# Mémoire de stage

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Sujet :

# Modeling the impacts of selective logging on tropical forests: First attempt with TROLL in French Guiana

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L'arbre est un organisme tellement généreux quil offre son ombre à ceux qui viennent labattre.

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*Francis Hallé*

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# Résumé

# INTRODUCTION

Tropical forests shelter over half the terrestrial species present on Earth, and provide numerous goods and services, of which many have important economic or societal value [Foley et al., 2007, Myers [1997]]. They represent a major carbon reservoir, holding up to half the estimated 558 Pg stored in vegetation worldwide [Houghton, 2005]. Tropical forests are currently facing multiple perils, including deforestation for pasture or food crops, and forest degradation, for example selective logging or fires [**?**]. Recently, Pearson et al. [2017] estimated a yearly total of 8.29 $Pg$ carbon loss from deforestation and forest degradation worldwide. Allthought deforestation is easy to evaluate with satellite images, and have raised much concern over past decades, estimating and regulating the extent and emissions from forest degradation is critical, yet challenging[**?**]. Selective logging is the principal anthropogenic forest disturbance [I cant find clear ref to say that]. It affected or will affect the majority of tropical forest outside protected areas [**?**]. In 2011, 403.000.000 hectares were officially designated for timber extraction in tropical rainforests [Blaser et al., 2011]. Two years earlier, Asner et al. [2009] reported that the annual rates (in terms of area) at which these forests are selectively logged approaches 20 times those of deforestation. It is espacially the case in the Amazon Basin, that encompasses half of all remaining tropical moist forest [**?**], and is an important carbon reservoir estimated to hold *ca.*90 PG of above-ground carbon [FAO, 2010, Saatchi et al. [2007],Malhi et al. [2006]]. Amazonia has been severly deforested since the early 1970s, and although overall rates substantially reduced [INPE, 2015, *in* Rappaport et al. [2018]], a recent rise of small-scale deforestation, close to forest degradation, was recently noticed [**?**]. Carbon emissions caused by forest degradation sums to those caused by deforestation, and represent up to 25% the carbon losses caused by the latter alone [Asner et al 2005]. In the Brazilian Amazon, selective logging impacted *ca. 2 Mha.y*[1] between 1999 and 2002 [Asner et al., 2005], raising its extent to equivalent to annual deforestation across this period and resulting in emissions of about 90 $TgC.y$[1] [Huang and Asner, 2010].

Selective logging have long rimed with irresponsible cutting [**?**], and non- or poorly regulated harvesting. Governmental and global policies, more than two decades ago, engaged a common endeavor to limit this trend with the introduction of Sustainable Forest Management [SFM; **?**]. Later on, the incentives such as REDD+ [Reducing Emissions from Deforestation and forest Degradation, UNFCCC, 2008] linked SFM and climate change to pursue one common cause, using financial incentives. To mitigate the adverse effects of conventional selective logging, a set of techniques and planning guidelines were introduced [FIRST REF RIL], under the name "Reduced impact logging" (RIL). RIL is increasingly implemented and promoted as a cornerstone to achieve both ecologically and economically viable forest management. It is somehow seen as a reasonable compromise between clearcutting and outright protection [**?**]. Some authors argue in favor of RIL's potential to sustain principal ecosystemic goods and services, such as the ecosystem's conservation value[^4], above-ground biomass, and timber yields [**?**]. Conversely, Others insist on the apparent non-sustainability of current practices, that they presnt as only leading to depletion of timber volumes, carbon stocks,

and biological diversity, due mismatches between minimum economical viability, and subtle ecosystem functioning on time scales far beyond ours [see **?**, and **?** for baffling yet excellent reviews].

There is no reported available dataset for more than two cutting cycles. We have insights, pieces of evidence that merchantable species stocks are depleted over two cutting cycles, or that ressource use-up is ensured at the third [**?**]. **?** however presented more optimistic results regarding timber volumes, but mostly because he accounted for the shift in logged species, that are probably of secondary interest, possibly harvested because of a lack of first grade timbers, in which case these results would not contradict those of **?**, althought these authors had quite a debate on this theme. Data on forest biomass recovery has also intensively been studied, yielding contrasted conclusions worldwide. Likely, carbon stocks is the first global ecosystemic variable to be recovered after a disturbance [Sist et al, 2015], but the nature of the stands is very different. A majority of commercial timber species are long-lived, shade-tolerant species, relying on complex pollination and dispersal strategies to maintain viable population sizes with such a low concentration of individuals per spatial unit. They are, in many cases, outcompeted by pionneer, light-responsive species, that contribute carbon stocks transiently and may slow others regeneration. Conversely, the inverse phenomenon have been described [XXX refing ref in **?**], where in some Centrafrican timber species, timber stocks are low and must be managed carefully, but high disturbance is needed to trigger regeneration.

