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

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# Highlights

* We analyzed biomass productivity by simulating forest growth.
* And evaluate long-term effects selective logging in various scenarios.
* The short-term output of the dynamic forest gap model is validated first time.
* This approach offers a novel tool for the evaluation of different silviculture strategies.
* A simulation experiment allows initial predictions about the resilience or forest degradation.

# 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 (Malhi and Grace, 2000), as they store about half of the Earth's terrestrial carbon (G. B. Bonan, 2008). However, about half of all humid tropical forests (> 4.0 108 ha) have been declared as production forests (Blaser et al., 2011). Hence, there is a risk that these production forests will lose their function as carbon stores (Putz et al., 2008). Depending on the type of management, it depends very much on the present strategy (e. g. logging intensity), whether they represent 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 current issues are: (*i.*) An incomplete understanding of the long-term effects of present forest management strategies on the growth of tropical forests (Werger et al., 2011); (*ii.*) a non-compliant use of the resource wood by different stakeholders (Huth et al., 2004; Molina, 2009; Reischl, 2012; Steffen et al., 2015).

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; World Bank, 2011) or certification systems for sustainable silviculture, such as FSC or PEFC (Clark and Kozar, 2011; Durst et al., 2006; Rotherham, 2011). All create incentives through performance-based compensation or certification of sustainably produced forest products 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). 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 (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, which was developed especially for tropical forests (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 for environmentally friendly land use 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. A good example of this is the fact that forest models can assess the long-term effects of current management actions and thus contribute to the decision-making process. 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 develop a consistent parameterization for Paracou so that biomass dynamics can be reproduced by the model for both primary forest and selectively logged forest?
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 does the relationship between the forest’s productivity and biomass balance change after selective logging?
4. How long does the recovery of the forest’s ecosystem functions take regarding different management intensities in the case of 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 for a simulation experiment that allowed us to compare the influence of disturbance of different intensities caused by selective logging. Both the forest stand structure and growth dynamics for the location were taken into account in the model parameterization. Subsequently, the simulation results of one of those logging scenarios were compared with another set of field measurements of Paracou (records over 32a on 18.75ha). Finally, different forest attributes were iteratively computed for each logging scenario by the forest model for a longer period of time, which were not yet available as field measurement data at different scales (gross primary production, aboveground biomass, leaf area index, Shannon diversity index).

# Methods

## 2.1 Description of the FORMIND forest model

On the basis of field observation data from forest inventories of the test site at Paracou in French Guiana (chap. 2.2), we adjusted the individual-based forest gap model FORMIND plus management module (Fischer et al., 2016; Huth et al., 2005, 2004). FORMIND is designed to analyze different variables related to the forest stand 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. Different logging strategies can be investigated: (*i.*) reduced impact logging, in which the damage is reduced by directing the logged trees' direction of fall to the closest gap and thus lower damage to the remaining forest stock. Furthermore, damages of future harvest able trees are excluded; and (*ii.*) conventional logging, in which a logged tree's direction of fall is arbitrarily chosen and damage to the remaining forest stock is uncontrollable.

The fundamental concept of forest gap models is the description of the succession in small-scale forest patches (gap: 20m x 20m) caused by falling large trees. The model landscape is defined as squared area from 1ha up to several km2 (in this study 16ha) being composed of such squared patches. The patches obtain an explicit spatial position, while 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 structure, the tree species composition and tree size distribution are calculated. The tree shape is simplified and described by cylindrical stems and crowns. The most important processes considered are tree growth, mortality and recruitment; Furthermore, the trees within a forest patch compete for space and light. Individual tree growth is based 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. Please, find a detailed model description in Fischer et al. (2016) or on the [homepage www.FORMIND.org](file:///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. Alpha diversity is slightly lower than in the forests of the western Amazon, but reaches the highest levels in French Guiana's regions. 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 on an area of (CIRAD, 2016; Dourdain and Hérault, 2015; Gourlet-Fleury et al., 2004).

