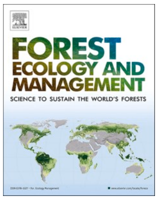
Forest Ecology and Management 496 (2021) 119440

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



Sustainability of Brazilian forest concessions

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ARTICLE INFO

Keywords:
Amazonian forest concessions
Sustainable forest management
Selective logging

ABSTRACT

In 2006, the Brazilian Forest Service (SFB) started an ambitious program to establish forest concessions so as to provide a legal framework for long-term sustainable timber production in Amazonian forests. Forest concessions in the Brazilian Amazon currently cover only 1.6 million ha (Mha) but we estimate the area of all potential concessions as 35 Mha. This paper assessed the conditions under which the present and potential concession system can ensure an annual production of 11 Mm^3. yr^{-1} to meet the estimated present timber demand. For this we used the volume dynamics with differential equations model (VDDE) calibrated for the Amazon Basin with a Bayesian framework with data from 3500 ha of forest plots monitored for as long as 30 years after selective logging. Predictions of commercial volume recovery rates vary with location.

We tested 27 different scenarios by using combinations of initial proportion of commercial volume, logging intensity and cutting cycle length. These scenarios were then applied to the current area of concessions and to the area of all potential concessions (35 Mha). Under current logging regulations and the current concession area (mean logging intensity of 15–20 $m^3.ha^{-1}$, a harvest cycle of 35 years and an initial commercial timber volume proportion of 20%), timber production can be maintained only for a single cutting cycle (35 years). Only the scenario with a logging intensity of 10 m^3ha^{-1} every 60 years with a 90% initial proportion of commercial timber species can be considered as sustainable. Under this scenario, the maximum annual production with the present concession areas is 159,000 m^3 (157–159), or less than 2% of the present annual production of 11 Mm^3. When considering all potential concession areas (35 Mha), under current rules, the total annual production is 10 Mm^3yr^{-1} (2–17 Mm^3yr^{-1}, 95% credibility interval) but is not maintained after the first logging cycle. Under the most sustainable scenario (see above) and a concession area of 35 Mha, the long-term sustainable annual production of timber reaches only 3.4 Mm^3yr^{-1}. Based on these results we argue that the concession system will not be able to supply the timber demand without substantial reforms in natural forest management practices and in the wood industry sector. We argue that alternative sources of timber, including plantations linked with forest restoration initiatives, must be promoted.

1. Introduction

In 2006, the Brazilian Forest Service (SFB) established a very ambitious system of long-term logging concessions (Brazil, 2006). The goals are to provide a legal framework for sustainable timber production in Amazonian forests while reducing illegal logging. Forest concessions in the Brazilian Amazon currently cover only 1.6 million ha (SFB, 2019a), but the SFB estimated that 20 Mha should be sufficient to ensure the sustainable timber supply of the industry (Vidal et al. 2020). The current timber production from established forest concessions is 221,000 m^3 per year, which is only 2% of the timber extracted from the region (SFB, 2019a). Given that these concessions are to be managed with a 50 cm

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https://doi.org/10.1016/j.foreco.2021.119440
Received 11 March 2021; Received in revised form 3 June 2021; Accepted 5 June 2021

minimum cutting diameter (with the exception of *Swietenia macrophylla*: 60 cm) and a 25–35 year cutting cycle, coupled with rising demand for wood products, an assessment of the expected timber production from these forests over the long-term is warranted.

In the Amazon, selective logging regulations typically set harvest cycles of 20–35 years with a logging intensity varying from 15 to 30 m^3 of harvested timber per ha. Such rules are based on an assumed post-logging rate of commercial timber volume increments of about 1 $m^3.ha^{-1}.year^{-1}$ (0.86 $m^3.ha^{-1}.year^{-1}$ in the Brazilian Amazon). These rules are set to accommodate processing technologies and market demands, rather than the biology and conservation of the harvested species (Sist and Ferreira, 2007). Although reduced-impact logging techniques were seen as a promising way to reduce damage and increase the rate of timber volume recovery (Schulze, Grogan, and Vidal 2008), most studies that assessed the long-term impacts of the reported application of such techniques in the tropics - including the Amazon - show that timber volume will recover at best 50% of its pre-logging value after the first cutting event, within the minimum harvest cycle duration fixed by legislation (Sist and Ferreira 2007; Putz et al. 2012, Avila et al. 2017). A recent simulation of post-logging timber volume recovery rates in the Amazon Basin confirmed these results at the regional level and showed that even with cutting cycles of 65 years and logging intensities of only 20 $m^3.ha^{-1}$, logged forests recover only 70% of their pre-logging timber stocks (Piponiot et al., 2019). Other researchers showed that current harvest regimes can only be sustained over multiple cycles if high-value slow-growing hardwoods are replaced by fast-growing species with low density wood of lower market value (Alder and Silva, 2000; Gardingen et al., 2006; Keller et al., 2004; Phillips et al., 2004; Schulze et al., 2008; Sist and Ferreira, 2007).

