Long-term effects of selective logging intensity on a production forest's succession of the Amazon

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# Highlights

# Simulation of long-term aboveground biomass changes for different logging intensities.

# Extrapolation of selected ecosystem functions by varying the cutting threshold of commercial tree species.

# Novel method for quantifying the recovery times of a production forest in French Guiana.

# High selective deforestation intensities prolong the recovery time of ecosystem functions.

# Pioneer tree species benefit in particular, as the species group composition is shifting.

# Abstract

There is an increasing concern, how far tropical production forests of the Amazon are managed sustainably. The Amazonian rain forest is an essential carbon reservoir, with a high degree of protective biodiversity, although it provides useful resources, e.g. for timber. The latter contributed to the fact that in the last five decades about one fifth of the Amazon forest has been lost. The implementation of effective silviculture strategies that are more economic and ecologically beneficial plays thus a central role to prevent loss of resilience or forest degradation. However, in order to identify effective silviculture strategies, there is a great need for methods supporting the decision-making process. One opportunity to estimate future forest stand structures is provided by dynamic forest growth models that are able to extrapolate field observation data in the long-term.

In this study, we applied the FORMIND forest growth model to a humid tropical lowland forest in the northeastern Amazon basin of French Guiana, Paracou. We analyzed simulation experiments for undisturbed forest growth and selective deforestation, which help us to understand the long-term effects of different damage intensities on the aboveground biomass production and tree species composition. For the first time we were able to validate simulation results of selective logging and undisturbed forest growth conditions with forest inventory data from the last 32 years. Our simulation results show that the model accurately maps aggregated forest attributes such as aboveground biomass and tree size distribution to the number of stems for both undisturbed forest growth and selective logging. We demonstrate that strategies for forest management with minimal logging intensity in the context of resilience have long-term advantages over intense strategies.

***Keywords:*** *forest gap model FORMIND, model parameterization, simulation experiment, logging intensity, recovery time, biomass productivity, gross primary production, leaf area index, Shannon index*

# Introduction

Intact forest ecosystems bind carbon in their living biomass and thus have a stabilizing effect on the global climate (Intergovernmental Panel on Climate Change., 2014; Pan et al., 2011; Watson et al., 2018). In particular, tropical forests play an important role in the global carbon cycle (Houghton et al., 2015; Malhi and Grace, 2000), as they store about 42% (363±28Pg C) of the Earth's terrestrial carbon in their live biomass (G. B. Bonan, 2008; Pan et al., 2013). However, acan be designated(Robinson, 1960)Hence, there is a risk that large areas of these forests will lose their function as carbon stores (Francis E. Putz et al., 2008). It depends on the present management strategy (e. g. logging intensity, cutting cycles), whether they are carbon sinks or sources (G. B. Bonan, 2008). In the context of climate protection and biodiversity conservation strategies, forest management plays therefore an important role. Against this background, two challenges are discussed: (*i.*) There is an inappropriate economic use of the resource wood (Huth et al., 2004; Molina, 2009; Reischl, 2012; Steffen et al., 2015), and (*ii.*) an incomplete understanding of the long-term effects of forest management strategies on the growth of tropical forests (Houghton et al., 2015; Werger et al., 2011).

On an international level, specific action programs are being implemented to counteract these two issues. Prominent examples are the climate protection instrument REDD+ (Danielsen et al., 2011; Mollicone et al., 2007; Tyukavina et al., 2015; World Bank, 2011) and certification systems for sustainable silviculture, such as FSC or PEFC (Clark and Kozar, 2011; Durst et al., 2006; Rotherham, 2011). All create incentives through compensation or certification to initiate a transformation of conventional forestry into sustainable forest management in tropical developing countries (Long, 2013). Several challenges are related to this. On the one hand, it is difficult to quantify the regional distribution of biomass and deforestation rates (Gibbs et al., 2007; Malhi and Grace, 2000; Van Breugel et al., 2011). The vegetation state is one of the most uncertain variables in the global carbon budget (Pan et al., 2013). On the other hand, the long-term effects of present forest management strategies on forest growth dynamics need to be studied (D’Amato et al., 2011; Houghton et al., 2015). Consequently, a successful implementation of such international action programs requires methods and knowledge to assess the impact of silviculture, such as selective logging, on forest growth in the tropics (De Sy et al., 2015; Molina, 2009; Reischl, 2012; Steffen et al., 2015).

In order to investigate effects of different logging intensities on the succession of a forest in the northeastern Amazon basin in French Guiana (Paracou), we applied the forest growth model FORMIND including a management module (Fischer et al., 2016; Kammesheidt et al., 2002). The Paracou test site is located in a forest area (so-called *Domaine Forestier Permanent*), which covers 2.4 106ha and is managed by the National Forest Service *NFS* of French Guiana (Gourlet-Fleury et al., 2004; CIRAD, 2016). About 45% of the country's production forest areas have been certified according to *PEFC* (Kurier, 2000; PEFC International, 2017) since 2013, but are not yet FSC certified. When the Paracou test site was built in 1982, the main focus was on wood and its sustainable renewal (CIRAD, 2016). The available forest inventory data from Paracou provide an excellent basis for the parameterization of forest models. Forest models can be used to assess the long-term effects of current management actions (Huth et al., 2004) and thus contribute to the decision-making process (De Sy et al., 2015). Complex interrelationships between ecosystem functions and management intensity can thus be revealed. In this context, we answer the following four research questions in this study:

1. Is it possible to reproduce the dynamics of a selectively logged forest by individual-based forest modeling?
2. How do different management intensities (*DBH* of lower cutting threshold) affect the ecosystem functions of the forest (biomass balance, gross primary production)?
3. How long does the recovery of the forest’s ecosystem functions take regarding different logging intensities?
4. How does the relationship between the forest’s productivity and biomass balance change after selective logging?