Paracou's forest is part of the *Caesalpiniaceae* and is surrounded by permanent production forest. The test site is managed by the Centre International de Recherche en Agronomie pour le Développement *CIRAD* (CIRAD, 2106). The FORMIND model adjustment was based on extensive, long-term data records from the Paracou test site. However, the forest inventory data set was divided according to the work steps of the model's parameterization, calibration, and validation. 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 (without buffer zone). 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, while in all other inventory years, the succession was recorded. The effects of logging were measured by aboveground biomass loss (-33tODM/ha) and stem number reduction of ca. 10ha-1, with a minimum diameter at breast height *dbh* between 0.5m-0.6m, belonging to 58 commercial tree species. Since gaps, skid trails and logging roads were mapped during the logging operation the confidence level of the data is high (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 normally measured at a breast height of 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 T0-control plots were used (*i.*) to parameterize the geometric tree relations (e. g. maximum stem diameter increment, maximum tree height), (*ii.*) to classify all existing 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 breaks down the functional traits, such as successional stage, stem diameter increment rates, and stratification, assigned by the species grouping for each of the eight *PFT*s. In the model, for example, slow-growing trees have lower stem diameter growth rates than fast-growing trees. Table 1 also lists the attribute values of mean aboveground biomasses and of mean tree numbers calculated from the forest inventory data used to calibrate the forest model. The FORMIND parameters describing the maximum photosynthesis (*pmax*), maximum growth rates of the diameter (*gmax, gdbhmax*) and the number of seeds (*Nseed*) are important for the succession of forest stands and the composition of tree species. Their parameter values could neither be derived from the data of the forest inventories nor quoted from the literature. Therefore, they were numerically calibrated and then fine-tuned using the dynamically dimensioned search *DDS* (Lehmann and Huth, 2015). During the model calibration and fine-tuning, we concentrated on the tree number-tree size distribution of each *PFT* in order to simulate the forest stand structure as realistically as possible over time [(figure A1.x)](#headerA1.1). The aim was to be able to make a quantitative statement about the quality of the simulation results. The modeled forest structure (e. g. species group composition) and growth dynamics (biomass productivity) should be as similar as possible to those observed. We maximized therefore the coefficient of determination of a linear regression model *R2*, which is the quotient of the variances of the simulated and observed values (Leyer and Wesche, 2007).

Furthermore, the management module was added to the calibrated forest model 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 proportion of commercially usable tree species of the 8 PFTs was calculated and the minimum *dbh* of the harvestable commercial trees with an average of 0.55m was also calculated. The parameter *dam1* describing the proportion of damaged trees in the residual forest stand per stem diameter class *damdia* is important to simulate the intensity of the disturbance during a selective logging event. We have determined this proportion of damage caused by man and machine out of the inventory data. Finally, for the parameterization of the T1-*RIL* the logged trees' direction of fall to the closest gap was controlled and damage to future harvestable trees was excluded. The simulation results of the aboveground biomass of this scenario were compared with forest inventory data from the T1-*RIL* 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 detailed information about the whole parameterization process, 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 The simulation experiment on selective logging

In total, we simulated 10 logging scenarios with a varying minimum *dbh* of harvestable commercial trees (*dbh* of lower cutting threshold) and two types of reference scenarios to indicate a consistent model parameterization. The first type of 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 T0-control plots (see chap. 2.2). As a second reference, we used parameter settings of the reduced impact logging scenario *RIL* according to Paracou’s T1 plots (see chap. 2.2) and compared simulation results during the post-logging phase of secondary forest succession. For the logging simulation we switched on the management module on top of the FORMIND forest model and simulated one logging event. The *dbh* of lower cutting threshold was varied in the interval 0.1m-1.0m in 0.1m-steps. The scenario with the *dbh* of lower cutting threshold of 0.55m was developed against the background of the experimental treatment method on the T1-*RIL* plots of the Paracou test site. The other 10 scenarios were fictitious and the model parameters for both the logged trees’ direction of fall to the closest gap were uncontrolled and damage to future harvestable trees was included into the simulation settings.

The simulation of forest succession for all scenarios began on a treeless (empty) area totaling 16 hectares. All simulation results were averaged over 1ha area. 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, but it was set to the time equaled zero. By doing so, we could count years after selective logging. 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 based on the assumption that forest succession (starting from a treeless area) must be balanced after this time in a mature state (see Appendix A1).

Based on the results of the simulation experiment, it was possible to estimate the long-term effects of different selective logging intensities on forest growth. Variation in logging intensity was expressed by varying the model parameter of *dbh* of lower cutting threshold. 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’*. Assessments on the long-term development of these variables at stand level have not been possible so far, as there have not yet been sufficient field measurements. For these variables, we also analyzed the mean recovery time after the simulated selective logging event. Therefore we used nearest least squares models to infer recovery time over dbh of lower cutting threshold (see A1). We finally modeled trends of gross primary production depending on the aboveground biomass changing during 30 years after the logging event using linear regression models (see A1). Standard deviations for the total forest stand’s A 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

The diagrams in Figure 1 represent selected simulation results of a moderate and an intensive logging scenario for the development of aboveground biomass (Figure 1.a, b) and gross primary production (Figure 1.c). It can clearly be seen that the selective 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 and an overall aboveground biomass that decreased by 109tODM /ha a year after logging. Compared to this, the impact of selective logging in the intensive 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.