In the Amazon, forest degradation due to illegal logging is a widespread (Brancalion et al., 2018; Finer et al., 2014; Potapov et al., 2017) and, in the Brazilian Amazon, it affects larger areas than deforestation (Matricardi et al., 2020). Without control of illegal logging and improved practices where logging is legal, timber yields from logged forests will decline dramatically (Piponiot et al., 2019; Putz et al., 2012), decreasing the likelihood of their meeting the demand for timber.

Although, the long term sustainability of selective logging in the region is largely questioned, the capacity of logging concessions in the Brazilian Amazon to sustain timber yields during successive cycles has still to be assessed. Here we use a timber recovery model (Piponiot et al., 2019) to estimate the timber volumes that could be produced by all the logging concessions in the Brazilian Amazon with different cutting cycle lengths, logging intensities, and lengths of the list of commercial species. Our assessment and analyses aim to assess the conditions needed to sustain timber yields during successive harvest cycles. It is beyond the scope of this paper to evaluate the socio-economic sustainability of the tested timber yield scenarios, nor do we address the impacts of climate change.

In this paper, we assess whether the annual timber yields from current and potential concession areas will be adequate to matcht the estimated present timber production of 11 $Mm^3.yr^{-1}$ (SFB, 2019a; Vidal et al., 2020).

2. Methods

2.1. Study areas - Brazilian concessions

Our study focuses on forest concessions in the Brazilian Amazon (Fig. 1). These concessions are located in public forests and currently cover 1.6 Mha, of which 1.05 Mha are managed by the SFB, and 0.6 Mha are managed by state-level agencies (SFB, 2019a). We defined the area of all potential concessions as the area of all public forests that are (i) in the Brazilian Amazon biome, (ii) designated for sustainable use, and (iii) not in community forests - although community forest management is legal and currently covers around 260,000 ha (Miranda 2020), indigenous territories, or military areas [(as defined in SFB (2019a), p. 112; Fig. 1]. Based on this definition, the potential concession area in the Brazilian Amazon covers an estimated 35 Mha.

2.2. The VDDE model

In this study we used the volume dynamics with differential equations model (VDDE; Piponiot et al., 2018). The VDDE model calculates the volume of all live trees ≥ 50 cm diameter at breast height (DBH), the

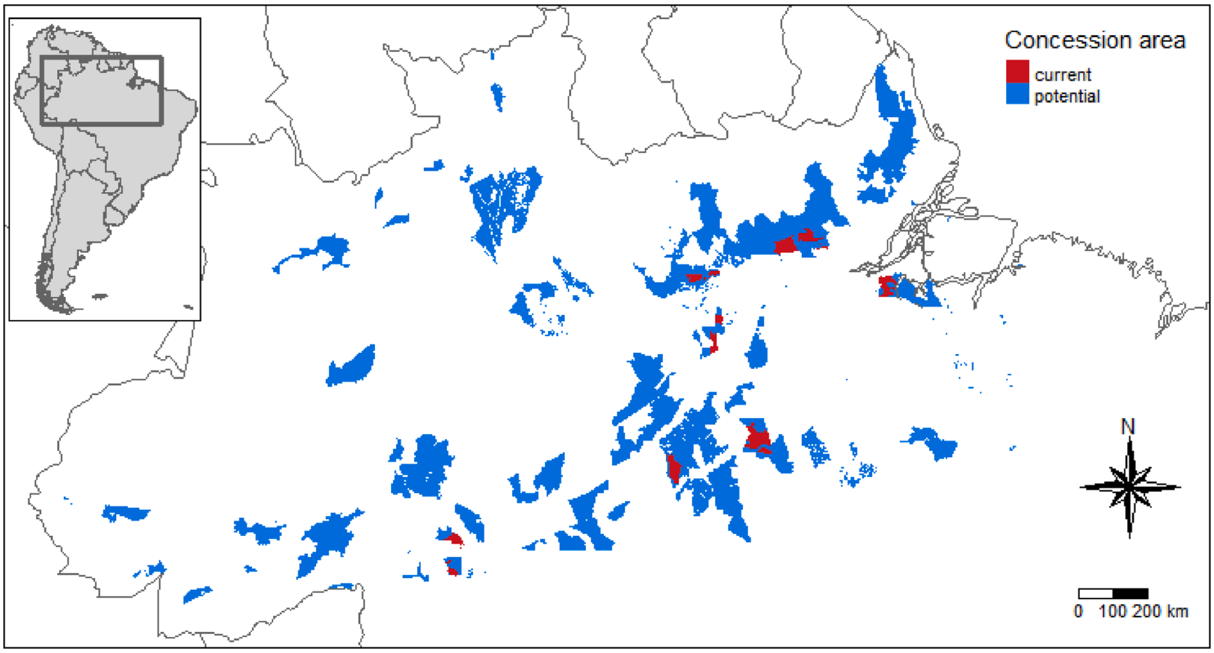

Fig. 1. Forest concessions in the Brazilian Amazon. Current federal concessions are in red; potential concessions (public forests designated for sustainable use) are in blue [retrieved from Brazilian Forest Service and IDEFLOR websites (IDEFLOR-BIO, 2021; SFB, 2020, 2019b)]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

standard minimum cutting size in the Brazilian Amazon. The portion of this volume composed of commercial species is referred to as the commercial volume.

