Piquia (*Caryocar glabrum*) could be used as substitutes [100]. The later report concluded that Cloeziana, Dabéma, and Mora performed poorly against marine attack. Only for Okan and Basralocus were good results found, and to a lesser extent for Garapa and Piquia [101]. A test in fresh water showed that LKTS like Araracanga (*Aspidosperma megalocarpon*), Cupiuba (*Goupia glabra*) and Manbarklak (*Eschweilera subglandulosa*) showed little decay after 11 years immersion and remained in good condition with no signs of decay [102].

5.6. Summary

The term lesser-known timber species can be confusing, especially as many of the LKTS are known and can have a large market share nationally but are not yet internationally commercialised. Information on the wood properties is well documented in many cases, however formal studies of these species are typically scarce. The studies are only partially comparable and focus on many different species. Once a species gains substantial interest of the market, it may be exploited heavily. Yet the timber market is conservative and still prefers only a set of few species. The advantage of a more diverse utilisation of species as for the timber stock recovery are documented [10]. This report has also shown that in most areas studied current logging intensities and cutting cycles cannot sustain timber yields for the species being cut, so using a wider list of species can support sustainable forest management under particular conditions and ensure the recovery potential of the forest. However, regrowth patterns of LKTS are understudied, so the promotion of species should be done cautiously. Yet, we see a trend towards diversification.

6. General summary

We reviewed recent scientific literature on tropical forest management and certification. In addition, we also consulted experts on this topic and based findings on the broader scientific literature and on our own experience.

Effects of timber exploitation on tropical forests

In 2012, Putz et al reported on a study of selectively logged tropical forest in an effort to “examine the extent to which these forests sustain timber production, retain species, and conserve carbon stocks.”. Their meta-analysis based on data from more than 100 publications “revealed substantial variability but that: timber yields decline by about 46% after the first harvest but are subsequently sustained at that level; 76% of carbon is retained in once-logged forests; and, 85–100% of species of mammals, birds, invertebrates, and plants remain after logging. Timber stocks will not regain primary-forest levels within current harvest cycles, but yields increase if collateral damage is reduced and silvicultural treatments are applied”. The authors went on to note that “Given that selectively logged forests retain substantial biodiversity, carbon, and timber stocks, this “middle way” between deforestation and total protection deserves more attention from researchers, conservation organizations, and policy-makers. Improvements in forest management are now likely if synergies are enhanced among initiatives to retain forest carbon stocks (REDD+), assure the legality of forest products, certify responsible management, and devolve control over forests to empowered local communities.”

The overall findings of the Putz et al. 2012 meta-analysis on the impact of timber exploitation in natural tropical forests remain supported. In terms of timber volume recovery, recent studies found that approximately 50% of the timber volume extracted during the first cut is recovered after one logging cycle. Higher recovery can be reached with substantial increases in logging cycle length or reductions in logging intensity. The main explanation for this low recovery is the fact that at first cut large and old trees are extracted, the “primary forest premium”. Thus, recovery percentages are likely higher during the second – and later – cycles, but few studies have examined this.

Compared to a decade ago, more studies are available on carbon recovery (mainly above ground biomass) in tropical forests managed for timber. Recent studies have shown that forest biomass and carbon stocks in selectively logged tropical forests can reach pre-logging levels within one typical logging cycle (20-30 years) when logging intensity is relatively low (< 30 m^3/ha).

Biodiversity levels in tropical production forests remain high and the total number of species may even increase after logging. Yet, the composition of animal and plant species shifts, typically with already more common species that benefit from disturbance increasing, while disturbance-sensitive species decline. There are, however, very few long-term studies assessing how composition of animal and plant species changes through time as the forest recovers from logging disturbances.

Impact of FSC certification

The majority of the reviewed studies examining FSC certification reported overall positive effects. This picture changes when evaluating per impact category. Environmental impacts were positive in half of the studies and negative in a quarter of cases. These impacts were related to biodiversity retention (including hunting bans), carbon storage and deforestation rates. Economic impacts were negative in two thirds of the studies, but the number of studies was very limited. Social impacts were also poorly studied, but generally found to be positive.

Effects of diversification of exploited species

Studies on lesser-known timber species (LKTS) remain limited in number, scope and scale. Most focused-on wood properties on a few species, reporting those on websites and reference guides. Of those assessed many species were found to be suitable for timber. Consequently, it would be useful for managers, the industry and the government to consolidate the existing information in one single database.

Very few studies have been conducted on the potential contribution of LKTS for sustaining timber yields in the long-term. An Amazon-wide simulation study showed that the inclusion of close to 500 LKTS, might increase timber recovery within the first logging cycle from 50 to 70%. But more information on these species is needed to be able to fully assess their contribution to sustaining timber yields, and to define adequate management practices to manage them properly.

7. Recommendations for FSC and its stakeholders

Based on our assessment focusing on recent scientific literature, consultation with experts and our own experience in studying tropical forest management, we have the following recommendations for FSC and its stakeholders:

1. Formulate measures and associated indicators that support a quantitative assessment of the criterion “harvest products ... at or below a level which can be permanently sustained” (criterion 5.2) in the FSC principles and criteria. This is needed to ascertain that timber production is sustained, either compared to the first cut or the second cut.
2. Promote species- and area-specific measures as indicators or standards for logging intensity, length of logging cycle and minimum cutting diameter. Encourage certified organizations to apply these in their monitoring and evaluation (criterion 8.2 lacks specificity) and in their evaluation of silvicultural treatments needed to enhance forest productivity (principle 10). Such indicators would reflect species-specific information about volume growth and minimum volume (recovery) after the first or second logging cycle. These indicators should be flexible and should be refined and adjusted to the local context as new information becomes available (as stipulated in criterion 8.3). These situation-specific criteria are needed to reduce the risk of population decline and loss.
3. Encourage measures and indicators that stimulate increasing the number of exploited timber species in certified forests. The current criterion (5.1) does not call explicitly for diversification. When diversifying, the maximum volume extracted per area should be kept within ecological limits, and congruent with measures considered in criterion 5.2. These indicators would help to sustain timber yields over time, either compared to the first cut or the second cut.
4. Facilitate and stimulate market access of certified tropical timber to substantially increase the proportion of certified natural tropical forests managed for timber. This is needed to increase the contribution of FSC certification to the conservation of tropical biodiversity, to the maintenance of important carbon stocks, and to the livelihood of local and indigenous people managing their forests for certified timber production.
5. Seek, explore and promote options to significantly increase the market value of FSC-certified tropical timber from natural forests, and to reduce costs incurred in the process of obtaining and renewing FSC certification. Both shifts are needed to overcome the sometimes-negative economic impact of FSC certification.
6. Initiate and support studies on social effectiveness and economic/financial implications of FSC certification. This is needed to support claims on social and economic advantages of certification, which – at present – lack clear evidence.
7. Initiate and support studies to determine the conditions that allow timber yields to be sustained over time (either compared to the first cut or the second cut), including the contribution of diversification of exploited species.
8. Where possible, encourage, promote and support larger-scale long-term studies with adequate replication and controls to permit robust conclusions on how forest recover from logging, and how timber volume recovery can be enhanced.