We will now have a look on the structural development of the forest stand by comparing the species group compositions of the selected simulation scenarios. In the moderate scenario (Figure 1.a) the tree species’ group composition of the secondary succession shifted slightly in about seven decades 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 steadily and slowly to the reference values of primary forest growth (time < 0a). In addition, Figure 1.a shows the temporal development of the observed aboveground biomass values as secondary succession of the forest between 1986 and 2016. The simulated logging event was assigned to the year of the observed one in 1986 on the T1-*RIL* plots of Paracou test site. In the period under consideration (1987-2016), the simulated aboveground biomass values matches the observed values well (R2 0.991, rmse 4.631tODM/ha). However, the forest model slightly underestimated the observed aboveground biomass of climax species during three decades after selective logging. Please find further information on the results of the model calibration in Appendix A1.

On the other hand, the intensive scenario (Figure 1.b) was characterized by a stronger shift in the species group composition during the secondary succession of the forest 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 productivity was followed by a phase, which was characterized by lower productivity rates.

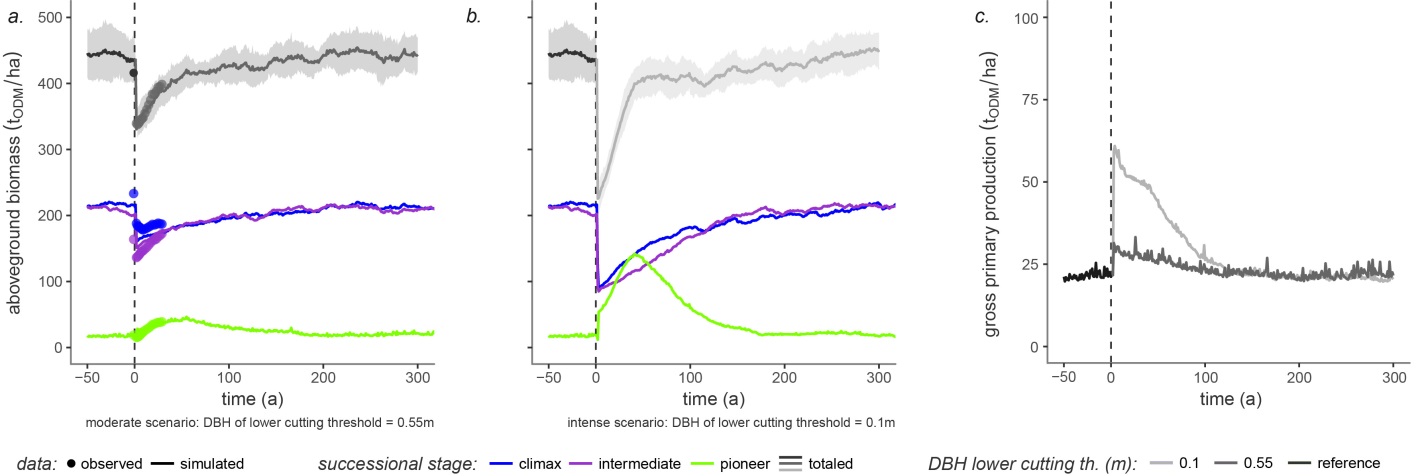


Figure 1: Development of the mean aboveground biomass plus standard deviation (a., b.) and the mean gross primary production (c.) of both the entire forest stand (grayish lines) and the tree species grouped according to functional traits of successional stage (colored lines; Averages of 16ha-simulations). 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-RIL plots. The year of logging (1986) was assigned to simulated time equaled 0.

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

Using the simulation results of every logging scenario, it was possible to investigate the effects of different thresholds regarding the lower cutting threshold of harvestable commercial trees on the productivity of the remnant forest stand’s aboveground biomass. Therefore, we experimentally varied this model parameter stepwise in between 0.1m-1.0m. The diagrams in Figure 2.a and 2.b show the correlations between the change in the lower cutting threshold values of the *dbh* 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 every year during the first three decades after logging. In general the following applied: The higher the lower cutting threshold value of the *dbh* of harvestable commercial trees was assumed, the smaller the number of trees harvested and the higher the remaining forest stand biomass. In the case of gross primary production, higher logging intensity resulted in a higher degree of regeneration. The stronger the rejuvenation of the remnant forest was and the higher was the productivity that was dominated by fast-growing pioneer species. 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.