We proceeded methodically as follows:

Firstly, the FORMIND forest model was parameterized for the Paracou test site in French Guiana on the basis of forest inventory data. These were recorded over 32 years on plots covering a total of 62.5 hectares of primary forest. Secondly, we have analyzed different logging scenarios in simulation experiments. The simulation results of one of those logging scenarios were compared with field measurements of Paracou (records over 32a on 18.75ha). Finally, different forest attributes (gross primary production, aboveground biomass, leaf area index, Shannon diversity index) were extrapolated for each logging scenario.

# Methods

## 2.1 Description of the FORMIND forest model

In this study we used the individual-based forest gap model FORMIND plus management module (Fischer et al., 2016; Huth et al., 2005, 2004). FORMIND was developed to analyze the structure and functions of tropical forests. In this study, the special interest in forest growth pointed at the secondary succession (after selective logging) of aboveground biomass as well as the gross primary productivity.

Forest gap models describe forest succession in small-scale forest patches (patch: 20m x 20m). The simulated forest area can range from 1ha up to several km2 (in this study 16ha) being composed of such squared patches. The trees within a patch are positioned explicitly depending on the light climate on the ground. The FORMIND model's general concept is shown schematically in the supplementary material ([Appendix A1.x](#headerA1.1)). In tropical forests, the high number of tree species is a particular challenge for forest models. In FORMIND, tree species are grouped into plant functional types *PFT* according to species-specific functional traits, such as maximum growth heights, maximum growth rates or light demands. In order to assess the forest dynamics and structure, the tree species composition and tree size distribution are calculated. The tree shape is simplified and described assuming cylindrical stems and crowns. The main processes considered are tree growth, mortality and recruitment; the trees within a forest patch compete for space and light. Individual tree growth is calculated on a carbon balance, for which eco-physiological processes, such as photosynthesis, respiration, carbon allocation, and litter fall are calculated.

The model architecture of FORMIND is modularized. This concept allows extending the forest model by switching on a management module to simulate different types of forest management, e.g. selective logging. All trees that meet certain criteria will be removed during one simulation time step (in this study 1a) from the model landscape on the patch level. Simultaneously, surrounding trees can be damaged, depending on the chosen logging strategy, intensity, cycle, the cutting thresholds, and the resulting damage. Different logging strategies can be investigated: (*i.*) reduced impact logging, in which the damage is reduced by directing the felled trees' direction to the closest gap and thus lower damage to the remaining forest stock. Furthermore, damages of future harvestable trees are excluded; and (*ii.*) conventional logging, in which a felled tree's direction of fall is arbitrarily chosen and damage to the remaining forest stock is uncontrollable. Please, find a detailed model description in Fischer et al. (2016) or on the [homepage www.FORMIND.org](C:\\Arbeit\\Diss\\TP3_Publikationen\\ArtikelTwo\\www.formind.org).

## 2.2 The Paracou test site and forest inventory data

The Paracou test site is located in French Guiana (Location: 5° 23'N; 52° 54'W, which belongs to the northeastern Amazon basin. More than 94% of the land area is covered with moist lowland *terra firme* rain forest that has a relatively high number of tree species (150-200 species per hectare). Wood extraction by selective logging mainly forms the country's third economic sector and is carried out exclusively in the National Forest Service's *NFS* forest area of the permanent forest estate of 2.4 106 hectare (Gourlet-Fleury et al., 2004). Paracou's forest is part of the *Caesalpiniaceae* and is surrounded by production forest (Galochet, 2018).

The test site is managed by the Centre International de Recherche en Agronomie pour le Développement *CIRAD* conducting forest inventories regularly (Gourlet-Fleury et al., 2004). The inventory design is depicted in the supplementary material ([figure A1.](#headerA1.2)x). Forest inventories were conducted as follows: each 9-hectare-plot was surrounded by a 25m wide buffer zone. The trees were exclusively inventoried within the core zone, on an area of 6.25ha, but the treatment has always been carried out on the entire 9-hectare-plot. Furthermore, there was one 25-hectare-plot on which undisturbed tree growth has been recorded. In order to parameterize and calibrate the forest model of FORMIND, we used the part of the inventory data set that belong to the T0-control and biodiversity plots (primary forest totaled 62.5ha). To parameterize and validate the management simulations, the plots with treatment T1 were chosen (18.75ha in total). This treatment refers to a so-called reduced impact logging *RIL* due to lower damage occurring on the remnant forest stand (see chap. 2.1; [A1.x)](#headerA1.3). Logging was applied in 1986 and in the consecutive years, the secondary succession was recorded. The impact of logging was quantified by aboveground biomass loss (-33tODM/ha) and stem number reduction of trees with a minimum diameter at breast height *DBH* between 0.5m-0.6m (cutting threshold) belonging to 58 commercial tree species (ca. -10ha-1). Skid trails and logging roads were mapped during the logging operation (Gourlet-Fleury et al., 2004). In the forest inventory data set all trees with a diameter at breast height *DBH* above were localized between the years -, and tree species were determined botanically. For each observed tree the stem circumference [cm] was measured at a breast height of 1.3m and then the *DBH* [m] was calculated. In some cases the normal *DBH*-measure was impossible; so that the measure point was adjusted according to rules [(see A1.x; table A1.x)](#headerA1.2). To eliminate errors that emerge in the forest inventory data, a correction of the primary circumference measurement was calculated. Furthermore, the damage status of the trees was recorded using a categorical code for each type of damage [(see A1.x; table A1.x)](#headerA1.2).