8.References

[1] F. E. Putz *et al.*, “Sustained Timber Yield Claims , Considerations , and Tradeoffs for Selectively Logged Forests,” no. July, pp. 1–7, 2022.

[2] M. Vogt and C. Weber, “Current challenges to the concept of sustainability,” *Glob. Sustain.*, vol. 2, 2019, doi: 10.1017/sus.2019.1.

[3] F. E. Putz and M. A. Pinard, “Reduced-Impact Logging as a Carbon-Offset Method,” *Conserv. Biol.*, vol. 7, no. 4, pp. 755–757, 1993, doi: 10.1046/j.1523-1739.1993.7407551.x.

[4] D. P. Edwards, J. A. Tobias, D. Sheil, E. Meijaard, and W. F. Laurance, “Maintaining ecosystem function and services in logged tropical forests,” *Trends Ecol. Evol.*, vol. 29, no. 9, pp. 511–520, 2014, doi: 10.1016/j.tree.2014.07.003.

[5] P. Sist, P. Pacheco, R. Nasi, and J. Blaser, “Management of natural tropical forests for the future,” vol. 32, pp. 1–4, 2015.

[6] F. E. Putz *et al.*, “Sustaining conservation values in selectively logged tropical forests: The attained and the attainable,” *Conserv. Lett.*, vol. 5, no. 4, pp. 296–303, 2012, doi: 10.1111/j.1755-263X.2012.00242.x.

[7] J. P. Romanelli, M. C. P. Gonçalves, L. F. de Abreu Pestana, J. A. H. Soares, R. S. Boschi, and D. F. Andrade, “Four challenges when conducting bibliometric reviews and how to deal with them,” *Environ. Sci. Pollut. Res.*, vol. 28, no. 43, pp. 60448–60458, 2021, doi: 10.1007/s11356-021-16420-x.

[8] S. Nakagawa *et al.*, “Research Weaving: Visualizing the Future of Research Synthesis,” *Trends Ecol. Evol.*, vol. 34, no. 3, pp. 224–238, 2019, doi: 10.1016/j.tree.2018.11.007.

[9] Z. Burivalova, Ç. H. Şekercioğlu, and L. P. Koh, “Thresholds of logging intensity to maintain tropical forest biodiversity,” *Curr. Biol.*, vol. 24, no. 16, pp. 1893–1898, 2014, doi: 10.1016/j.cub.2014.06.065.

[10] C. Piponiot *et al.*, “Can timber provision from Amazonian production forests be sustainable?,” *Environ. Res. Lett.*, vol. 14, no. 6, 2019, doi: 10.1088/1748-9326/ab195e.

[11] C. Piponiot *et al.*, “Optimal strategies for ecosystem services provision in Amazonian production forests,” *Environ. Res. Lett.*, vol. 14, no. 12, 2019, doi: 10.1088/1748-9326/ab5eb1.

[12] P. Sist *et al.*, “Sustainability of Brazilian forest concessions,” *For. Ecol. Manage.*, vol. 496, no. June, p. 119440, 2021, doi: 10.1016/j.foreco.2021.119440.

[13] W. D. Hawthorne, D. Sheil, V. K. Agyeman, M. Abu Juam, and C. A. M. Marshall, “Logging scars in Ghanaian high forest: Towards improved models for sustainable production,” *For. Ecol. Manage.*, vol. 271, pp. 27–36, 2012, doi: 10.1016/j.foreco.2012.01.036.

[14] R. J. W. Brienen and P. A. Zuidema, “Incorporating persistent tree growth differences increases estimates of tropical timber yield,” *Front. Ecol. Environ.*, vol. 5, no. 6, pp. 302–306, Aug. 2007, doi: 10.1890/1540-9295(2007)5[302:RCPTGD]2.0.CO;2.

[15] P. Sist, R. Fimbel, D. Sheil, R. Nasi, and M. H. Chevallier, “Towards sustainable management of mixed dipterocarp forests of Southeast Asia: Moving beyond minimum diameter cutting limits,” *Environ. Conserv.*, vol. 30, no. 4, pp. 364–374, Dec. 2003, doi: 10.1017/S0376892903000389.

[16] D. B. Clark and D. A. Clark, “Abundance, growth and mortality of very large trees in neotropical lowland rain forest,” 1996.

[17] R. S. A. R. Van Rompaey, “Contribution of big trees to total forest production: a case study in Taï National Park, Côte d’Ivoire,” 1997.

[18] D. B. Lindenmayer, W. F. Laurance, and J. F. Franklin, “Global decline in large old trees,” *Science*, vol. 338, no. 6112. American Association for the Advancement of Science, pp. 1305–1306, Dec. 07, 2012, doi: 10.1126/science.1232439.

[19] J. W. Ferry Slik *et al.*, “Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics,” 2013.

[20] J. A. Lutz, A. J. Larson, M. E. Swanson, and J. A. Freund, “Ecological importance of large-diameter trees in a temperate mixed-conifer forest,” *PLoS One*, vol. 7, no. 5, May 2012, doi: 10.1371/journal.pone.0036131.

[21] R. Jalonen, L. T. Hong, S. L. Lee, J. Loo, and L. Snook, “Integrating genetic factors into management of tropical Asian production forests: A review of current knowledge,” *Forest Ecology and Management*, vol. 315. pp. 191–201, Mar. 01, 2014, doi: 10.1016/j.foreco.2013.12.011.

[22] P. Sist, L. Mazzei, L. Blanc, and E. Rutishauser, “Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon,” *For. Ecol. Manage.*, vol. 318, pp. 103–109, 2014, doi: 10.1016/j.foreco.2014.01.005.

[23] B. Finegan *et al.*, “Does functional trait diversity predict above-ground biomass and productivity of tropical forests? Testing three alternative hypotheses,” *J. Ecol.*, vol. 103, no. 1, pp. 191–201, Jan. 2015, doi: 10.1111/1365-2745.12346.

[24] J. A. Prado-Junior *et al.*, “Conservative species drive biomass productivity in tropical dry forests,” *J. Ecol.*, vol. 104, no. 3, pp. 817–827, May 2016, doi: 10.1111/1365-2745.12543.

[25] A. T. Fotis *et al.*, “Above-ground biomass is driven by mass-ratio effects and stand structural attributes in a temperate deciduous forest,” *J. Ecol.*, vol. 106, no. 2, pp. 561–570, Mar. 2018, doi: 10.1111/1365-2745.12847.

[26] P. A. Martin, A. C. Newton, M. Pfeifer, M. S. Khoo, and J. M. Bullock, “Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis,” *For. Ecol. Manage.*, vol. 356, pp. 224–233, 2015, doi: 10.1016/j.foreco.2015.07.010.

[27] E. Rutishauser *et al.*, “Current Biology Rapid tree carbon stock recovery in managed Amazonian forests,” *Curr. Biol.*, vol. 25, pp. 775–792, 2015, doi: 10.1016/j.

[28] A. Chaudhary, Z. Burivalova, L. P. Koh, and S. Hellweg, “Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs,” *Sci. Rep.*, vol. 6, pp. 1–10, 2016, doi: 10.1038/srep23954.