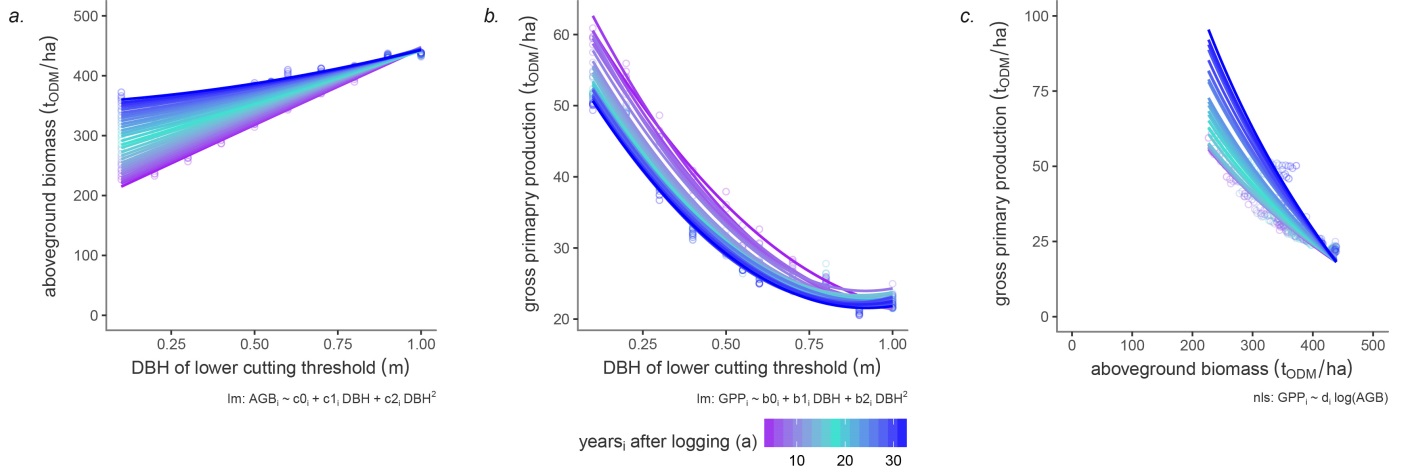


Figure 2: Interrelationships between aboveground biomass (a.) or gross primary production (b.) and minimum *dbh* of harvestable commercial trees during three decades after the selective logging event (0a < time ≤ 30a; see Figure 1). The trend lines were determined using the linear regression of a second-degree polynomial. Relationships of gross primary productivity to the aboveground biomass (c.) during three decades after the selective logging event (0a < time ≤ 30a; see Figure 1). The trend lines were determined using a least square regression of a logarithmic AGB.

In a further analysis of the experimental simulation results on different intensities of selective logging, we evaluated the mean recovery time of the remaining forest stand regarding different variables, such as aboveground biomass, gross primary production, leaf area index, and Shannon-index (Figure 3). In this study, it was possible for the first time to establish the correlations between logging intensity and the recovery time of the *dbh* of lower cutting threshold of harvestable commercial trees of these variables. The trend lines were modeled as nearest least squares of a logarithmic *dbh*. Interestingly, the mean recovery time of each variable and each management strategy is different. For instance, the aboveground biomass’ recovery phase of the intense scenario took about three times longer (138a) than that of the Shannon-index (38a). The Shannon-index gave the equal distribution of the eight tree species groups *PFT* in the simulations. This means, the more equally distributed the tree species groups were, the lower the index value was.

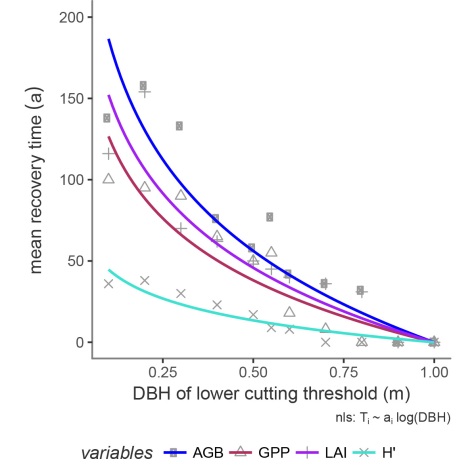


Figure 3: Evaluation of the simulation scenarios. Development of the mean recovery time of different forest attributes (aboveground biomass AGB, gross primary productivity GPP, leaf area index LAI, and Shannon index H') depicted in relation to the minimum dbh of harvestable commercial tree species. The dots correspond to the regeneration time of each variable determined from the simulation scenarios. The trend lines were derived by modeling the nearest least squares of a logarithmic dbh.

# Discussion

## 4.1 Consistent model parameterization of both primary and selectively logged forests

One of the challenges of this study was to develop a consistent 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 (e. g. productivity of aboveground biomass) and the forest structure (e. g. distribution of the tree size among the number of trees) as accurately as possible, despite aggregation of field observation data. The accuracy of the forest model was achieved by calibration with the inventory data of the T0-control plots of Paracou. We compared observed and simulated variables (tree size-tree number distributions, aboveground biomass values). The forest model slightly overestimated the observed mean aboveground biomass (AGBobs 418tODM/ha) by 5%. Rutishauser et al. (2010) provided an additional indication that the forest model well reflects the observed forest dynamics and structure. They assume that the aboveground biomass of the T0-control plots in the years 1991 and 2007 averaged between 388tODM/ha and 443tODM/ha. This ideally supports our findings. Additionally, group-specific differences in variance between simulated and observed biomass values were small (R2 0.994, rmse 4.659tODM/ha).