## 2.3 Parameterization of the FORMIND forest model

The forest inventory data of the undisturbed plots (T0-control) were used (*i.*) to parameterize tree allometry (e. g. maximum stem diameter increment, maximum tree height), (*ii.*) to classify tree species into plant functional types *PFT*, (*iii.*) and to calibrate and fine-tune some remaining uncertain parameter values. Each tree species has been assigned to one of eight *PFT*s, corresponding to the species-specific 95% quantiles of both maximum stem diameter increment and maximum tree height. The tree species were divided into three classes of growth rates and four height classes. Table 1 shows the functional traits assigned for each of the eight *PFT*s. Table 1 also lists the attribute values of mean aboveground biomasses and of mean tree numbers calculated from the forest inventory plots. A few parameters were numerically calibrated (*pmax,gmax, gDBHmax,Nseed*) using the dynamically dimensioned search *DDS* (Lehmann and Huth, 2015). For the model calibration we used the tree size distribution of each *PFT* in order to reproduce the forest stand structure as realistically as possible over time [(figure A1.x)](#headerA1.1). To compare the simulated results and forest inventory data we visualized both in 1:1 plots. We maximized the *R2*, which is the quotient of the variances of the simulated and observed values (Leyer and Wesche, 2007).

Furthermore, a management module was added in order to investigate the effects of selective logging. The FORMIND parameters for the management module were determined from the forest inventory data of the T1-*RIL* plots: The proportions of commercially usable tree species per PFT as well as the minimum *DBH* of the harvestable commercial trees (average of 0.55m) were calculated. The parameter *dam1* describes the proportion of damaged trees in the residual forest stand per stem diameter class *damdia* during a selective logging event. We have determined this proportion of damage out of the inventory data. The simulation results of this scenario were compared with forest inventory data from the logged plots (T1 plots), such as the stem number and stem volume of the harvested commercial trees as well as the loss of the mean aboveground forest biomass. For more information about the parameterization, please, see [Appendix A1](#headerA1).

Table 1: Grouping of tree species into eight plant function types *PFT* for the Paracou test site (T0-control plots). Functional traits were assigned to each *PFT*. Besides, attribute values of the mean aboveground biomass, mean basal area, and mean stem number were calculated (averaged over all forest inventory years 1984-2016; *ODM*: organic dry matter).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| PFT | successional state | growth rates | stratification | mean stem numbers [ha-1] | mean biomass [tODM/ha] | mean basal area [m2/ha] |
| 1 | climax | slow growing | under-story | 2.11 | 0.20 | 0.02 |
| 2 | climax | slow growing | sub-canopy | 236.63 | 59.23 | 5.05 |
| 3 | mid | semi-fast growing | sub-canopy | 15.07 | 3.91 | 0.38 |
| 4 | pioneer | fast growing | sub-canopy | 5.20 | 1.70 | 0.19 |
| 5 | climax | slow growing | canopy | 154.59 | 122.86 | 8.09 |
| 6 | mid | semi-fast growing | canopy | 174.64 | 184.91 | 13.25 |
| 7 | pioneer | fast growing | canopy | 16.90 | 14.32 | 1.34 |
| 8 | mid | whole range | emergent | 15.50 | 30.68 | 2.40 |
| total |  |  |  | 620.64 | 417.81 | 30.72 |

## 2.4 Simulation of different selective logging intensities



For the simulation of selective logging we switched on the management module and simulated a single logging event. To simulate different selective logging intensities we varied the *DBH* of lower cutting threshold (minimum *DBH* of harvestable commercial trees) in the interval 0.1m-1.0m in 0.1m-steps. In total, we simulated 10 logging scenarios with a varying cutting threshold and two reference scenarios. The first reference illustrated the undisturbed growth of primary forest in an equilibrium phase, before selective logging took place (pre-logging phase). To simulate primary forest growth, we adopted parameter settings conforming to Paracou’s undisturbed control plots (T0; see chap. 2.2). As a second reference, we used parameter settings of the reduced impact logging scenario according to Paracou’s T1 plots. This referred to the logging scenario with a cutting threshold of *DBH* equal to 0.55m (so-called *moderate scenario*), where the fall direction of the felled trees to the nearest gap was controlled. In this case, the simulation results were compared with the associated field data (T1) during the secondary forest succession (post-logging phase). In the other 10 logging scenarios, the direction of fall of felled trees to the nearest gap was not controlled and potentially harvestable trees were damaged. One of these scenarios, with a DBH of lower cutting threshold of 0.1m, was referred to as an *intense scenario*.