In the VDDE model, total volume dynamics are the result of two ecosystem processes: volume gains due to tree growth and volume losses due to tree mortality. Both processes are expressed as a function of a hidden variable, forest maturity τ, which increases progressively over time in the absence of disturbance.

Annual volume growth $g(\tau)$ and mortality $m(\tau)$ are modelled as follows:

$$\forall\tau > 0, \begin{cases} g(\tau) = \alpha_G\left(1 - e^{-\beta_G\cdot\tau}\right) - \theta\cdot vol(\tau) \\ m(\tau) = \alpha_M\left(1 - e^{-\beta_M\cdot\tau}\right) \end{cases}$$

where τ is the forest maturity; α_G is the asymptotic gross volume productivity; α_M is the asymptotic volume mortality; β_G and β_M are the rates at which the asymptotic gross volume productivity and asymptotic volume mortality are respectively reached; θ is the relative maintenance cost; $vol(\tau)$ is the total volume at maturity τ.

The total volume $vol(\tau)$ can be calculated from the equations of annual volume growth and mortality (see Piponiot et al., 2018) as:

$$vol(\tau) = \frac{\alpha_G}{\theta}\left(1 - \frac{\theta\cdot e^{-\beta_G\cdot\tau} - \beta_G\cdot e^{-\theta\cdot\tau}}{\theta - \beta_G}\right) - \frac{\alpha_M}{\theta}\left(1 - \frac{\theta\cdot e^{-\beta_M\cdot\tau} - \beta_M\cdot e^{-\theta\cdot\tau}}{\theta - \beta_M}\right)$$

The total volume increases with the forest maturity, and tends towards the asymptotic volume $vmax = \frac{\alpha_G - \alpha_M}{\theta}$, for high values of maturity of the forest. When a disturbance occurs, whether natural (e.g., a large windthrow) or anthropogenic (e.g., logging), it abruptly reduces the maturity of the forest, and thus its total volume.

The model was calibrated for the Amazon Basin with a Bayesian framework with data from 3500 ha of an extensive network of plots scattered throughout the Amazon Basin, among which 845 ha are from 15 sites monitored for as long as 30 years after selective logging (Piponiot et al., 2019; Sist et al., 2015). Most of these plots were reportedly logged with some form of reduced-impact logging techniques (skid trail planning, directional felling, vine cutting, etc.; Sist et al., 2015, Piponiot et al. 2019), similar to what is strongly recommended and generally done in Brazilian logging concessions (SFB 2019a). These data allow predictions of commercial volume recovery rates to vary with location. Amazon-scale predictions of asymptotic gross volume productivity and asymptotic volume are based on results from the FORMIND simulator (Rödig et al., 2017); predictions of pre-logging forest maturity are based on aggregated data from the Rainfor network (Johnson et al., 2016). Other model parameters (β_G, β_M, and θ) were assumed to be constant across the Amazon. Data and detailed methodology for the Amazon-wide model calibration are provided in Piponiot et al. (2019).

Only a portion of all trees over 50 cm DBH are of commercial value. In this study, the pre-logging proportion of commercial volume was set for each simulation (see "Simulations"). Because logging targets commercial species, the proportion of commercial volume decreases after logging, and increases between logging events through recruitment of < 50 cm DBH trees, as described in Piponiot et al. (2018).

Around 20–50% of large trees in Amazonian natural forests have hollows or other defects that make them unsuitable for timber harvesting (Valle et al., 2006). Following Piponiot et al. (2019), we multiplied all timber volumes in our simulations by a factor $(1 - Pdef)$, with $Pdef$ the proportion of defective volume modelled as:

$$Pdef \sim \mathscr{B}eta(6, 14)$$

where $\mathscr{B}eta(6, 14)$ is the beta distribution of shape parameters $\alpha = 6$ and $\beta = 14$.

2.3. *Testing scenarios*

Modalities of selective logging can vary substantially according to the number of timber species considered as commercial, logging intensity and cutting cycle duration. To account for these possible variations, we tested 27 different scenarios by using combinations of the following inputs: (i) initial proportion of commercial volume: 20% (highly selective), 50% (intermediate) or 90% (non-selective); (ii) logging intensity: 10 m^3 ha^{-1} (low), 20 m^3ha^{-1} (intermediate) or 30 m^3ha^{-1} (high); (iii) cutting cycle length: 20 years (short), 35 years (intermediate) or 60 years (long). The remaining VDDE model parameters (as defined in "Modelling Framework") are defined spatially at a resolution of 1°

Each logging cycle includes the harvest itself as a function of logging intensity and forest characteristics (i.e. the spatially explicit VDDE parameters, defined in " Modelling framework") and the post-logging volume recovery phase, which varies with logging cycle length and forest characteristics. Logging lowers both the total volume and the proportion of commercial volume, but both then increase during the recovery phase, although the proportion of commercial volume takes longer to recover because it relies solely on the recruitment of trees < 50 cm DBH (Piponiot et al., 2018). These two steps are sequentially repeated to simulate 1000 years of logging.

Uncertainties are propagated throughout the model by drawing all parameter values from their calibrated distribution (from Piponiot et al., 2019), and simulating logging cycles with these parameter values. This process is repeated 100 times and summary statistics (medians and 95% credibility intervals) are calculated at each time step.