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-*RIL* plots). Deviations between simulated and observed aboveground biomass values during 30 years after logging differed only little (R2 0.991, rmse 4.631tODM/ha). This means group-specific biomass productivity and structure of selectively logged forest was well represented by the simulations (Figure 1.a; figure A1.x). A reason for this qualitatively good model performance was the excellent data basis of Paracou’s forest inventory data. Another reason were methods used for calibration and fine-tuning, which took simulated and observed numbers of trees per size class (tree size-tree number-distribution) into account explicitly reflecting the structure of a forest stand (Huth and Ditzer, 2000; Köhler et al., 2001). During the fine-tuning it was also essential to select a corresponding target function for the *DDS* procedure (see A1.x; Lehmann and Huth, 2015). With the FORMIND forest model inclusive management-module it is now possible to estimate, quantitatively and in the long term, forest stand variables depending on aboveground biomass productivity and tree size-tree number distribution for both primary and selectively logged forest types, such as those found at Paracou.

## 4.2 Effects of different selective logging intensities on ecosystem functions

A further objective of this study was the estimation of forest stand characteristics, such as *LAI*, Shannon index *H'*, and gross primary production *GPP*, all of which have not yet been measured on different scales of the stand. We simulated secondary succession after selective logging in a series of scenarios in which different intensities of the minimum *dbh* of harvestable commercial trees were assumed. A specific logging scenario (minimum *dbh* of the harvestable trees 0.55m) was compared with the field observation data of the Paracou T1-*RIL* plots over about 30 years (1987-2016; see Figure 1.a). For each year considered after logging, aboveground biomass and gross primary production were derived for all parameter variations (linear regression models; see Figure 2.a, b). Similarly, gross primary production was related to aboveground biomass (model of the smallest squares; see Figure 2.c). An innovative part of this study is that these diagrams allow different forest management strategies to be evaluated. This is particularly valuable in the case of *GPP*, as there have not yet been any measurements on different scales of forest stand. However, in the diagrams in Figure 2 we looked at 30 years after logging. At the end of this period, the simulated forest stand did not recover completely. If the effects of forest management strategies are to be assessed in the longer term, the time period would have to be extrapolated. The question was how long the forest would take to recover.

## 4.3 Recovery time of ecosystem functions after selective logging

Recovery time is directly linked to the policy of management techniques (i. e. permissible harvest volumes and cutting cycle lengths) and indirectly to forest based climate protection policies. In the two considered logging scenarios (moderate vs. intensive; see Figure 1) it was already clear that the forest structure (species group composition) changed after logging: the stronger and longer, the more intensive the management strategy. Similarly to the results of Figure 2, we modeled the relationship between the dbh of the lower cut threshold and the recovery time of four forest variables (Shannon index *H'*, leaf area index *LAI*, gross primary production *GPP*, aboveground biomass *AGB*). Firstly, the Shannon index is one of the most widely used biodiversity indicators (Spellerberg and Fedor, 2003). In this way, the ratio of the number of individuals of a species group *PFT* to the sum of all trees in the forest was determined and thus a comparative measure for the indication of diversity. Combining this fact with the findings on the entire logging scenario set and the curve form of the Shannon index (see figure 3), it became clear that the *PFTs* had recovered at the latest after about 50 years of simulation with regard to the succession phase of the forest. In principle, other forest attributes (e. g. biomass) can be used instead of the number of trees to calculate *H'*. At this point, however, the calculation based on the number of individuals provided important information on the duration of forest structure recovery. Secondly, this relatively short mean recovery time as for *H’* did not apply to aboveground biomass, gross primary production, and crown density (*LAI*). Their curves (nearest least squares models) in Figure 3 show that the recovery period lasted at least twice as long until the state of a primary forest was balanced. Their recovery time increased almost exponentially as the selective logging strategy intensified. Exemplarily for the intense scenario (see Figure 3 and Figure 1.b), it can be interpreted that the total number of individuals already equaled that of the pre-logging phase after ca. 50 years, and not only pioneers were present, but the structure of a mature forest has recovered after more than a century. We conclude that moderate logging strategies are advantageous for the resilience of the forest stand. A similar species composition as well as biomass balance could already be achieved 77 years after logging, as in the reference (pre-logging). This is important against the background of carbon fixation and biodiversity debates. E.g. the yield of the intense scenario was 10 times higher as that of the moderate scenario, but the recovery of biomass, a dense crown cover and species diversity of the remaining forest stand took up to 138 years. The simulation experiment also showed that the structure of the forest stand was changed so much after the intervention of intense scenario that a different type of forest would result.