[29] Z. Burivalova, T. F. Allnutt, D. Rademacher, A. Schlemm, D. S. Wilcove, and R. A. Butler, “What works in tropical forest conservation, and what does not: Effectiveness of four strategies in terms of environmental, social, and economic outcomes,” *Conserv. Sci. Pract.*, vol. 1, no. 6, p. e28, 2019, doi: 10.1111/csp2.28.

[30] Z. Buřivalová, C. Rosin, J. Buchner, V. C. Radeloff, and N. Ocampo-Peñuela, “Conservation responsibility for bird species in tropical logged forests,” *Conserv. Lett.*, no. December 2021, pp. 1–10, 2022, doi: 10.1111/conl.12903.

[31] M. Campos-Cerqueira, J. L. Mena, V. Tejeda-Gómez, N. Aguilar-Amuchastegui, N. Gutierrez, and T. M. Aide, “How does FSC forest certification affect the acoustically active fauna in Madre de Dios, Peru?,” *Remote Sens. Ecol. Conserv.*, vol. 6, no. 3, pp. 274–285, 2020, doi: 10.1002/rse2.120.

[32] A. B. Castro, P. E. D. Bobrowiec, S. J. Castro, L. R. R. Rodrigues, and R. F. Fadini, “Influence of reduced-impact logging on Central Amazonian bats using a before-after-control-impact design,” *Anim. Conserv.*, vol. 25, no. 2, pp. 311–322, 2022, doi: 10.1111/acv.12739.

[33] D. Morgan *et al.*, “Impacts of Selective Logging and Associated Anthropogenic Disturbance on Intact Forest Landscapes and Apes of Northern Congo,” *Front. For. Glob. Chang.*, vol. 2, no. July, 2019, doi: 10.3389/ffgc.2019.00028.

[34] D. Morgan *et al.*, “African apes coexisting with logging: Comparing chimpanzee (Pan troglodytes troglodytes) and gorilla (Gorilla gorilla gorilla) resource needs and responses to forestry activities,” *Biol. Conserv.*, vol. 218, no. October 2017, pp. 277–286, 2018, doi: 10.1016/j.biocon.2017.10.026.

[35] J. Polisar *et al.*, “Using certified timber extraction to benefit jaguar and ecosystem conservation,” *Ambio*, vol. 46, no. 5, pp. 588–603, 2017, doi: 10.1007/s13280-016-0853-y.

[36] M. W. Tobler *et al.*, “Do responsibly managed logging concessions adequately protect jaguars and other large and medium-sized mammals? Two case studies from Guatemala and Peru,” *Biol. Conserv.*, vol. 220, no. September 2017, pp. 245–253, 2018, doi: 10.1016/j.biocon.2018.02.015.

[37] R. C. Goodman *et al.*, “Carbon emissions and potential emissions reductions from low-intensity selective logging in southwestern Amazonia,” *For. Ecol. Manage.*, vol. 439, no. November 2018, pp. 18–27, 2019, doi: 10.1016/j.foreco.2019.02.037.

[38] R. Sollmann *et al.*, “Quantifying mammal biodiversity co-benefits in certified tropical forests,” *Divers. Distrib.*, vol. 23, no. 3, pp. 317–328, 2017, doi: 10.1111/ddi.12530.

[39] E. Bohnett *et al.*, “Examining diversity of terrestrial mammal communities across forest reserves in Sabah, Borneo,” *Biodivers. Conserv.*, vol. 31, no. 5–6, pp. 1709–1734, 2022, doi: 10.1007/s10531-022-02423-8.

[40] J. E. Bicknell, M. J. Struebig, D. P. Edwards, and Z. G. Davies, “Improved timber harvest techniques maintain biodiversity in tropical forests,” *Curr. Biol.*, vol. 24, no. 23, pp. R1119–R1120, 2014, doi: 10.1016/j.cub.2014.10.067.

[41] P. O. Cerutti *et al.*, “Social impacts of the forest stewardship council certification in the Congo Basin,” *Int. For. Rev.*, vol. 19, no. 1, pp. 50–63, 2017, doi: 10.17528/cifor/004487.

[42] K. Kitayama *et al.*, “Biodiversity observation for land and ecosystem health (BOLEH): A robust method to evaluate the management impacts on the bundle of carbon and biodiversity ecosystem services in tropical production forests,” *Sustain.*, vol. 10, no. 11, 2018, doi: 10.3390/su10114224.

[43] B. W. Griscom *et al.*, “Reduced-impact logging in Borneo to minimize carbon emissions and impacts on sensitive habitats while maintaining timber yields,” *For. Ecol. Manage.*, vol. 438, no. December 2018, pp. 176–185, 2019, doi: 10.1016/j.foreco.2019.02.025.

[44] P. M. Umunay, T. G. Gregoire, T. Gopalakrishna, P. W. Ellis, and F. E. Putz, “Selective logging emissions and potential emission reductions from reduced-impact logging in the Congo Basin,” *For. Ecol. Manage.*, vol. 437, no. February, pp. 360–371, 2019, doi: 10.1016/j.foreco.2019.01.049.

[45] E. A. Ellis *et al.*, “Reduced-impact logging practices reduce forest disturbance and carbon emissions in community managed forests on the Yucatán Peninsula, Mexico,” *For. Ecol. Manage.*, vol. 437, no. November 2018, pp. 396–410, 2019, doi: 10.1016/j.foreco.2019.01.040.

[46] P. W. Ellis *et al.*, “Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests,” *For. Ecol. Manage.*, vol. 438, no. November 2018, pp. 255–266, 2019, doi: 10.1016/j.foreco.2019.02.004.

[47] V. P. Medjibe, F. E. Putz, and C. Romero, “Certified and uncertified logging concessions compared in Gabon: Changes in stand structure, tree species, and biomass,” *Environ. Manage.*, vol. 51, no. 3, pp. 524–540, 2013, doi: 10.1007/s00267-012-0006-4.

[48] I. Tritsch *et al.*, “Multiple patterns of forest disturbance and logging shape forest landscapes in Paragominas, Brazil,” *Forests*, vol. 7, no. 12, pp. 1–15, 2016, doi: 10.3390/f7120315.

[49] E. Rutishauser *et al.*, “Rapid tree carbon stock recovery in managed Amazonian forests,” *Curr. Biol.*, vol. 25, no. 18, pp. R787–R788, 2015, doi: 10.1016/j.cub.2015.07.034.

[50] P. Potapov *et al.*, “The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013,” *Sci. Adv.*, vol. 3, no. 1, pp. 1–14, 2017, doi: 10.1126/sciadv.1600821.

[51] J. S. Brandt, C. Nolte, and A. Agrawal, “Deforestation and timber production in Congo after implementation of sustainable forest management policy,” *Land use policy*, vol. 52, pp. 15–22, 2016, doi: 10.1016/j.landusepol.2015.11.028.

[52] P. Rana and E. O. Sills, “Does certification change the trajectory of tree cover in working forests in the tropics? An application of the synthetic control method of impact evaluation,” *Forests*, vol. 9, no. 3, 2018, doi: 10.3390/f9030098.

[53] P. Groenendijk, F. Bongers, and P. A. Zuidema, “Using tree-ring data to improve timber-yield projections for African wet tropical forest tree species,” *For. Ecol. Manage.*, vol. 400, pp. 396–407, 2017, doi: 10.1016/j.foreco.2017.05.054.