The results are then multiplied by the area of current or potential concessions (see "Study areas") in each 1° pixel, and by a factor $\pi = 58\%$. This factor π, which was calibrated with data from logging concessions in French Guiana, reflects the ratio between logged areas and the initially allocated areas, mostly because of slope restrictions and riparian reserves, but also heavy forest degradation by illegal logging and other disturbances (Piponiot et al., 2019; Veríssimo et al., 2006).

For each scenario we determined the duration of maintained timber production, i.e. the time before timber stocks become insufficient to maintain a constant timber production, as illustrated in Fig. 2. This maintained production is different from sustained timber production which theoretically shows a constant timber yield and stock over time (Fig. 2).

3. Results

None of the scenarios with an initial commercial volume proportion of 20% are sustainable after the first logging cycle (Fig. 3; Table 1). The present logging practices in the Brazilian Amazon usually correspond to a proportion of commercial species around 20%, a mean logging intensity of 15–20 $m^3.ha^{-1}$ and a harvest cycle of 35 years. Under such rules, timber yields are maintained only for a single cutting cycle (35 years, grey line in Table 1). Scenarios with higher proportions of commercial timber show longer durations of maintained production: 70 yr (35–140) and 175 yr (35–350) when the proportion of commercial species is respectively 50% and 90%.

Only 4 out of all 27 scenarios (bold rows in Table 1) have median durations of maintained production over 500 years, and only one is close to a sustained timber production *sensu stricto* (10 $m^3.ha^{-1}$ every 60 years with a 90% initial proportion of commercial timber species, Fig. 4). Three of these scenarios have an initial proportion of commercial volume of 90%, and three correspond to low intensity logging (10 $m^3.ha^{-1}$) with a cutting cycle of 60 years (Table 1).

Current timber harvested from the Brazilian Amazon is estimated at 11 Mm^3 per year (SFB, 2019a; Vidal et al., 2020) and can be therefore considered as a production target to satisfy the present market demand. Current concessions cannot come close to satisfying this target for even one cycle under any scenario (Fig. 3). The maximum annual production from the current concession areas is 1.43 $Mm^3.yr^{-1}$, which can only be reached under the most intensive scenarios: 30 $m^3.ha^{-1}$ of timber extracted every 20 years, with an initial proportion of commercial

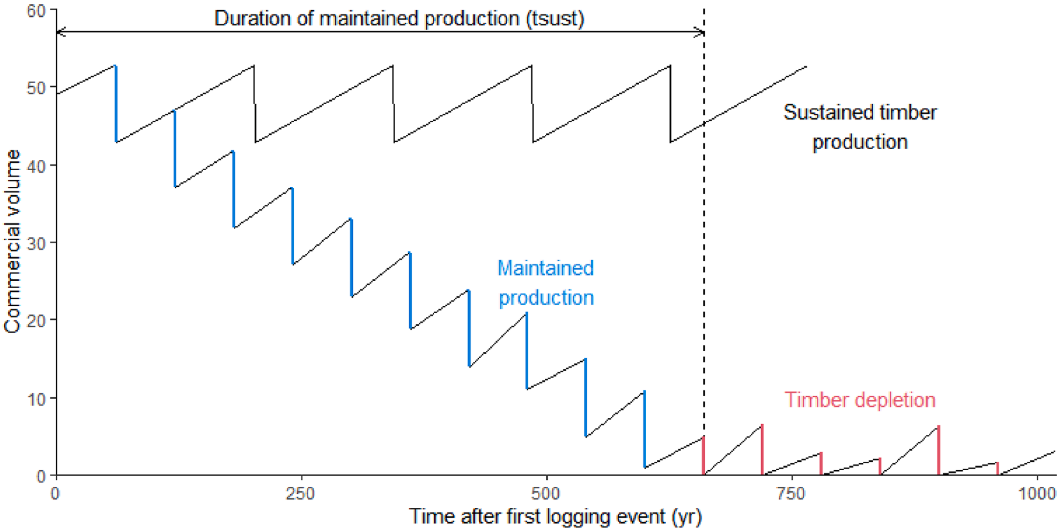

Fig. 2. Illustration of the duration of maintained and sustained timber production. The x-axis represents years after the first selective harvest, and the y-axis represents commercial volumes as simulated by the model with a logging intensity of 10 $m^3.ha^{-1}$ and a logging cycle of 60 years and 50% of commercial species. At each harvest, commercial volumes decrease (blue segments). If logging cycles are not long enough to allow recovery, the commercial volume decreases until it is not sufficient to maintain a constant production (10, 20 or 30 $m^3.ha^{-1}$, red segments). The time taken to reach this limit is the duration of the maintained production. In the sustained timber production scenario, with a longer harvest cycle, both timber yield and stocks remain constant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

timber ≥ 50% (Fig. 3). Under such conditions, the maximum duration of maintained production is 40 yr (20–80) (Fig. 3). Under the present harvesting practices of 20 m^3ha^{-1} every 35 years with only 20% of the volume of trees ≥ 50 cm DBH of commercial species, the annual production from the first harvest is only 473,000 m^3 and that yield will not be maintained after the first cutting cycle (35 years). Finally under the most sustainable scenario (10 $m^3.ha^{-1}$, 60 years and 90% of commercial species, Table 1 bold characters and grey shadow, and Fig. 4), the maximum annual harvest with the present concession areas is 160,000 m^3 which is very much less than the present annual harvest of 11 Mm^3.