The simulation for all scenarios began on a treeless (empty) area of 16 hectares. Annual time steps and a total of 800 years were simulated. A single logging event took place after the 500th simulation time step. This was then assigned to the observed logging event in the year 1986. By doing so, we could count years after selective logging (time of logging equals zero). Of the total of 800 simulated years, we analyzed the last 350 years of each simulation scenario. The time intervals [1; 300] corresponded to the post-logging phase and the time interval [-50; 0] to the pre-logging phase. Simulation results for the time interval [-500; -51] were excluded from further analysis (see Appendix A1).

Beyond the analysis of aboveground biomass *AGB* for the three successional stages (see Table 1) and the overall forest stand, the forest model was used to extrapolate the development of the entire forest stand’s gross primary production *GPP,* leaf area index *LAI* and Shannon-index *H’*. For these variables, we also analyzed the mean recovery time after logging. Therefore we used nearest least squares models to infer recovery time over logarithmic *DBH* of lower cutting threshold (see A1). In our study, we used the Shannon-index H' to explain the diversity of tree species groups PFT, taking into account the abundance as well as the diversity of species groups and (Spellerberg and Fedor, 2003). A change in H' should illustrate the impact of damage on forest structure in different selective logging scenarios, where pi is the proportion of individuals belonging to the ith PFT and *P* the total number of PFTs in the data set (Huston, 1994):

(1).

H' has been standardized and can range between 0 and 1.In general, the higher the index is, the better the equal distribution of species groups (Huston, 1994). Standard deviations for the total forest stand’s aboveground biomass were given to measure the deviation from the average forest attributes and to interpret the stability of the ecosystem (Leyer and Wesche, 2007).

# Results

## 3.1 Biomass dynamics of a selectively logged forest

First we analyzed selected simulation results of a moderate and an intensive logging scenario for the development of aboveground biomass (Figure 1.a, c) and gross primary production (Figure 1.d). It can clearly be seen that the first logging event (time = 0a) in both scenarios was followed by an immediate decline in aboveground biomass accompanied by an increase in productivity in comparison to the reference (mean AGBref 439tODM /ha, mean sdref ±67tODM /ha; averaged over 16ha simulation area). Generally, the decline in aboveground biomass was directly proportional to the intensity of selective logging, but the increase in productivity was indirectly proportional. In the simulation experiment, the logging intensity was expressed by the minimum stem diameter at breast height *DBH* of harvestable commercial trees (*DBH* of lower cutting threshold). In the moderate scenario, 10 trees per hectare were harvested with an overall commercial bole volume around 39m3/ha. Aboveground biomass decreased by 109tODM /ha a year after logging. Compared to this, the impact of selective logging in the intense scenario’s overall aboveground biomass was twice as strong directly after logging. In this scenario, e.g. more than 306 commercial trees were harvested per hectare, with a totaled stem volume of 116m3/ha, so that the overall aboveground biomass decreased by 211tODM /ha.

In a second step we explored the structural development of the forest stand by comparing the species group compositions of the moderate and the intense scenarios. In the moderate scenario (Figure 1.a) the tree species’ group composition shifted slightly in about 70-80 years after logging: the aboveground biomass of the pioneer species recovered faster than that of the climax or intermediate tree species. After these seven decades both the forest stand structure and the overall biomass returned to the reference values of primary forest growth (pre-logging phase). The comparison of the simulated and observed aboveground biomass per species group (PFTs grouped by successional stage) between 1986 and 2016 shows that our model can reproduce the dynamics and species group composition of a selectively logged forest (Figure 1.b). Overall, the simulated aboveground total biomass values correspond well to the observed values during the post-logging phase (R2 0.991, rmse 4.6tODM/ha). However, the forest model slightly underestimated the observed aboveground biomass of climax species during three decades after selective logging. For the post-logging phase, the forest model also slightly overestimated the observed total mean aboveground biomass (418tODM/ha) with 5%. The deviations between observed and simulated biomass values were less than the observed standard deviation (sdobs ±67tODM/ha) (see also Appendix A1).

The intense scenario (Figure 1.c) was characterized by a stronger shift in the species group composition and the aboveground biomass was only slowly recovering (138a) compared to the moderate scenario. A rapid increase in the forest stand’s overall aboveground biomass was particularly noticeable during about 50 years after logging. This rapid increase was dominated mainly by the increase of fast-growing pioneer species’ biomass. The initial phase of rapid gross primary production was followed by a phase, which was characterized by lower productivity rates (Figure 1.d).