[54] R. Loveridge *et al.*, “Certified community forests positively impact human wellbeing and conservation effectiveness and improve the performance of nearby national protected areas,” *Conserv. Lett.*, vol. 14, no. 6, pp. 1–9, 2021, doi: 10.1111/conl.12831.

[55] D. A. Miteva, C. J. Loucks, and S. K. Pattanayak, “Social and environmental impacts of forest

management certification in Indonesia," *PLoS One*, vol. 10, no. 7, pp. 1–11, 2015, doi: 10.1371/journal.pone.0129675.
[56] F. W. Cubbage *et al.*, "Community Forestry Enterprises in Mexico: Sustainability and Competitiveness," *J. Sustain. For.*, vol. 34, no. 6–7, pp. 623–650, 2015, doi: 10.1080/10549811.2015.1040514.
[57] M. G. Scudder, J. L. Herbohn, and J. Baynes, "The failure of eco-forestry as a small-scale native forest management model in Papua New Guinea," *Land use policy*, vol. 77, no. February, pp. 696–704, 2018, doi: 10.1016/j.landusepol.2018.06.023.
[58] Hermudananto and N. Supriatno, "Evaluation of timber harvesting planning in Indonesian certified small and low-intensity managed forests," *J. Trop. For. Sci.*, vol. 32, no. 3, pp. 283–288, 2020, doi: 10.26525/jtfs32.3.283.
[59] O. Espinoza and M. J. Dockry, "Forest certification in Bolivia: A status report and analysis of stakeholder perspectives," *For. Prod. J.*, vol. 64, no. 3–4, pp. 80–89, 2014, doi: 10.13073/FPJ-D-13-00086.
[60] C. L. McDermott, L. C. Irland, and P. Pacheco, "Forest certification and legality initiatives in the Brazilian Amazon: Lessons for effective and equitable forest governance," *For. Policy Econ.*, vol. 50, pp. 134–142, 2015, doi: 10.1016/j.forpol.2014.05.011.
[61] F. Kleinschroth, C. Garcia, and J. Ghazoul, "Reconciling certification and intact forest landscape conservation," *Ambio*, vol. 48, no. 2, pp. 153–159, 2019, doi: 10.1007/s13280-018-1063-6.
[62] C. G. Bousfield, M. R. Massam, I. A. Acosta, C. A. Peres, and D. P. Edwards, "Land-sharing logging is more profitable than land sparing in the Brazilian Amazon," *Environ. Res. Lett.*, vol. 16, no. 11, 2021, doi: 10.1088/1748-9326/ac2b5f.
[63] A. Karsenty, "Certification of tropical forests: A private instrument of public interest? A focus on the Congo Basin," *For. Policy Econ.*, vol. 106, no. February, p. 101974, 2019, doi: 10.1016/j.forpol.2019.101974.
[64] S. Lhoest, M. Dufrêne, C. Vermeulen, J. Oszwald, J. L. Doucet, and A. Fayolle, "Perceptions of ecosystem services provided by tropical forests to local populations in Cameroon," *Ecosyst. Serv.*, vol. 38, no. January 2018, p. 100956, 2019, doi: 10.1016/j.ecoser.2019.100956.
[65] P. Waldhoff and E. Vidal, "Community loggers attempting to legalize traditional timber harvesting in the Brazilian Amazon: An endless path," *For. Policy Econ.*, vol. 50, pp. 311–318, 2015, doi: 10.1016/j.forpol.2014.08.005.
[66] C. Bocci, B. Sohngen, B. Finnegan, and B. Milian, "An analysis of migrant characteristics in forest-dwelling communities in northern Guatemala," *For. Policy Econ.*, vol. 140, no. February, p. 102733, 2022, doi: 10.1016/j.forpol.2022.102733.
[67] F. Luijckx, "Let them be known : On how FSC can promote Congo Basin Lesser Known Timber Species to the Chinese market," 2020.
[68] F. B. C. Yeom, "Lesser-known tropical wood species: how bright is their future?," *Unasylva*, vol. 36, no. 145, pp. 2–16, 1984.
[69] A. W. Mohd-Jamil and A. S.K., "Glossary of Terminologies of Malaysian Timber Species and Groups," *Adv. Electr. Electron. Mater.*, vol. 114, no. February, pp. 687–696, 2022, doi: 10.1002/9781118998564.gloss.
[70] M. Barany, A. L. Hammett, and P. Araman, "Lesser used species of Bolivia and their relevance to sustainable forest management," *For. Prod. J.*, vol. 53, no. 7–8, pp. 28–33, Jul. 2003.
[71] J. K. Vanclay, "Lessons from the queensland rainforests: Steps towards sustainability," *J. Sustain. For.*, vol. 3, no. 2–3, pp. 1–27, 1996, doi: 10.1300/J091v03n02_01.
[72] T. S. Fredericksen, F. E. Putz, P. Pattie, W. Pariona, and M. Pena-Claros, "Sustainable forestry in Bolivia: Beyond planned logging," *J. For.*, vol. 101, no. 2, pp. 37–40, 2003, doi: 10.1093/jof/101.2.37.
[73] M. Schulze, J. Grogan, C. Uhl, M. Lentini, and E. Vidal, "Evaluating ipê (Tabebuia, Bignoniaceae) logging in Amazonia: Sustainable management or catalyst for forest degradation?," *Biol. Conserv.*, vol. 141, no. 8, pp. 2071–2085, 2008, doi: 10.1016/j.biocon.2008.06.003.
[74] P. O. Cerutti, S. Sombo, M. Vandenhaute, and Y. P. Senguela, "État du secteur forêt-bois en