All these observations concern utterly short time-scales, from a tree's perspective. To compensate the data-gap, and produce at least conservative estimates of what our actions yield, over time-scales that we cannot apprehend, the use of models is a relevant approach. After all, this is the only source of *a priori* information that we can use to orientate long-term management decisions.

(((Transition vers un petit chapitre sur les quelques modèles et leurs prédictions))) - Few models focused on the effects of logging in a yield-estimation framework - Often estimated carbon recovery, using satellite images, gap models, correlative approach, etc,etc,etc - Some models did silvicultural simulations, for example .... All the guys with FORMIND, Selva, etc Individual models: ouverture sur notre problématique ((Transition vers le vif du sujet))

We used TROLL to bring a first contribution to the study of selective logging with a spatially-explicit, individual-based model that simulates jointly carbon and biodiversity, and explicitely accounts for the influence of species-specific functional traits on individuals life cycle (growth, mortality, recruitment, reproduction) (OK, c'est probablement un peu too much). Our aims were 1- to use a model offering a good representation of species neutral and functional diversity, to get as colse as possible to the actual logged forests; 2- to implement a realistic spatialisation that models logging practices as explicitly as can be, given field reality in French Guiana and the models limits, and based upon the first version of the logging module developed by Schmitt [2017]; 3- to include and explore actual possible scenarii for the wood industry in French Guiana 4- to enable testing a wider range of scenarii, making a generic tool to build something bigger upon, adaptable to other study scale with some, but few modifications. To match these goals, we followed four steps. Firstly, we inferred a new species

input dataset for French Guiana forests. Secondly, we attempted a validation and calibration of post-logging recovery with TROLL, using real censuses from logged and undisturbed plots of the Paracou disturbance experiment, which ultimately yielded other questions about TROLL's spatiallisation. Thirdly, we updated the existing selective logging module to include multiple cutting cycles; main track extent adaptation consistently with target volumes; conventional-logging-like secondary tracks design; a new harvested tree designation method, that allows testing scenarii relative to harvested species interest ranks; and both logging damages spatially-explicit, and continuous monitoring of the trees biometry by timber category. Finally, we did a pilot-experiment, simulating two cutting cycles, two target volumes, three diversification scenarii, RIL and CL, on two initial forests with contrasted initial timber stocks. This report details every part in this natural order. [4]: This term needs a clear definition. XXX

# TROLL MODEL

## Overview

In a few words, TROLL simulates every tree starting from 1 meter high (formerly, 1 cm dbh) in a spatialized light environment, where every process of the trees life cycle are modeled according to global rates, species-specific traits, and photosynthetic rates influenced by individual-level light incomes. TROLL can thus be defined as an individual-based and spatially explicit forest growth model, along with SORTIE [**??**] and FORMIND [**??**]. Actually, TROLL can be qualified with many adjectives. The most important among them are individual tree-based, spatially-explicit, and process- and physiology-based.