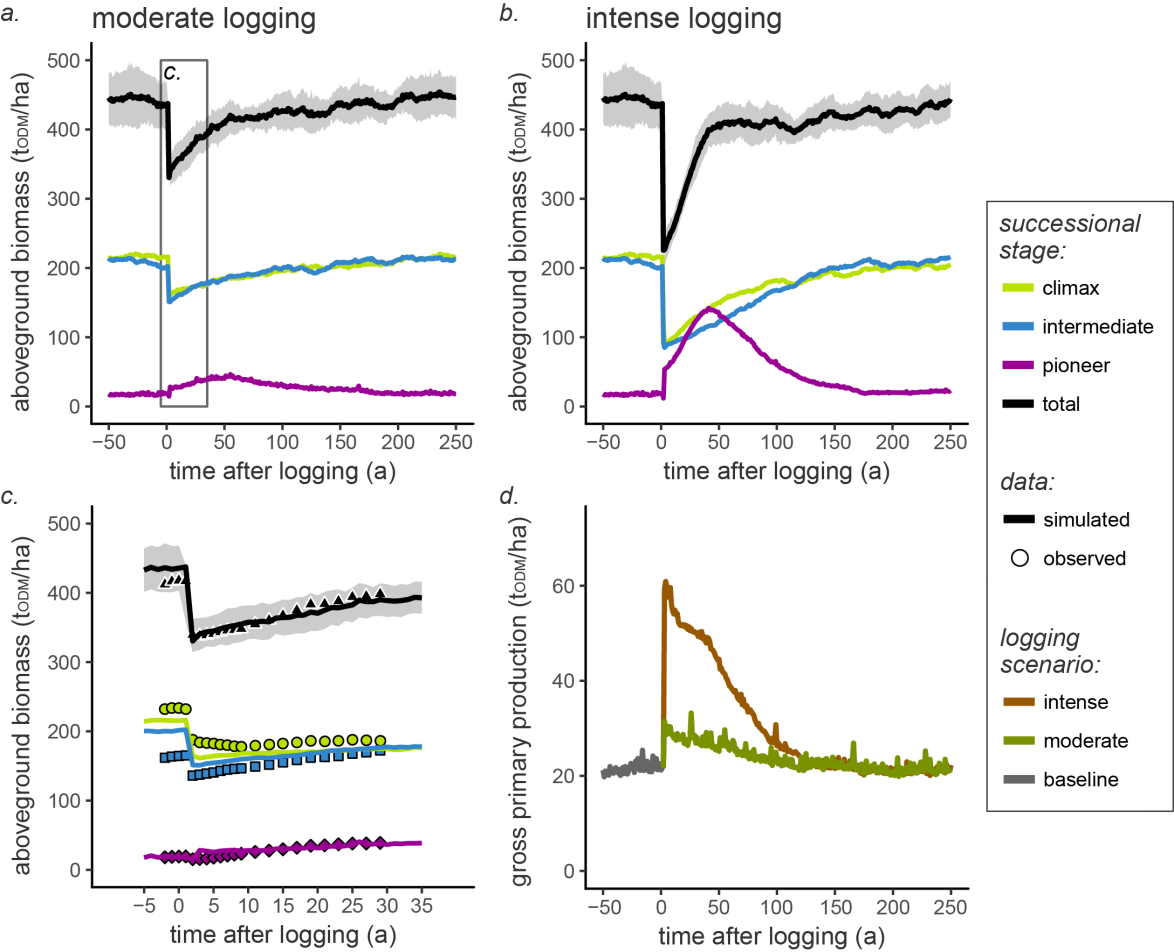


Figure 1: Development of the mean aboveground biomass plus standard deviation (a., b.) and the mean gross primary production (d.) of both the entire forest stand (grayish lines) and the tree species grouped according to functional traits of successional stage (colored lines; Averages of 16ha-simulations). The dashed lines indicate the moment of the selective logging event (time=0a) after a 50-year spin-up time, which reflects primary forest growth as a reference (dark gray). The selected simulation results refer to parameter settings used in the FORMIND forest model of a moderate (light gray) and an intense (medium gray) selective logging scenario in which the minimum *DBH* values of harvestable commercial trees were varied. The dots in the left panel indicate mean annual aboveground biomass values calculated on basis of Paracou’s forest inventory data of the T1 plots. The year of logging (1986) was assigned to simulated time equaled 0. b.) Comparison of the temporal development of observed (dots) and simulated (line graph) aboveground biomasses after logging. Light-demanding pioneers are reddish, shade-tolerant climate species are greenish, emergent are violet, and intermediate species are bluish-colored. The simulated logging was assigned to the observed logging event in the year 1986.

## 3.2 Effect of different selective logging intensities on ecosystem functions

In a third step we investigated the impacts of different logging intensities on the productivity of the remnant forest stand’s aboveground biomass in a set of simulation scenarios. Therefore, we experimentally varied the *DBH* of the lower cutting threshold stepwise in 0.1m-intervals between 0.1m-1.0m. The diagrams in Figure 2.a and 2.b show the correlations between a changing cutting threshold and the remaining forest stand biomass (Figure 2.a) or gross primary production (Figure 2.b). The correlations are given as linear regression models for discrete years during the first six decades after logging. In general the following applied: The higher the cutting threshold of harvestable commercial trees was, the smaller the number of trees harvested and the higher the remaining forest stand biomass. In the case of gross primary production, a higher logging intensity resulted in a longer recovery time as well as a higher productivity. Analogous to Figure 2.a and 2.b, the diagram in Figure 2.c represents the relationships revealed between the forest’s gross primary production and changes in the remaining forest stand biomass for every year during the three decades after selective logging. The interactions revealed by our model simulations are non-linear.