When considering all potential concession areas (35 Mha), the annual production of 11 Mm^3yr^{-1} could be maintained, at best, for 175 yr (35–350) if 90% of the initial volume is commercial, logging intensity is 20 m^3 ha^{-1} and cutting cycles are 35 years (Fig. 3; Table 1). The two others scenarios that yield close to 11 Mm^3 during the first 250 years (Fig. 3) use logging intensities of 10 and 30 $m^3.ha^{-1}$ and logging cycles of 20 and 60 years, respectively. Under current rules (20 $m^3.ha^{-1}$ every 35 years and 20% proportion of commercial timber), the total annual production is 10 Mm^3yr^{-1} but is not maintained after the first logging cycle (Fig. 3). Under the most sustainable scenario (10 $m^3.ha^{-1}$, 60 years and 90% of commercial species, Table 1 and Fig. 4) and a concession area of 35 Mha, the annual production of timber would reach only 3.4 Mm^3 (Fig. 3).

4. Discussion

The VDDE model is well suited to study timber recovery in forest concessions throughout the Brazilian Amazon. It is important to note that we have not included in our scenarios the potential effects of climate change-related disturbances such as fires and droughts, despite the likelihood of their future increase in the region (Davidson et al., 2012). The model also ignores the possible losses of forest concession areas due to deforestation. Our results are therefore likely to be relatively optimistic, and correspond to the potential productivity of wood under the most favorable conditions.

The modeling scenarios relied only on unassisted natural regeneration and were focused on stocks and potential harvest volumes of commercial tree species as a group rather than on sustained production at the species level. Issues such as potential regeneration failure and loss of genetic diversity must be considered if attempting to manage for sustained production from particular commercial tree species, and the uniform harvest rules assessed here are not expected to affect all commercial species equally (Sebenn et al. 2008, Vinson et al. 2015). The scenarios considered also do not consider the potential benefits of the application of silvicultural treatments (e.g., liana cutting) to increase growth and yield.

According to the results of our simulations, several challenges need to be addressed to maintain timber yields from concessions in the Brazilian Amazon. The first is to lengthen minimum harvest cycles and reduce maximum logging intensities so as to at least fit the most sustainable scenario of 10 $m^3.ha^{-1}$ of timber harvested every 60 years with a 90% proportion of commercial species. Under such a scenario, the annual production with 35Mha of concession is only 3.4 Mm^3, far below the targeted 11 Mm^3. Our simulations also suggest that the production of 11 Mm^3 can be sustained for at best 170 years with a 90% proportion of commercial species, which is far higher than the 20% currently observed.

Changing the harvest rules (intensity and duration of harvest cycles) decrease the annual timber production for the same area. Increasing the area of concessions must be therefore a priority if concessions are to meet the timber demand from the Amazon. Establishment of new forest concessions in the Brazilian Amazon has been slow; 15 years after creation of the Brazilian Forest Service, active concessions cover only 1.6 M ha of the target area of 20Mha. It is beyond the scope of this paper to analyze the reasons for this slow rate of granting forest concessions in Brazil. However, according to Vidal et al. 2020, there is a lack of interest among timber companies to apply for concessions due at least in part to low stumpage prices, while local communities question the presence of concessions and potential impacts on traditional indigenous community rights and livelihoods. Moreover, nowadays, the main factor limiting the expansion of forest concessions in Amazonia is illegal logging, which represented 44% of all timber production between 2015 and 2016 in Parà State (Vidal et al. 2020). Legally harvested timber, which requires substantial long-term investments in machinery, human resources and infrastructure among others, competes poorly with illegal logging, which drives market prices down because of low-cost production linked to the absence of high investments. According to Brazilian foresters, the main actions to promote forest concessions in the Amazon are the