République Centrafricaine (2021),” 2021.
[75] R. L. Youngs and A. L. Hammett, “Diversity, productivity, profitability, sustainability, and the Tao of underutilized species,” *For. Prod. J.*, vol. 51, no. 1, pp. 29–35, 2001.
[76] R. J. Karsten, H. Meilby, and J. B. Larsen, “Regeneration and management of lesser known timber species in the Peruvian Amazon following disturbance by logging,” *For. Ecol. Manage.*, vol. 327, pp. 76–85, Sep. 2014, doi: 10.1016/j.foreco.2014.04.035.
[77] V. Haag, G. Koch, H. G. Richter, R. Evans, J. A. S. Guzmán, and U. Schmitt, “Wood anatomical and topochemical analyses to characterize juvenile and adult wood of lesser-known species from Central America (Mexico),” *IAWA J.*, vol. 40, no. 4, pp. 785–803, 2019, doi: 10.1163/22941932-40190256.
[78] V. Haag, G. Koch, E. Melcher, and J. Welling, “Characterization of the wood properties of cedrelinga cateniformis as substitute for timbers used for window manufacturing and outdoor applications,” *Maderas Cienc. y Tecnol.*, vol. 22, no. 1, pp. 23–36, 2020, doi: 10.4067/S0718-221X2020005000103.
[79] M. Meléndez-Cárdenas *et al.*, “Surface quality of Peruvian amazon woods submitted for planning and sanding,” *Floresta*, vol. 49, no. 4, pp. 671–680, 2019, doi: 10.5380/rf.v49.
[80] M. C. Custodio, M. Tomazello-Filho, M. E. B. Carneiro, and S. Nisgoski, “Axial and radial evaluation of the basic density and fiber dimensions of Guazuma crinita martius wood,” *Floresta*, vol. 50, no. 2, pp. 1143–1150, 2020, doi: 10.5380/rf.v50i2.58356.
[81] L. L. Tuisima-Coral, J. E. Odicio-Guevara, J. C. Weber, D. Lluncor-Mendoza, and B. Lojka, “Variación de las propiedades físicas en troncos de Guazuma crinita, una especie maderable en el Amazonas Peruano,” *Madera Bosques*, vol. 23, no. 1, pp. 53–61, 2017, doi: 10.21829/myb.2017.2311534.
[82] E. J. Uetimane and A. C. Ali, “Relationship between mechanical properties and selected anatomical features of Ntholo (Pseudolachnostylis Maprounaefolia),” *Journal of Tropical Forest Science*, vol. 23, no. 2. Forest Research Institute Malaysia, pp. 166–176, 2011.
[83] M. B. De Oliveira, J. R. M. Da Silva, P. R. G. Hein, and J. T. Lima, “Establishment of quality classes for hardwood floorings by simulated use,” *Cerne*, vol. 25, no. 1, pp. 105–109, Jan. 2019, doi: 10.1590/01047760201925012618.
[84] N. A. Siam *et al.*, “Anatomical and physical properties of three lesser-known timber species from Malaysia,” *BioResources*, vol. 17, no. 1, pp. 1090–1105, 2021, doi: 10.15376/biores.17.1.1090-1105.
[85] C. K. Muthumala, W. V. T. D. Amarasinghe, and T. S. Mudalige, “Assessment of Wood Properties in Lesser-Known Shorea spp. in Sri Lanka,” in *Lecture Notes in Civil Engineering*, 2022, vol. 174, pp. 477–485, doi: 10.1007/978-981-16-4412-2_36.
[86] L. Aguda *et al.*, “Mechanical properties of ficus vallis-choudae (Delile), A lesser utilized species in Nigeria,” *BioResources*, vol. 15, no. 3, pp. 6550–6560, 2020, doi: 10.15376/biores.8.3.6550-6560.
[87] I. Brémaud, Y. El Kaïm, D. Guibal, K. Minato, B. Thibaut, and J. Gril, “Characterisation and categorisation of the diversity in viscoelastic vibrational properties between 98 wood types,” *Ann. For. Sci.*, vol. 69, no. 3, pp. 373–386, Apr. 2012, doi: 10.1007/s13595-011-0166-z.
[88] I. Lhate, L. Cristóvão, and M. Ekevad, “Machining properties of lesser used wood species from Mozambique,” *Wood Res.*, vol. 62, no. 4, pp. 635–644, 2017.
[89] T. F. Shupe, F. X. Aguilar, R. P. Vlosky, M. Belisle, and A. Chavez, “Wood properties of selected lesser-used Honduran wood species,” *J. Trop. For. Sci.*, vol. 17, no. 3, pp. 438–446, Jul. 2005, Accessed: Sep. 03, 2022. [Online]. Available: https://www.jstor.org/stable/23616677.
[90] G. A. Quartey, “Anatomical Properties of Three Lesser Utilised Ghanaian Hardwood Species,” *Mater. Sci. Appl.*, vol. 06, no. 12, pp. 1111–1120, 2015, doi: 10.4236/msa.2015.612110.
[91] T. F. Döbert, B. L. Webber, J. B. Sugau, K. J. M. Dickinson, and R. K. Didham, “Logging, exotic plant invasions, and native plant reassembly in a lowland tropical rain forest,” *Biotropica*, vol. 50, no. 2, pp. 254–265, 2018, doi: 10.1111/btp.12521.
[92] S. Augustina, I. Wahyudi, I. W. Darmawan, J. Malik, E. Basri, and Y. Kojima, “Specific gravity and dimensional stability of boron-densified wood on three lesser-used species from Indonesia,” *J.*

Korean Wood Sci. Technol., vol. 48, no. 4, pp. 458–471, 2020, doi: 10.5658/WOOD.2020.48.4.458.

[93] T. H. Booth, “Estimating potential range and hence climatic adaptability in selected tree species,” *For. Ecol. Manage.*, vol. 366, pp. 175–183, Apr. 2016, doi: 10.1016/j.foreco.2016.02.009.

[94] L. López-Toledo, A. Murillo-García, M. Martínez-Ramos, and D. R. Pérez-Salicrup, “Demographic effects of legal timber harves ting on Guaiacum sanctum L., an endangered neo tropical tree : Implications for conservation,” *Interciencia*, vol. 36, no. 9. pp. 650–656, 2011.

[95] L. Lopez-Toledo, G. Ibarra-Manríquez, D. F. R. P. Burslem, E. Martínez-Salas, F. Pineda-García, and M. Martínez-Ramos, “Protecting a single endangered species and meeting multiple conservation goals: An approach with Guaiacum sanctum in Yucatan Peninsula, Mexico,” *Divers. Distrib.*, vol. 18, no. 6, pp. 575–587, 2012, doi: 10.1111/j.1472-4642.2011.00857.x.

[96] U. Balza and R. C. De Gouvenain, “Twenty-year assessment of Lignum-vitae (Guaiacum sanctum, zygophyllaceae) in the Palo Verde national park of Costa Rica,” *Rev. Biol. Trop.*, vol. 67, no. 6, pp. 1269–1277, 2019, doi: 10.15517/rbt.v67i6.38338.

[97] J. P. Cornelius, R. Pinedo-Ramírez, C. S. Montes, L. J. Ugarte-Guerra, and J. C. Weber, “Efficiency of early selection in calycophyllum spruceanum and guazuma crinita, two fast-growing timber species of the peruvian amazon,” *Can. J. For. Res.*, vol. 48, no. 5, pp. 517–523, 2018, doi: 10.1139/cjfr-2017-0407.

[98] L. Putzel, P. Cronkleton, A. M. Larson, M. Pinedo-Vasquez, O. Salazar, and R. Sears, “Peruvian smallholder production and marketing of bolaina (Guazuma crinita), a fast-growing Amazonian timber species : call for a pro-livelihoods policy environment,” *Peruvian Smallhold. Prod. Mark. bolaina (Guazuma crinita), a fast-growing Amaz. timber species call a pro-livelihoods policy Environ.*, no. 23, pp. 1–6, 2013, doi: 10.17528/cifor/004257.

[99] L. Freitas Alvarado, R. Zárate Gómez, D. Del Castillo Torres, A. Dávila Díaz, C. Villacorta Gonzáles, and J. Benavides Ríos, “Silvicultura de un rodal de regeneración natural de Calycophyllum spruceanum (Benth.) Hook. f. ex K. Schum (Rubiaceae) en la llanura aluvial inundable de Iquitos, Amazonía Peruana,” *Folia Amazonica*, vol. 30, no. 1. pp. 71–86, 2021, doi: 10.24841/fa.v30i1.545.

[100] S. Dupray, J. Simm, and J. Williams, “Lesser-known timbers for maritime and riverine construction,” *Proc. Inst. Civ. Eng. Constr. Mater.*, vol. 162, no. 4, pp. 157–165, Nov. 2009, doi: 10.1680/coma.2009.162.4.157.