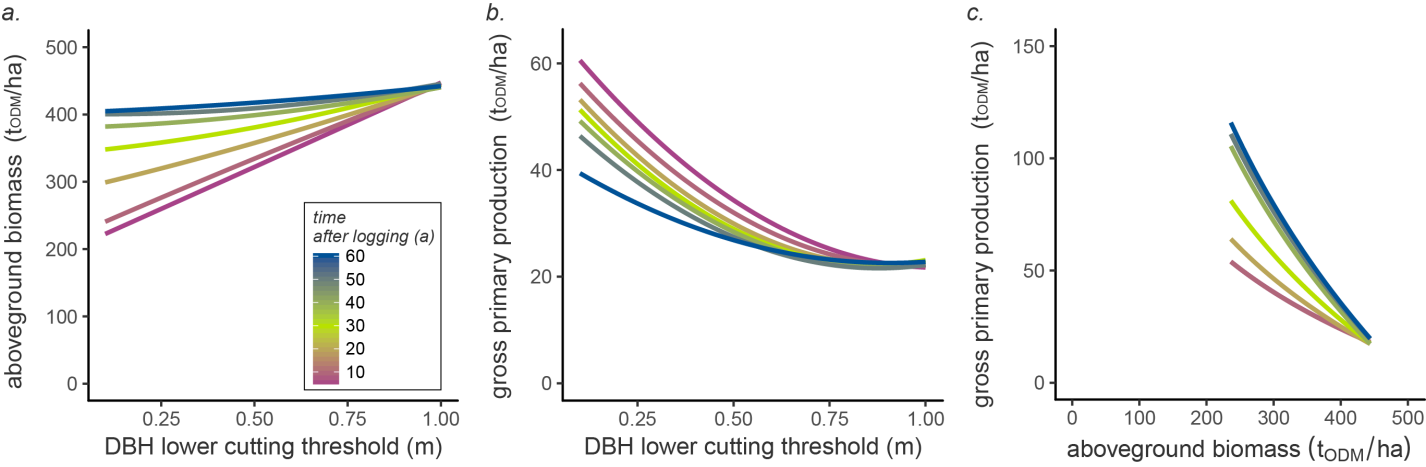


Figure 2: Interrelationships between aboveground biomass (a.) or gross primary production (b.) and minimum *DBH* of harvestable commercial trees during three decades after the selective logging event (0a < time ≤ 60a; see Figure 1). The trend lines were determined using the linear regression of a second-degree polynomial. Relationships of gross primary productivity to the aboveground biomass (c.) during three decades after the selective logging event (0a < time ≤ 60a; see Figure 1). The trend lines were determined using a least square regression of a logarithmic AGB.

Further, we analyzed extrapolated variables, such as the aboveground biomass, gross primary production, crown density (given as leaf area index), and species-group diversity (given as Shannon-index) and compared the duration that the entire forest stand needed to recover on average after logging (mean recovery time; Figure 3). The bar chart in Figure 3.b highlights the mean recovery times of these four variables of the moderate and intense logging scenarios that had been shown in Figure 1. Compared to the intensive scenario, the forest stand takes at least twice as long to recover as in the moderate scenario. This applies to all four variables examined. With the help of the trends fitted to each variable of the entire scenario set, different management strategies can be evaluated (Figure 3.a). We found logarithmic interactions between the different *DBH* of lower cutting threshold and mean recovery time (see A1). The Shannon-index recovered latest after 40 years in the more intense scenarios (e.g. *DBH* of lower cutting threshold 0.1m). Generally, the variables calculated on basis of the biomass (gross primary production, leaf area index) took at least twice as long and the aboveground biomass almost three times longer.

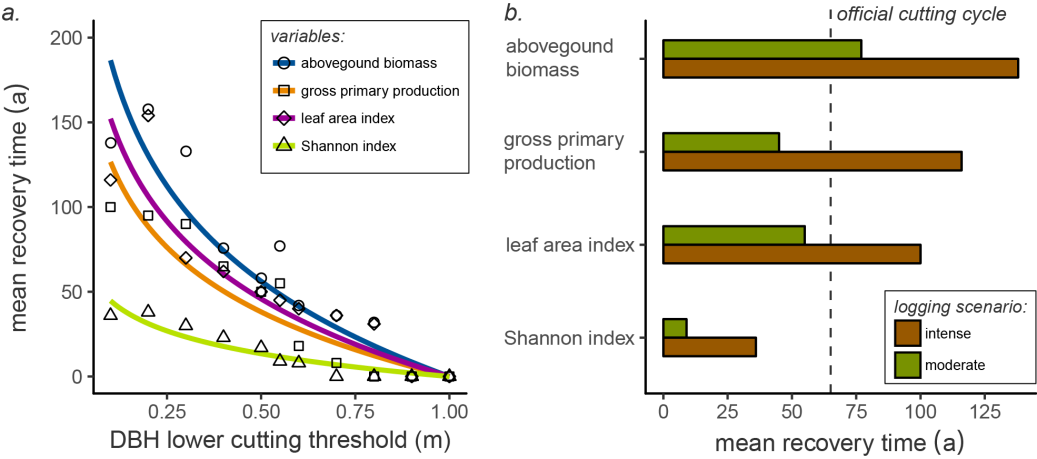


Figure 3: Evaluation of different management strategies in a set of logging scenarios. (a.) Development of the mean recovery time of different forest variables (aboveground biomass, gross primary productivity, leaf area index, and Shannon index) depicted in relation to the logging intensity (DBH of lower cutting threshold). The dots correspond to the recovery time of each variable determined from the simulation scenarios. The trend lines were derived by modeling the nearest least squares of a logarithmic DBH. (b.) Comparison of mean recovery times for the moderate and intense logging scenarios (DBH lower cutting threshold 0.55, 0.1m) regarding these examined variables. The dashed line indicates French Guiana’s official 65-years cutting cycle.