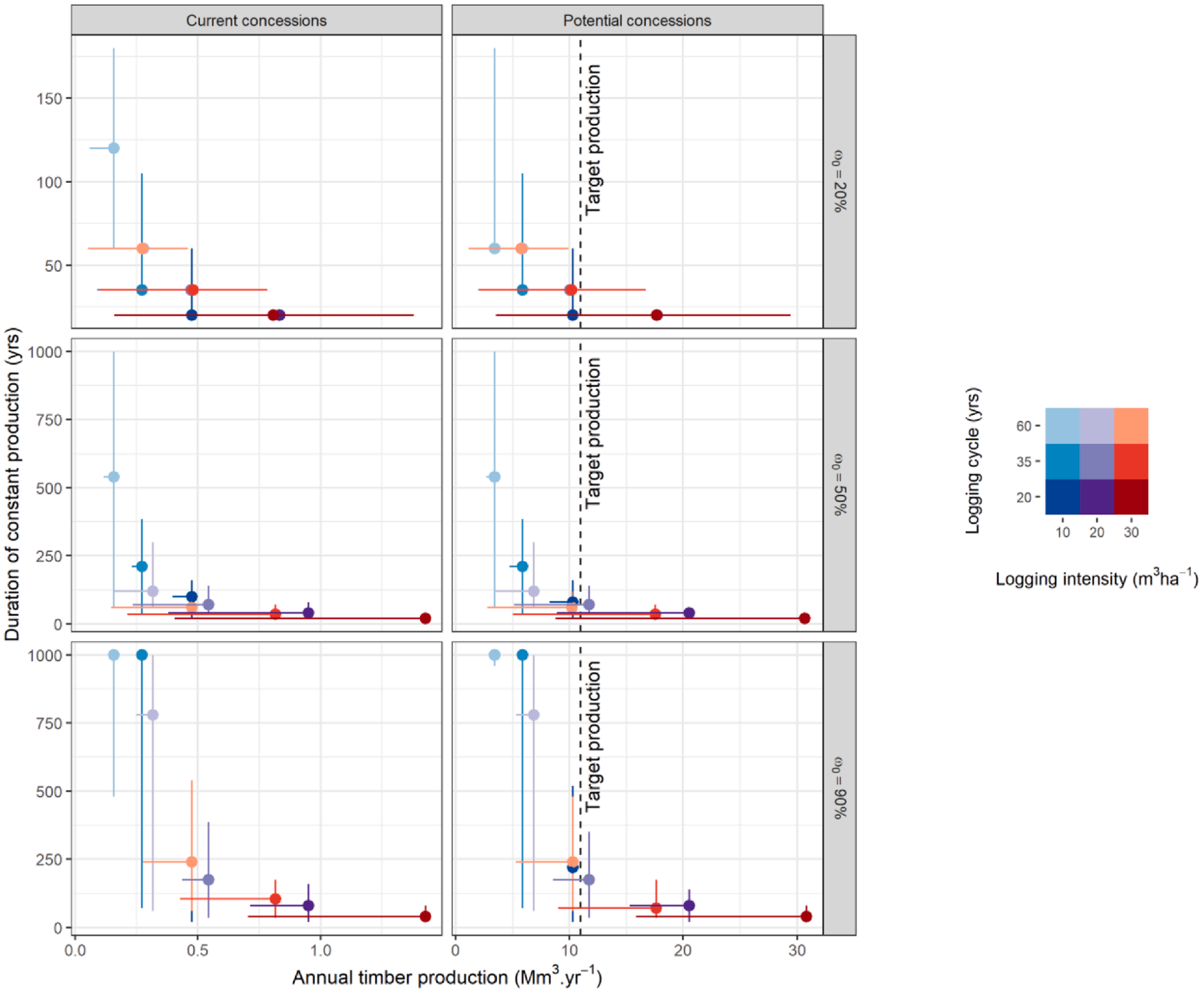

Fig. 3. Tradeoffs between timber production and sustainability. The x-axis is the annual timber production under each scenario, and in all areas considered in the scenario (left panels: current concessions; right panels: potential concessions). The y-axis is the duration of maintained production in each scenario, in years. The points are the median values over all simulations for each scenario; the vertical and horizontal error bars are the 95% credibility intervals. Colors represent logging rules (3 logging intensities × 3 logging cycle lengths) and the 3 values of initial proportion of commercial volume (ω_0) are represented by different panels, in increasing order from top to bottom. The target production of timber is 11 $\text{Mm}^3\ \text{yr}^{-1}$, which corresponds to the current timber production in Brazilian Amazonian forests. Only a few scenarios in the right panels (all potential concessions) are above this target, and all have a median duration of constant production $<$ 500 years.

following: (i) identify ways to value and differentiate the concessionaire from traditional timber companies that operate on private properties (ii) streamline or reduce bureaucratic requirements (e.g. the environmental licensing process, which is currently under the responsibility of multiple environmental agencies); (iii) improve relationships with local communities; (iv) improve transparency and stakeholder communication; (v) promote research on the social, economic, and biological impacts of concessions; (vi) identify ways to strengthen and promote community-based forest management; and (vii) support capacity-building initiatives for forest management.

One possible way to increase legal timber production would be to promote community forest management in conservation units. In 2010, protected areas in the Brazilian amazon covered 44% of the total area of the region or around 220 Mha (Veríssimo et al., 2011). Among these, conservation units that allow forest management for timber production cover about 55 million hectares. In these units, community forest management has enormous potential to contribute significantly to timber production in the region. Estimates suggest that if half of this area were under sustainable forest-management regimes, 5.6 Mm^3 of timber could be annually harvested (in Vidal et al. 2020). Community forest management could take different forms, from comprehensive management by the communities themselves to partnerships between communities and logging companies (Hildemberg Cruz et al., 2011).