[101] M. Meaden, J. Williams, and J. Simm, *Alternative hardwood timbers for use in marine and fresh water construction*. 2011.

[102] R. K. W. M. Klaassen and J. G. M. Creemers, “State of the wooden construction, fresh water marina, Akkrum,” pp. 1–40, 2020.

9. Annex

Supplementary Table 1 Search strings used for literature searches in Scopus and Web of Science, per chapter

Chapter	Topic	Search strings
3	Social impact	"sustainable forest*" or "responsible forest*" or "sustainable forest management" or "conventional forest management" or "community forest management" or "certified forest management" and "tropical forest*" or "tropical forest* management" or "tropical" and "social*" or "social impact" or "social analysis" or "socio-ecological" or "socio-economic" and not "plantation" or "planted tree*" or "palm" or "palm oil" or "restoration"
3	Economic impact	"tropical forest*" or "tropical forest* management" and "economic impact" or "economic analysis" or "cost-benefit analysis" or "cost-benefit" or "financial impact" or "financial analysis" and not "plantation" or "planted tree*" or "palm" or "palm oil" or "restoration"
3	Logging intensity	"intensive logging" or "extensive logging" or "intensive vs. extensive logging" or "logging intensity" or "timber yield" or "sustained yield" or "cutting cycle" and "tropical forest*" or "tropical forest* management" and not "plantation" or "planted tree*" or "palm" or "palm oil" or "restoration"
4	Certification	"certification" or "forest* certification" or "FSC" or "Forest Stewardship Council" or "PEFC[7]" and "tropical forest*" or "tropical forest* management" and not "plantation" or "planted tree*" or "palm" or "palm oil"
5	Lesser-known timber species	"lesser known timber species" or "lesser-known timber species" or "lesser known species" or "lesser-known species" or "lesser used timber species" or "lesser-used timber species" or "lesser used species" or "lesser-used species"

[7] Programme for the Endorsement of Forest Certification Schemes

Supplementary Table 2 Summary of studies on lesser-known timber species. Family, country of study, type of study and main outcome of the study are provided

Species	Family	Country	Type of study	Outcome	Reference
Acacia nigrescens	Fabaceae	Mozambique	Machining properties	Difficult to be machined, density 1112 kg /m³	Lhate et al 2017
Albizia ferruginea	Fabaceae	Ghana	Anatomical properties	Tylosis, fibre length 1196µm, density 603 kg/m³	Quartey 2015
Anadenanthera colubrina	Fabaceae	Bolivia	Stock growth	Volume 3.09 m³/ha	Barany et al 2003
Aniba sp. / Ocotea sp. / Qualea sp.	Lauraceae / Vochysieaceae	Peru	Regeneration		Karsten et al 2014
Apuleia leiocarpa	Fabaceae		Maritime and freshwater construction	durable against fungi decay, good resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Aspidosperma australe	Apocynaceae	Bolivia	Stock growth	Volume 0.68 m³/ha	Barany et al 2003
Aspidosperma megalocarpon	Apocynaceae		Fresh water construction	little decay (sheet piles)	Klaassen et al 2020
Aspidosperma sp.	Apocynaceae	Peru	Regeneration		Karsten et al 2014
Aspidosperma spp.	Apocynaceae	Bolivia	Stock growth	Volume 1.6 m³/ha	Barany et al 2003
Astronium urundeuva	Anacardiaceae	Bolivia	Stock growth	Volume 2.75 m³/ha	Barany et al 2003
Atrocarpus scortechinii	Moracaeae	Malaysia	Physical and anatomical properties	Deposits and extractives, fibre length 1421 µm, density 504 kg/m³, tangential shrinkage 3.8 %	Siam et al 2022
Autranella congolensis	Sapotaceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, low resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Autranella congolensis	Sapotaceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009
Bagassa guianensis	Moraceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Bagassa guianensis	Moraceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009

Blighia sapida	Sapindaceae	Ghana	Anatomical properties	Crystals, fibre length 1127µm, density 892 kg/m³	Quartey 2015
Bowdichia nitida	Fabaceae	Brazil	Mechanical performance	Intermediate floor quality class, density 897 kg/m³	De Oliveira et al 2019
Brosimum utile	Moraceae	Peru	Regeneration		Karsten et al 2014
Caesalpinia pluviosa	Fabaceae	Bolivia	Stock growth	Volume 1.83m³/ha	Barany et al 2003
Calophyllum brasiliense	Calophyllaceae	Honduras	Physical and mechanical properties	Radial shrinkage 3.9%, tangential shrinkage 5.5%, volume shrinkage 9.6%	Shupe et al 2005
Calophyllum brasiliense	Calophyllaceae	Bolivia	Stock growth	Volume 2.65 m³/ha	Barany et al 2003
Calycophyllum multiflorum	Rubiaceae	Bolivia	Stock growth	Volume 1.13 m³/ha	Barany et al 2003
Calycophyllum spruceanum	Rubiaceae	Peru	Financial analysis	Early selection is more attractive	Cornelius et al 2018
Calycophyllum spruceanum	Rubiaceae	Peru	Regeneration	Volume 40.1 m³/ha, Basal area 7.7 m², 85% good crown illumination small trees, 49% poor crown illumination saplings, 44% acceptable crown shape small trees, 47% acceptable crown shape saplings, 55% acceptable stem shape small trees, 48% acceptable stem shape saplings	Freitas Alvarado et al 2021
Calycophyllum spruceanum	Rubiaceae	Peru	Surface quality	Best surface quality, roughness by cutting plane 7.44 (planing), 1.97 (sanding)	Mélendez-Cárdenas et al 2019
Cariniana domestica	Lecythidaceae	Peru	Surface quality	Regular surface quality, roughness by cutting plane 7.43 (planing), 3.43(sanding)	Mélendez-Cárdenas et al 2019
Cariniana estrellensis	Lecythidaceae	Bolivia	Stock growth	Volume 5.27 m³/ha	Barany et al 2003
Cariniana sp.	Lecythidaceae	Peru	Regeneration		Karsten et al 2014
Caryocar glabrum	Caryocaraceae		Maritime and freshwater construction	durable against fungi decay, good resistance to shipworms, high resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Caryocar sp.	Caryocaraceae	Peru	Regeneration		Karsten et al 2014
Cecropia sp.	Urticaceae	Peru	Regeneration		Karsten et al 2014