# Discussion

## 4.1 Aspects of the model approach

One of the challenges of this study was to develop a parameterization of the FORMIND forest model for the Paracou test site in French Guiana. For this purpose it was important to simulate the succession of the primary forest as accurately as possible. The accuracy of the forest model was achieved by calibration with the extensive inventory data of the undisturbed control plots (T0) of Paracou. The forest model slightly overestimated the observed mean aboveground biomass (AGBobs 418tODM/ha) by 5% (AGBsim 439tODM/ha). Using allometry for moist tropical forests of Chave et al. (2005), Rutishauser et al. (2010) obtained values between 388tODM/ha and 443tODM/ha for the aboveground biomass of the control plots in 1991 and 2007. This ideally supports the range our findings.

Furthermore, we tested simulation results of one of the selective logging scenarios (*DBH* of lower cutting threshold 0.55m) with an independent set of Paracou’s forest inventory data (T1 plots). Deviations between simulated and observed aboveground biomass values during 30 years after logging were negligible. This means productivity and forest structure of logged forest was well represented by the model simulations. A reason for this qualitatively good model performance was the excellent data basis of Paracou’s forest inventory data. The inventory data set of Paracou in French Guiana is a specialty in the tropics in terms of good data quality and data availability. This and the close cooperation with the National Forest Service *NFS* help to further develop such model studies, from which other tropical regions with limited access to data can also benefit. With the FORMIND forest model inclusive management-module it is now possible to estimate in the long term the development of forest stand variables for both primary and logged forest at Paracou. The model can be easily applied to simulate further forest management strategies by varying model parameters such as the cutting threshold, cutting cycle or number of trees of commercial tree species to be harvested. The methodology can also be modified to obtain new knowledge on the dynamics of forests after logging or to test novel management strategies, such as the impact of modernized techniques to reduce logging damage while maintaining logging intensity (Putz et al., 2008a); given that such modern techniques are currently used in less than 5% of selectively logged forest areas (Putz et al., 2008b). Logging residues can also be used for new purposes, e.g. as energy wood for bioenergy production (Hillring, 2006). Energy wood can further be extracted from forest thinning (Heikkilä et al., 2009). However, there are concerns about environmental and economic challenges in harvesting and processing thinning into bioenergy (Mangoyana, 2011). The forest model can be adapted and parameterized flexibly to take such developments into account.

The approach of this model study was based on the grouping of over 700 observed tree species into eight plant functional types PFT at the Paracou site. This aggregation is suitable for applications with process-based models such as FORMIND, which are based on photosynthesis production as one of the main processes of tree growth (Köhler et al., 2000). This was also valid with increasing model complexity (forest model plus management-module), as required by this study's investigation. The advantages of aggregation are that information from all trees recorded was included in the model parameterization. This had a positive effect on the forest model's accuracy and the robustness of model outcomes. The model's sensitivity to small changes in the parameter values proved stable and the parameterization effort was manageable. However, the representation of temporal changes in tree species diversity is an obstacle to a detailed understanding of ecosystem processes with the concept of PFTs. In contrast, Maréchaux and Chave (2017) developed another process- and individual-based model in which 139 tree species were parameterized for the Paracou site. This high number of represented species in a forest model allows reproducing trait variability between species in more detail compared to the PFT approach. However, a very detailed data basis is essential, as in the case of the Paracou site, and the model parameterization is laborious, especially for rare tree species. The latter could mean that only subsets of data on selected tree species are considered, making it difficult to investigate complex interactive processes on the entire forest stand. In addition, transferring the model concept to other locations is challenging. Nevertheless, such a species-specific model approach could be perspectively used to evaluate the interactions between logging and the species composition determining the forest structure. The approach with the FORMIND forest model does not represent the tree species composition, rather the functional composition, which is important for the evaluation of the effects of logging.