The last, and probably the most important biophysical challenge for sustaining timber yields from Amazonian forests is to increase the list of commercial species so that at least 50% of the volume from trees $\geq$ 50 cm DBH in each harvest cycle would have commercial value. Piponiot et al. (2019) showed that by considering all species that have been registered as commercial at least once, 80–95% of the volume trees $\geq$ 50 cm DBH could have commercial value (Brazil, 1973). This result is encouraging, but it could mean that in the list of commercial species, some may have less favorable mechanical properties and lower market prices than species harvested in the first logging cycle. The harvesting and valuation of these new species must involve drastic changes in the entire wood supply chain. One of the first barriers is at the sawmill level: processing a large variety of species with different mechanical properties poses technical challenges for sawmills (Vidal et al. 2020). In addition, only about 40% of the volume entering sawmills is processed into lumber, and most of the remaining material is burned or left unused (De Lima et al., 2020; Pereira et al., 2010). Improving the efficiency and diversification of sawmills could therefore help to improve the productivity and therefore to increase the sawn-wood production (Vidal et al. 2020). The absence of public policy supporting the import of modern equipment and inadequate support for the industrial sector

Table 1
Sustainability of all 27 scenarios, characterized by the duration of constant timber production (yrs, last 2 columns). The first 3 columns correspond to the input variables: the proportion of commercial volume (%); logging intensity ($m^3.ha^{-1}$); harvest cycle length (yr). The last column is the duration of maintained timber production in potential concession areas, as the median value of all iterations, followed by the 95% credibility interval (between parentheses). Grey shadowed line: current logging practices, bold characters maintained timber production $\geq$ 500 years, Grey shadowed line with bold characters: the longest sustained timber production $\geq$ 1000 years with the *lowest timber stock reduction over time (see also* Fig. 4*, blue line).*

Commercial volume	Logging intensity	Logging cycle	Duration of maintained production
20%	10 $m^3.ha^{-1}$	20 yr	20 yr (20–60)
		35 yr	35 yr (35–105)
		60 yr	60 yr (60–180)
	20 $m^3.ha^{-1}$	20 yr	20 yr (20–20)
		35 yr	35 yr (35–35)
		60 yr	60 yr (60–60)
	30 $m^3.ha^{-1}$	20 yr	20 yr (20–20)
		35 yr	35 yr (35–35)
		60 yr	60 yr (60–60)
50%	10 $m^3.ha^{-1}$	20 yr	80 yr (20–160)
		35 yr	210 yr (35–385)
		60 yr	**540 yr (60–>1000)**
	20 $m^3.ha^{-1}$	20 yr	40 yr (20–60)
		35 yr	70 yr (35–140)
		60 yr	120 yr (60–300)
	30 $m^3.ha^{-1}$	20 yr	20 yr (20–40)
		35 yr	35 yr (35–70)
		60 yr	60 yr (60–120)
90%	10 $m^3.ha^{-1}$	20 yr	220 yr (20–520)
		35 yr	**>1000 yr (70–>1000)**
		60 yr	**>1000 yr (960–>1000)**
	20 $m^3.ha^{-1}$	20 yr	80 yr (20–140)
		35 yr	175 yr (35–350)
		60 yr	**780 yr (60–>1000)**
	30 $m^3.ha^{-1}$	20 yr	40 yr (20–80)
		35 yr	70 yr (35–175)
		60 yr	240 yr (60–480)

(sawmills, furniture manufacturing, etc.) is an important obstacle to develop a modern wood industry sector in the Brazilian Amazon. To achieve this goal and make the country a major producer of finished wood products instead of a supplier of raw materials for other countries, it will be critical for all the actors interested in development of this sector (e.g., research institutions, banks and other lenders) to act in an organized manner. Changing consumer habits is also a powerful lever to increase the commercial value of some lesser-known wood species, and has been the goal of advertising campaigns by environmental NGOs (FSC, 2016). Consumers unwillingness to pay high prices for lesser-known wood species combined with unfair competition from illegal logging continue to threaten the financial profitability of improved tropical forest management. The economic and ecological sustainability of logging are therefore linked to forest law enforcement and the fight against illegal logging.

Among the impediments to timber volume recovery after selective logging is that most of the higher valued timber species in the Amazon region are relatively slow growing and suffer from competition from others trees and lianas (reviewed by Finegan 2015). For this reason, sustaining timber yields generally requires both extending the time between harvests and applying silvicultural treatments such as the liberation of future crop trees (FCTs) from competition (Wadsworth and Zweede 2006; Mills et al., 2019; Roopsind et al., 2018). For example, in both moist tropical and dry forests of Bolivia such treatments doubled FCT growth rates (Dauber et al. 2005; Villegas et al., 2009). Although demonstrated to be effective, silvicultural treatments prescribed to increase stocking and growth of commercial timber species are seldom applied in the field. Cost concerns about applying treatments that only pay dividends after decades are exacerbated by uncertainties about continued access to the managed forests such as non-renewal of logging permits, invasions, and social conflicts. Regarding silvicultural intensification, it would help to know more about the disaggregated costs and various benefits of these treatments for more forests (e.g., Ruslandi et al. 2017). Moreover, our understanding of the long-term benefits of such treatments are still very site specific. Further research on the long term benefits of silvicultural treatment at regional and global scales contribute to the promotion of such practices with specific recommendations.