Based on the extrapolation of the biomass productivity of forest stands beyond the period of Paracou's forest inventory data, we were able to estimate the forest structure and succession. The recovery period of biomass production could be used as an indicator for the identification of ecologically and economically efficient forest management strategies. In the context of resilience theory, the species group composition of forest ecosystems varies over time, often depending on natural disturbances and climate fluctuations (Thompson, 2011). Such fluctuations, however, remain more or less constant within the framework of the natural fluctuations related to a state of equilibrium (Sakschewski et al., 2016). In a mature state, forests can produce a variety of products and services that can be useful to mankind (Simula, 2009). However, changes in forest conditions may result from a loss of resilience, with partial or complete conversion to a different ecosystem type than potentially expected for the site. Such changes in status lead to a reduction in the production of goods and ecosystem services (Assessment Millennium Ecosystem, 2005; Brockerhoff et al., 2017; Ferraz et al., 2014; Patterson and Coelho, 2009). Therefore, a change in species composition can be used as an indicator of degradation (Thompson, 2011). Our results of the simulation experiment on disturbing the growth dynamics and structure of the forest in Paracou have shown that the conservation of species composition is crucial in the choice of management strategy and can be a key factor for the long-term conservation of the forest ecosystem. The FORMIND forest model plus management module can be used to estimate the harvest yield of a logging event. This is possible because the forest model calculates on the basis of individual trees.

## 4.4 Conclusion and perspectives

The protection of the Amazon rainforests 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, 2014; Malhi and Grace, 2000; Pan et al., 2011; Watson et al., 2018). In addition to other ecosystem services (Assessment Millennium Ecosystem, 2005), the Amazon provide**s** useful resources such as wood.High deforestation rates, which have long contributed to the degradation of the Amazon forests 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, such as those found in French Guiana's production forests similar to Paracou. We linked empirical data from the Paracou test site and forest modeling. We have succeeded in developing a consistent 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 the model results of a simulation experiment. By comparing these with field data (Paracou’s forest inventories), quantitative statements on the variability of the selective logging intensity of commercial tree species were made possible in exemplary 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.

With regard to our methodological and scientific findings, the following questions still need to be answered: How do repeated logging events affect forest succession, resilience, and structure? What role does the specification of minimum stem diameters of harvestable commercial trees play in this context? Furthermore, there are different types of disturbance to forest stands caused by logging events leading to damages, such as tree felling for skid trails, thinning, and firewood exploitation. Hence, what may the long-term influences be on forest growth regarding these management strategies? Moreover, taking environmental factors, such as climate change, into account: what influence may this have on future forest growth and structure? Can such studies being conducted for the Paracou site be extended to the entire Amazon region? 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. This methodological approach will 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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# References

Assessment Millennium Ecosystem, 2005. Ecosystems And Human Well-Being: Synthesis. Washington, DC.

Blaser, J., Sarre, A., Poore, D., Johnson, S., 2011. Status of Tropical Forest Management 2011, ITTO Technical Series. https://doi.org/10.1017/S0032247400051135

Bonan, G., 2008. Carbon cycle: Fertilizing change. Nat. Geosci. 1, 645–646. https://doi.org/10.1038/ngeo328

Bonan, G.B., 2008. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. Science (80-. ). 320, 1444–1449. https://doi.org/10.1126/science.1155121

Brockerhoff, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O.B., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I.D., van der Plas, F., Jactel, H., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. 26, 3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Clark, M.R., Kozar, J.S., 2011. Comparing sustainable Forest Management certifications standards: A Meta-Analysis. Ecol. Soc. https://doi.org/10.5751/ES-03736-160103

D’Amato, A.W., Bradford, J.B., Fraver, S., Palik, B.J., 2011. Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. For. Ecol. Manage. 262, 803–816. https://doi.org/10.1016/j.foreco.2011.05.014

Danielsen, F., Skutsch, M., Burgess, N.D., Jensen, P.M., Andrianandrasana, H., Karky, B., Lewis, R., Lovett, J.C., Massao, J., Ngaga, Y., Phartiyal, P., Poulsen, M.K., Singh, S.P., Solis, S., Sørensen, M., Tewari, A., Young, R., Zahabu, E., 2011. At the heart of REDD+: A role for local people in monitoring forests? Conserv. Lett. 4, 158–167. https://doi.org/10.1111/j.1755-263X.2010.00159.x

Dourdain, A., Hérault, B., 2015. Allometric equations in the Guiana Shield: REDD+ for the Guiana Shield. Paracou.