## Long-term effects of logging intensity on forest functions

The recovery times of primary aboveground biomass vary with the intensity of timber harvest, as published in the literature (Huang and Asner, 2010; Rutishauser et al., 2015; Vidal et al., 2016) and examined in this study. This study also supports others who concluded that logging strategies postulating reduced impacts do not necessarily ensure full recovery of forest biomass; at least not within government-specific thresholds of minimum cutting cycles (Huth et al., 2004; Keller et al., 2007; Sist and Ferreira, 2007; Valle et al., 2007; Zarin et al., 2007). This can also be said of the Amazon, whose forest management practices differ between countries. The minimum cutting cycles are fixed between 30-60 years with harvests of 10-30m3/ha, mostly not long enough to restore commercial timber reserves. In particular, in French Guiana, with an official cutting cycle of 65 years and a mean logging intensity of 8-29 m3/ha (averaged over the last 15 years), reduced impact logging-techniques are used to practice (Piponiot et al., 2016). This study’s simulation scenario at moderate logging conditions (*DBH* lower cutting threshold 0.55m) showed that this period took about 10 years longer to restore the aboveground biomass for forest types found at Paracou test site. Literature research has shown that for the Amazon region so far no empirical information on recovery times of primary crown cover density, gross primary production, and the functional diversity of species group abundance is available. Hence, we were able for the first time to demonstrate that the official cutting cycle of 65 years, under assumptions of the moderate logging scenario, may be sufficient for the restoration of the crown cover density, gross primary production, and the functional diversity of species groups at the study site Paracou.

Although forest management strategies are already being improved, often through financial incentives from international forest conservation initiatives (e.g. REDD+, certification: FSC, PEFC), only about 5% of the permanent forest estates of ITTO member states are managed sustainably (Blaser et al., 2011; Mather and Needle, 1998). It is therefore essential for these decision-makers to evaluate recovery times as an indicator of sustainable forest management in the tropics (F. E. Putz et al., 2008). Based on the assumptions of our simulation scenarios, it is recommended not to select site-specific cutting thresholds below 0.5m if the restoration of the forest’s functions is to be less than 65 years. In addition, it became clear that the relationship between aboveground biomass and gross primary production is variable: both change as a function of the logging intensity and the time after logging. In order to be able to make adequate statements, it is crucial to consider the state of succession of a selectively logged forest stand (temporal aspect). Moreover, the intensity of logging must be known, as this determines the forest’s structural composition. Our results are perfectly complemented by Rödig et al., (in press): By increasing the disturbance intensity (anthropogenic and natural), also smaller trees (e.g. in the forest’s understory) are being felled. The remaining aboveground stand biomass is being reduced likewise resulting in a strong shift in the species group composition. This is accompanied by an increasing period of recovery of ecosystem functions. A similar pattern was found in another study evaluating the species richness of different animal species between logged and unlogged tropical forests (Burivalova et al., 2014). They found the variability between taxa was accompanied by lower diversity, mainly explained by the intensity of logging.

Unfortunately, declining recovery rates after disturbance reflect a loss of forest resilience (Poorter et al., 2016). However, a loss of resilience may cause changes in forest conditions with a partial or complete conversion to another ecosystem type than is potentially expected for a site (Thompson, 2011). Hence, a permanent change in species composition can be used as an indicator of less forest resilience. With the help of simulation results of future studies, more detailed statements may be addressed about processes of resilience of the investigated forest in French Guiana. Key priorities include sustainable harvesting practices (in the sense of REDD+ or forest certifiers) to prevent negative impacts on ecosystem functions and services. Climate change should also be taken into account to identify additional impacts on the global carbon balance (IPCC, 2014a). In the future, we intend to develop reduced impact strategies by means of further simulation experiments showing the best possible relationship between maximum yield and minimum impact of logging on forest growth. Furthermore, we intend to evaluate the effects of a wider range of management strategies in the context of climatic changes on long-term forest growth dynamics by implementing an updated version of the management module into the model architecture.

## 4.4 Conclusion

The protection of tropical forests contributes significantly to the conservation of biodiversity, the stabilization of the global climate, and the preservation of an important component in the global carbon cycle (G. Bonan, 2008; G. B. Bonan, 2008; Huntingford et al., 2008; IPCC, 2014b; Malhi and Grace, 2000; Pan et al., 2011; Watson et al., 2018). In addition to other ecosystem services (Assessment Millennium Ecosystem, 2005), the Amazon providesuseful resources such as wood. However, high deforestation rates have long contributed to the degradation of the Amazon forests and are problematic (IPCC, 2014; Global Forest Watch, 2014).A considerable portion of the area is designated as production forest, which is why forest management strategies must be ecologically and economically efficient to conserve resources. According to the concept of planetary boundaries, natural resources are used sustainably if one wants to remain in a safe operating space (Molina, 2009; Reischl, 2012; Steffen et al., 2015). This could prevent over-exploitation of the resources of the Amazon’s production forests with simultaneous forest degradation (Malhi et al., 2008; Nepstad et al., 2008; Nobre et al., 2016).

Against this background, we successfully implement a mechanistic model approach in this study, which can be used to investigate different strategies of selective logging in humid lowland rainforest types similar to the study site’s Paracou in French Guiana. We linked empirical data from the test site and forest modeling. We have succeeded in developing a parameterization for the FORMIND forest model including a management-module, so that it is now possible to conduct simulation experiments estimating the long-term effects of current forestry on future forest growth and structure. In this respect, we took a first step by examining results of simulation scenarios. In addition, the forest model was able to evaluate variables (gross primary production, leaf area index, and Shannon-index) whose empirical measurement on different scales is complex or has not yet been carried out. This methodological approach may allow the development of forest management strategies that are more economic and ecological friendly. Knowledge gained through such simulation experiments can help decision-makers (REDD+ and FSC-labeling).

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