Our simulations suggest that, under present regulations, the production of timber from forest concessions in the Brazilian Amazon can be sustained for only one harvest cycle. Additional sources of timber should be sought from plantations of exotic or native species, enriched secondary or degraded forests, and silvo-pastoral and other agroforestry

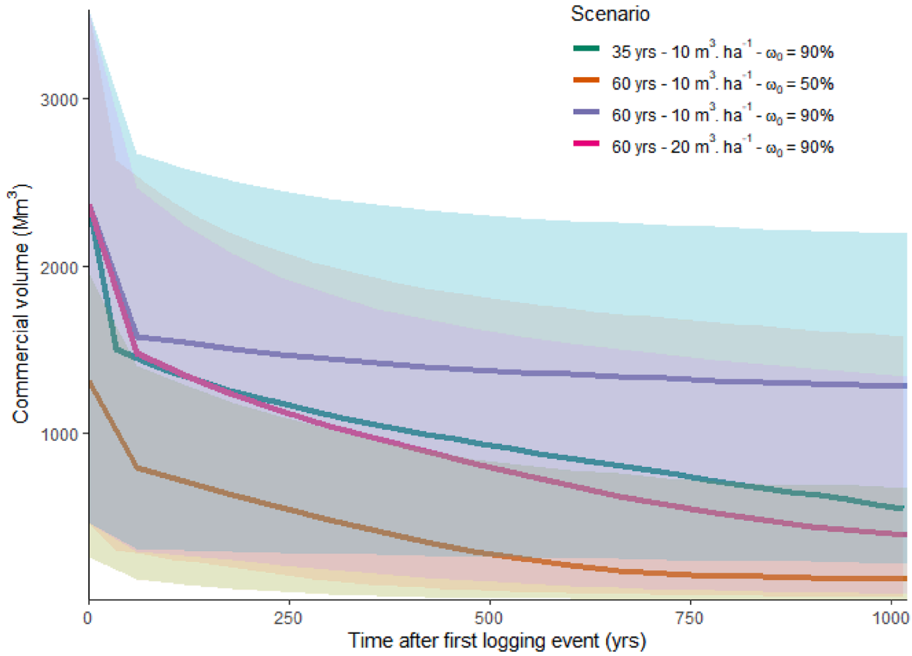

Fig. 4. Commercial volume stocks in all potential concession areas for the 4 scenarios with a duration of maintained production > 500 years. The x-axis is the time after the first logging event (in years); the y-axis is the total commercial volume stocks in all potential concession areas, in Mm^3. The colors represent the 4 scenarios, with the thick lines corresponding to the median and the shaded areas to the 95% credibility interval over all iterations. The scenario extracting 10 m^3ha^{-1} every 60 years with a proportion of commercial timber of 90% (top blue line) is the most sustainable, with a median duration > 1000 years and an almost constant commercial timber stock. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

systems that could be part of the forest restoration programs under the Bonn Challenge Initiative (; Ngo Bieng et al., 2021). Tree plantations in Brazil are concentrated in the South (SFB, 2019) and cover 9.8 Mha of which 75% is *Eucalyptus* (SFB 2019). In the Brazilian Amazon, plantations cover around 940,000 ha which 83% is *Eucalyptus* (SFB 2019). In contrast, plantations of species other than *Eucalyptus* and Pinus only cover around 160,000 ha representing 17% of the total plantation area in the Brazilian Amazon (SFB 2019). These numbers show that in the Brazilian Amazon, plantations of timber native species in the Amazon are still very poorly developed and could be promoted in landscape restoration programs. The rising interest in tropical forest restoration, crystallized by the Bonn Challenge in 2011, enhance opportunities to contribute to this forest transition encouraging restoration of economically viable timber plantations in deforested areas in the Amazon Basin while promoting the sustainable management, the conservation and natural regeneration of remaining natural forests. Yields from these forest restoration programs could decrease pressure on natural production forests – allowing larger areas to be set aside for conservation, and allowing lower-intensity management of production areas. Unfortunately, in the past, industrial plantation, including those for saw timber and veneer, were generally installed after clearance of natural forests (Arttu Malkamäki et al., 2018). For this reason it is crucial that timber plantation schemes be carried out in the context of landscape restoration programs. The promotion and development of a diversified approach to timber production in which natural forest and plantation management are complementarys, would yield a diversity of assets (carbon, biodiversity, cultural, timber) and promote specific markets and uses of timber from natural forests with possibly higher prices than timber from plantations. This new market for timbers extracted from natural forests with higher prices should take into account the specific wood properties of old natural timber, the costs of sustainable forest management practices and the environmental services provided by well managed natural forests. However, in practice, logged-over forests in the region still cover several hundred millions hectares that are accessible and still provide a cheap source of timber. Specific markets for timbers extracted from managed natural forests cannot be possibly promoted or developed while illegal logging and deforestation remain the main sources of timber. Strong public involvement in fighting both deforestation and forest degradation by illegal logging are urgently needed to promote diversified tropical silviculture and sustainable natural forest management in the Amazon. Finally, restoration initiatives could be a way to promote such new scheme of tropical forest management and silviculture in the Brazilian amazon.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by Cirad, the Forest Tree and Agroforestry CGIAR program in the framework of the TmFO network (www.tmfo.org). Edson Vidal thanks the National Council for Scientific and Technological Development (CNPq) for a productivity grant (309319/2018-8).

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