Durst, P.., McKenzie, P.., Brown, C.., Appanah, S., 2006. Challenges facing certification and eco-labelling of forest products in developing countries. Int. For. Rev. 8, 193–200. https://doi.org/10.1505/ifor.8.2.193

Ferraz, S.F.B., Ferraz, K.M.P.M.B., Cassiano, C.C., Brancalion, P.H.S., da Luz, D.T.A., Azevedo, T.N., Tambosi, L.R., Metzger, J.P., 2014. How good are tropical forest patches for ecosystem services provisioning? Landsc. Ecol. 29, 187–200. https://doi.org/10.1007/s10980-014-9988-z

Fischer, R., Bohn, F., Dantas de Paula, M., Dislich, C., Groeneveld, J., Gutiérrez, A.G., Kazmierczak, M., Knapp, N., Lehmann, S., Paulick, S., Pütz, S., Rödig, E., Taubert, F., Köhler, P., Huth, A., 2016. Lessons learned from applying a forest gap model to understand ecosystem and carbon dynamics of complex tropical forests. Ecol. Modell. 326, 124–133. https://doi.org/10.1016/j.ecolmodel.2015.11.018

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ. Res. Lett. 2, 45023. https://doi.org/10.1088/1748-9326/2/4/045023

Gourlet-Fleury, S., Ferry, B., Molino, J.-F., Petronelli, P., Schmitt, L., 2004. Paracou expérimental plots: key features, in: Ecology and Management of a Neotropical Rainforest : Lessons Drawn from Paracou, a Long-Term Experimental Research Site in French Guiana. pp. 3–60.

Huntingford, C., Fisher, R.A., Mercado, L., Booth, B.B.., Sitch, S., Harris, P.P., Cox, P.M., Jones, C.D., Betts, R.A., Malhi, Y., Harris, G.R., Collins, M., Moorcroft, P., 2008. Towards quantifying uncertainty in predictions of Amazon “dieback.” Philos. Trans. R. Soc. B Biol. Sci. 363, 1857–1864. https://doi.org/10.1098/rstb.2007.0028

Huth, A., Ditzer, T., 2000. Simulation of the growth of a lowland Dipterocarp rain forest with FORMIX3. Ecol. Modell. 134, 1–25. https://doi.org/10.1016/S0304-3800(00)00328-8

Huth, A., Drechsler, M., Köhler, P., 2005. Using multicriteria decision analysis and a forest growth model to assess impacts of tree harvesting in Dipterocarp lowland rain forests. For. Ecol. Manage. 207, 215–232. https://doi.org/10.1016/j.foreco.2004.10.028

Huth, A., Drechsler, M., Köhler, P., 2004. Multicriteria evaluation of simulated logging scenarios in a tropical rain forest. J. Environ. Manage. 71, 321–333. https://doi.org/10.1016/j.jenvman.2004.03.008

Intergovernmental Panel on Climate Change., 2014. Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the IPCC Fifth Assessment Report 2014.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on. Cambridge Univ. Press. … 1132 pp.

Kammesheidt, L., Köhler, P., Huth, A., 2002. Simulating logging scenarios in secondary forest embedded in a fragmented neotropical landscape. For. Ecol. Manage. 170, 89–105. https://doi.org/10.1016/S0378-1127(01)00783-6

Köhler, P., Ditzer, T., Ong, R.C., Huth, A., 2001. Comparison of measured and modelled growth on permanent plots in Sabahs rain forests. For. Ecol. Manage. 144, 101–111. https://doi.org/10.1016/S0378-1127(00)00364-9

Kurier, H., 2000. Query whether the comparison between the PEFC and FSC is reliable with respect to competition in certification. Holz - Kurier 55, 14.

Lehmann, S., Huth, A., 2015. Fast calibration of a dynamic vegetation model with minimum observation data. Ecol. Modell. 301, 98–105. https://doi.org/10.1016/j.ecolmodel.2015.01.013

Leyer, I., Wesche, K., 2007. Multivariate Statistik in der Ökologie. Eine Einführung., Springer-Lehrbuch. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-37706-1

Long, A., 2013. REDD + , Adaptation , and sustainable forest management : toward effective polycentric global forest governance. Trop. Conserv. Sci. 6, 384–408.

Malhi, Y., Grace, J., 2000. Tropical forests and atmospheric carbon dioxide. Trends Ecol. Evol. 15, 332–337. https://doi.org/10.1016/S0169-5347(00)01906-6

Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W., Nobre, C.A., 2008. Climate change, deforestation, and the fate of the Amazon. Science (80-. ). https://doi.org/10.1126/science.1146961

Molina, M.J., 2009. Planetary boundaries: Identifying abrupt change. Nat. Reports Clim. Chang. 115–116. https://doi.org/10.1038/climate.2009.96

Mollicone, D., Freibauer, A., Schulze, E.D., Braatz, S., Grassi, G., Federici, S., 2007. Elements for the expected mechanisms on “reduced emissions from deforestation and degradation, REDD” under UNFCCC. Environ. Res. Lett. 2, 45024. https://doi.org/10.1088/1748-9326/2/4/045024

Nepstad, D.C., Stickler, C.M., Filho, B.S., Merry, F., 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. Philos. Trans. R. Soc. B Biol. Sci. 363, 1737–1746. https://doi.org/10.1098/rstb.2007.0036