Cedrelinga cateniformis	Fabaceae	Peru	Physical, mechanical and anatomical properties	Tangential shrinkage 3.8%, fibre length 1439µm, no crystals	Haag et al 2020
Cedrelinga cateniformis	Fabaceae	Peru	Regeneration		Karsten et al 2014
Cedrelinga cateniformis	Fabaceae	Bolivia	Stock growth	Volume 4.14 m³/ha	Barany et al 2003
Clarisia racemosa	Moraceae	Peru	Regeneration		Karsten et al 2014
Clarisia racemosa	Moraceae	Bolivia	Stock growth	Volume 0.6 m³/ha	Barany et al 2003
Copaifera paupera	Fabaceae	Peru	Surface quality	Good surface quality, roughness by cutting plane 7.19 (planing), 2.89 (sanding)	Mélendez-Cárdenas et al 2019
Cordia allidora	Boraginaceae	Bolivia	Stock growth	Volume 0.06 m³/ha	Barany et al 2003
Cylicodiscus gabunensis	Fabaceae		Fresh water construction	partially decayed (sheet piles)	Klaassen et al 2020
Cylicodiscus gabunensis	Fabaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, good resistance to abrasion	Meaden et al 2011
Cylicodiscus gabunensis	Fabaceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009
Desbordesia glaucescens	Irvingiaceae		Maritime and riverine construction	Resistance to attrition, but less resistance to gribble attack and shipworm	Dupray et al 2009
Dicorynia guianensis	Fabaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, good resistance to abrasion	Meaden et al 2011
Dinizia excelsa	Fabaceae		Fresh water construction	little decay (sheet piles and landing stages)	Klaassen et al 2020
Dinizia excelsa	Fabaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, good resistance to abrasion	Meaden et al 2011
Dinizia excelsa	Fabaceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009
Dipteryx micrantha	Fabaceae	Peru	Regeneration		Karsten et al 2014
Dipteryx odorata	Fabaceae	Brazil	Mechanical performance	High floor quality class, density 1158 kg/m³	De Oliveira et al 2019

Dipteryx odorata	Fabaceae	Bolivia	Stock growth	Volume 4.21 m³/ha	Barany et al 2003
Enterolobium schomburgkii	Fabaceae		Maritime and freshwater construction	durable against fungi decay, good resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Enterolobium schomburgkii	Fabaceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009
Erisma uncinatum	Vochysiaceae	Bolivia	Stock growth	Volume 3.77 m³/ha	Barany et al 2003
Erythrophleum ivorense	Fabaceae		Fresh water construction	little decay (sheet piles)	Klaassen et al 2020
Erythrophleum ivorense	Fabaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, high resistance to abrasion	Meaden et al 2011
Erythrophleum ivorense	Fabaceae		Maritime and riverine construction	Resistance to attrition, but less to gribble attack	Dupray et al 2009
Eschweilera subglandulosa	Lecythidaceae		Fresh water construction	no decay (freshwater poles and landing stages)	Klaassen et al 2020
Eucalyptus botryoides	Myrtaceae	Australia	Climate adaptability	Growth index 0.32-0.63, min temperature 1-9.3°C, Moisture index 0.5-0.93, Mean annual temperature 18.2°C, potential mean annual temperature 22°C	Booth 2016
Eucalyptus cloeziana	Myrtaceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Eucalyptus cloeziana	Myrtaceae		Maritime and riverine construction	Resistance to shipworm, but less to gribble attack and attrition	Dupray et al 2009
Eucalyptus globulus	Myrtaceae	Australia	Climate adaptability	Growth index 0.03-0.45, min temperature -2.1-8.4°C, Moisture index 0.56-1, Mean annual temperature 14.7°C, potential mean annual temperature 21.2°C	Booth 2016

Eucalyptus kruseana	Myrtaceae	Australia	Climate adaptability	Growth index 0.08-0.1, min temperature 4.2-4.7°C, Moisture index 0.12-0.17, Mean annual temperature 18.8°C, potential mean annual temperature 19.8°C West coast, potential mean annual temperature 21.2°C East coast	Booth 2016
Ficus vallis-choudae	Moracaeae	Nigeria	Mechanical properties	Impact bending strength 20.5 N/mm², Modulus of rupture 85.8 N/mm², Modulus of elasticity 7090 N/mm², Max shear strength 10.7 N/mm²	Aguda et al 2020
Goupia glabra	Goupiaceae		Fresh water construction	no decay (sheet piles)	Klaassen et al 2020
Goupia glabra	Goupiaceae		Maritime and freshwater construction	durable against fungi decay, good resistance to shipworms, high resistance to gribble attack and low resistance to abrasion	Meaden et al 2011
Goupia glabra	Goupiaceae		Maritime and riverine construction	Resistance to gribble attack and shipworm, but less against attrition	Dupray et al 2009
Guaiacum sanctum	Zygophyllaceae	Costa Rica	Population growth	Annual population decline 1.75%	Balza et al 2019
Guaiacum sanctum	Zygophyllaceae	Mexico	Population structure	Stem density between 278 - 1732 ind/ha	Lopéz-Toledo et al 2011
Guaiacum sanctum	Zygophyllaceae	Mexico	Population structure	29% of all forest trees are G. sanctum, mean above ground carbon content 92.2 MG C / ha	Lopéz-Toledo et al 2012
Guarea grandifolia	Meliaceae	Honduras	Physical and mechanical properties	Radial shrinkage 2.6%, tangential shrinkage 6.3%, volume shrinkage 8.8%	Shupe et al 2005
Guarea spp.	Meliaceae	Bolivia	Stock growth	Volume 0.98 m³/ha	Barany et al 2003
Guazuma crinita	Malvaceae	Peru	Financial analysis	Early selection is more attractive	Cornelius et al 2018
Guazuma crinita	Malvaceae	Peru	Financial evaluation	Well suited to sustainable smallholder forest management and timber production, processing and marketing, profit between 1631$ - 2094$ from 4800 boards sold in Pucallpa	Putzel et al 2013
Guazuma crinita	Malvaceae	Peru	Physical and anatomical properties	Density 5 years 358 kg/m³ 8 years 396 kg/m³, fibre length 5 years 1369 µm 8 years 1362µm	Custodio et al 2020

Guazuma crinita	Malvaceae	Peru	Physical properties	Density 430 kg/m³, radial shrinkage 3.4%, tangential shrinkage 5%, volume shrinkage 8.4%	Tuisima-Coral et al 2017
Huertea cubensis	Tapisciaceae	Honduras	Physical and mechanical properties	Radial shrinkage 2.9%, tangential shrinkage 6.2%, volume shrinkage 9.1%	Shupe et al 2005
Hura crepitans	Euphorbiaceae	Bolivia	Stock growth	Volume 23.73 m³/ha	Barany et al 2003
Hymenaea courbaril	Fabaceae	Bolivia	Stock growth	Volume 1.85 m³/ha	Barany et al 2003
Ilex tectonica	Aquifoliaceae	Honduras	Physical and mechanical properties	Radial shrinkage 2.5%, tangential shrinkage 5.9%, volume shrinkage 8.4%	Shupe et al 2005
Klainedoxa gabonensis	Irvingiaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, low resistance to gribble attack, high resistance to abrasion	Meaden et al 2011
Klainedoxa gabonensis	Irvingiaceae		Maritime and riverine construction	Resistance to attrition and shipworm, but less to gribble attack	Dupray et al 2009
Lecythis paraensis	Lecythidaceae		Maritime and freshwater construction	good resistance to shipworms, good resistance to gribble attack, good resistance to abrasion	Meaden et al 2011
Litsea costalis	Lauraceae	Malaysia	Physical and anatomical properties	Medium size vessels, absence of tylosis and deposits, silica, fibre length 1309 µm, density 485 kg/m³, tangential shrinkage 1.5%	Siam et al 2022
Lonchocarpus castilloi	Fabaceae	Mexico	Anatomical and chemical properties	no tyloses, crystals	Haag et al 2019
Lophira alata	Ochnaceae		Fresh water construction	little decay (sheet piles, free water poles and landing stages)	Klaassen et al 2020
Lysiloma latisiliquum	Fabaceae	Mexico	Anatomical and chemical properties	no tyloses, crystals	Haag et al 2019
Macaranga hosei	Euphorbiaceae	Malaysia	Physical and anatomical properties	Medium size vessels, absence of tylosis and deposits, fibre length 1161µm, density 474 kg/m³, tangential shrinkage 2.2%	Siam et al 2022
Manilkara bidentata	Sapotaceae	Peru	Regeneration		Karsten et al 2014

Manilkara spp	Sapotaceae		Maritime and freshwater construction	very durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, low resistance to abrasion	Meaden et al 2011
Manilkara zapota	Sapotaceae	Mexico	Anatomical and chemical properties	tyloses, crystals	Haag et al 2019
Mezzettia leptopoda	Annonaceae	Indonesia	Chemical modification and densification	Specific gravity of densified wood increased with compression ratio, but not by pre-treatment applied, densified wood without pre-treatment provides a better dimensional stability	Augustina et al 2020
Mimosa scabrella	Fabaceae	Brazil	Mechanical performance	Low floor quality class, density 621 kg/m³	De Oliveira et al 2019
Mora excelsa	Fabaceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Ormosia sp.	Fabaceae	Peru	Regeneration		Karsten et al 2014
Palaquium lanceolatum	Sapotaceae	Indonesia	Chemical modification and densification	Specific gravity of densified wood increased with compression ratio, but not by pre-treatment applied, densified wood without pre-treatment provides a better dimensional stability	Augustina et al 2020
Parinari excelsa	Chrysobalanaceae		Maritime and freshwater construction	moderately durable against fungi decay, good resistance to shipworms, good resistance to gribble attack, high resistance to abrasion	Meaden et al 2011
Parinari excelsa	Chrysobalanaceae		Maritime and riverine construction	Resistance to attrition, but less to gribble attack	Dupray et al 2009
Pericopsis angolensis	Fabaceae	Mozambique	Machining properties	Intermediate to be machined, density 926 k/m³	Lhate et al 2017
Pericopsis angolensis	Fabaceae	Mozambique	Physical and mechanical properties	Density 865 kg/m³, bending strength 105 N/mm², Impact bending strength 76 N/mm², radial shrinkage 2%, tangential shrinkage 4%	Ali et al 2008

Piptadeniastrum africanum	Fabaceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, good resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Platymiscium yucatanum	Fabaceae	Mexico	Anatomical and chemical properties	no tyloses, crystals	Haag et al 2019
Pouteria sp.	Sapotaceae	Peru	Regeneration		Karsten et al 2014
Protium sp.	Burseraceae	Peru	Regeneration		Karsten et al 2014
Pseudolachnostylis maprouneifolia	Phyllanthaceae	Mozambique	Anatomical and mechanical properties	notable differences between density and mechanical performance of sapwood and heartwood	Uetimane et al 2011
Pseudolachnostylis maprouneifolia	Phyllanthaceae	Mozambique	Machining properties	Difficult to be machined, density 751 kg/m^3	Lhate et al 2017
Pterogyne nitens	Fabaceae	Bolivia	Stock growth	Volume 0.27 m^3/ha	Barany et al 2003
Roseodendron donnell-smithii	Bignoniaceae	Mexico	Anatomical and chemical properties	tyloses, no crystals	Haag et al 2019
Schizolobium amazonicum	Fabaceae	Peru	Regeneration		Karsten et al 2014
Shorea astylosa	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Very high density	Muthumala et al 2022
Shorea congestiflora	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Medium density	Muthumala et al 2022
Shorea disticha	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Medium density	Muthumala et al 2022
Shorea stipularis	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Medium density	Muthumala et al 2022
Shorea trapezifolia	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Density 1044 kg/m^3	Muthumala et al 2022
Shorea zeylanica	Dipterocarpaceae	Sri Lanka	Physical and mechanical properties	Density 517 kg/m^3	Muthumala et al 2022
Simarouba amara	Simaroubaceae	Brazil	Thermomechanical treatment	Applied temperatures and pressure altered the colour of the timber and enhanced the dynamic modulus of elasticity	Freitas et al 2016
Simarouba sp.	Simaroubaceae	Peru	Regeneration		Karsten et al 2014

Sindora wallichii	Fabaceae	Indonesia	Chemical modification and densification	Specific gravity of densified wood increased with compression ratio, but not by pre-treatment applied, densified wood without pre-treatment provides a better dimensional stability	Augustina et al 2020
Staudtia kamerunensis	Myristicaceae		Maritime and freshwater construction	durable against fungi decay, low resistance to shipworms, high resistance to gribble attack and good resistance to abrasion	Meaden et al 2011
Staudtia kamerunensis	Myristicaceae		Maritime and riverine construction	Resistance to gribble attack and shipworm, but less against attrition	Dupray et al 2009
Sterculia apetala	Sterculiaceae	Bolivia	Stock growth	Volume 0.37 m^3/ha	Barany et al 2003
Sterculia appendiculata	Sterculiaceae	Mozambique	Machining properties	Easy to be machined, density 604 kg/m^3	Lhate et al 2017
Sterculia appendiculata	Sterculiaceae	Mozambique	Physical and mechanical properties	soft wood	Ali et al 2008
Sterculia quinqueloba	Sterculiaceae	Mozambique	Physical and mechanical properties	easy to be machined, density 780 kg/m^3, radial shrinkage 1.3%, tangential shrinkage 2.5%, modulus of elasticity 10200 n/mm^2, Modulus of rupture 71 N/mm^2	Ali et al 2008
Sterculia rhinopetala	Sterculiaceae	Ghana	Anatomical properties	Fibre length 1479µm, density 945 kg/m^3	Quartey 2015
Tabebuia impetiginosa	Bignoniaceae	Brazil	Mechanical performance	High floor quality class, density 1067 kg/m^3	De Oliveira et al 2019
Tabebuia rosea	Bignoniaceae	Mexico	Anatomical and chemical properties	no tyloses, no crystals	Haag et al 2019
Terminalia amazonia	Combretaceae	Honduras	Physical and mechanical properties	Radial shrinkage 2.8%, tangential shrinkage 5.1%, volume shrinkage 7.9%	Shupe et al 2005
Terminalia buceras	Combretaceae	Mexico	Anatomical and chemical properties	no tyloses, crystals	Haag et al 2019
Terminalia oblonga	Combretaceae	Bolivia	Stock growth	Volume 7.37 m^3/ha	Barany et al 2003
Terminalia sp.	Combretaceae	Peru	Regeneration		Karsten et al 2014
Virola koschnyi	Myristicaceae	Honduras	Physical and mechanical properties	Radial shrinkage 2.6%, tangential shrinkage 6.2%, volume shrinkage 8.8%	Shupe et al 2005

Virola sp. / Iryanthera sp.	Myristicaceae	Peru	Regeneration		Karsten et al 2014
Vochysia guatemalensis	Vochysiaceae	Honduras	Physical and mechanical properties	Radial shrinkage 1.6%, tangential shrinkage 4.4%, volume shrinkage 6%	Shupe et al 2005