Nobre, C.A., Sampaio, G., Borma, L.S., Castilla-Rubio, J.C., Silva, J.S., Cardoso, M., 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proc. Natl. Acad. Sci. 113, 10759–10768. https://doi.org/10.1073/pnas.1605516113

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World’s Forests. Science (80-. ). 333, 988–993. https://doi.org/10.1126/science.1201609

Pan, Y., Birdsey, R.A., Phillips, O.L., Jackson, R.B., 2013. The Structure, Distribution, and Biomass of the World’s Forests. Annu. Rev. Ecol. Evol. Syst. 44, 593–622. https://doi.org/10.1146/annurev-ecolsys-110512-135914

Patterson, T.M., Coelho, D.L., 2009. Ecosystem services: Foundations, opportunities, and challenges for the forest products sector. For. Ecol. Manage. 257, 1637–1646. https://doi.org/10.1016/j.foreco.2008.11.010

Putz, F.E., Zuidema, P.A., Pinard, M.A., Boot, R.G.A., Sayer, J.A., Sheil, D., Sist, P., Elias, Vanclay, J.K., 2008. Improved tropical forest management for carbon retention. PLoS Biol. 6, 1368–1369. https://doi.org/10.1371/journal.pbio.0060166

Reischl, G., 2012. Designing institutions for governing planetary boundaries - Lessons from global forest governance. Ecol. Econ. 81, 33–40. https://doi.org/10.1016/j.ecolecon.2012.03.001

Rotherham, T., 2011. Forest management certification around the world - Progress and problems. For. Chron. 87, 603–611. https://doi.org/10.5558/tfc2011-067

Rutishauser, E., Wagner, F., Herault, B., Nicolini, E.A., Blanc, L., 2010. Contrasting above-ground biomass balance in a Neotropical rain forest. J. Veg. Sci. 21, 672–682. https://doi.org/10.1111/j.1654-1103.2010.01175.x

Sakschewski, B., von Bloh, W., Boit, A., Poorter, L., Peña-Claros, M., Heinke, J., Joshi, J., Thonicke, K., 2016. Resilience of Amazon forests emerges from plant trait diversity. Nat. Clim. Chang. 1. https://doi.org/10.1038/nclimate3109

Simula, M., 2009. TOWARDS DEFINING FOREST DEGRADATION: COMPARATIVE ANALYSIS OF EXISTING DEFINITIONS. Rome.

Spellerberg, I.F., Fedor, P.J., 2003. A tribute to Claude Shannon (1916-2001) and a plea for more rigorous use of species richness, species diversity and the “Shannon-Wiener” Index. Glob. Ecol. Biogeogr. 12, 177–179. https://doi.org/10.1046/j.1466-822X.2003.00015.x

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science (80-. ). 347, 1259855–1259855. https://doi.org/10.1126/science.1259855

Thompson, I., 2011. Biodiversity, ecosystem thresholds, resilience and forest degradation. Unasylva 62, 25–30.

Van Breugel, M., Ransijn, J., Craven, D., Bongers, F., Hall, J.S., 2011. Estimating carbon stock in secondary forests: Decisions and uncertainties associated with allometric biomass models. For. Ecol. Manage. 262, 1648–1657. https://doi.org/10.1016/j.foreco.2011.07.018

Watson, J.E.M., Evans, T., Venter, O., Williams, B., Tulloch, A., Stewart, C., Thompson, I., Ray, J.C., Murray, K., Salazar, Alvaro, McAlpine, C., Potapov, P., Walston, J., Robinson, J., Painter, M., Wilkie, D., Filardi, C., Laurance, W.F., Houghton, R.A., Maxwell, S., Grantham, H., Samper, C., Wang, S., Laestadius, L., Runting, R.K., Silva-Chávez, G.A., Lindenmayer, D.B., 2018. The exceptional value of intact forest ecosystems. Nat. Ecol. Evol. in press. https://doi.org/10.1038/s41559-018-0490-x

Werger, M.J.A., Poels, R., Ketner, P., Jonkers, W., 2011. Sustainable Management of Tropical Rainforests: the CELOS Management System., Tropenbos Series 25.

World Bank, 2011. Estimating the Opportunity Costs of REDD. Finance 262. https://doi.org/10.1016/j.jenvman.2003.12.013

Global Forest Watch, 2014. World Resources Institute. Accessed online (2017-08-20): www.globalforestwatch.org.

CIRAD, 2016. Paracou Research Station, a large scale forest disturbance experiment in Amazonia. Experimental Design. Accessed online (2017-10-22): <https://paracou.cirad.fr/experimental-design>.

PEFC International, 2017. PEFC - Caring for our forests globally. The French Guianese forest-based sector strengthens its commitment to PEFC certification. Accessed online (2017-10-23): <https://pefc.org/news-a-media/general-sfm-news/1200-the-french-guianese-forest-based-sector-strengthens-its-commitment-to-pefc-certification>.