TROLL simulates two classes of objects: species, and trees. Trees are simulated in a tridimensional (voxel) space of one-meter resolution, in which the light environment is explicitly computed. One tree can settle in each horizontal pixel of $1m^2$. Each tree has a number of attributes, which we can classify into two categories: biometric, state variables, and species-specific variables (see Figure .
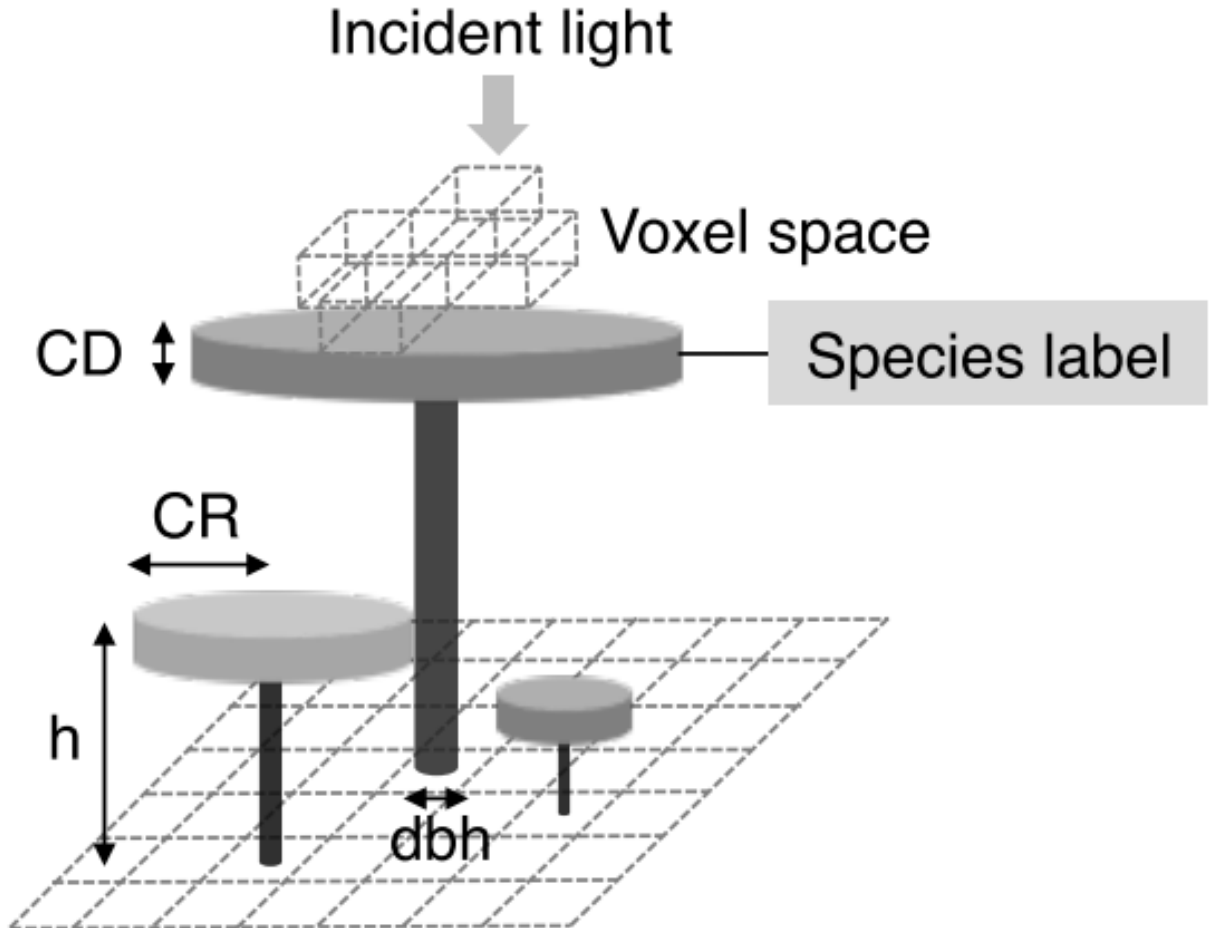


The firsts encompass tree age, diameter at brease height ($dbh$), height ($h$), crown radius

($CR$) and depth ($CD$), leaf area ($LA$). The second encompass five functional traits and two allometric parameters (*cf.* Table 1). Species are linked to trees with by a species label, which is inherited from the parent (mother) tree.

Table 1: Species-specific parameters used in TROLL from **?**. Data originates from the BRIDGE [Baraloto et al., 2010] and TRY [Kattge et al., 2011] datasets.

| Abbreviation | Description | Units |
|---|---|---|
| $LMA$ | leaf mass per area | $g.m^{-2}$ |
| $N_m$ | leaf nitrogen content per dry mass | $mg.g^{-1}$ |
| $P_m$ | leaf phosphorous content per dry mass | $mg.g^{-1}$ |
| $wsg$ | wood specific gravity | $g.cm^{-3}$ |
| $dbh_{thresh}$ | diameter at breasth height threshold | $m$ |
| $h_{lim}$ | asymptotic height | $m$ |
| $a_h$ | parameter of the tree-height-dbh allometry | $\mu$ |

Tree geometry is derived from its diameter according to allometric relations (XXX refs), whereas leaf area varies dynamically within each tree crown. Contrasting with other forest simulators, TROLL models tree growth as the result of an explicitly computed carbon balance between assimilation by photosynthesis, emissions from respiration (XXX), and allocation to the different tree compartments. Assimilation is computed according to climate input data, over half-hourly periods of a representative day, and influences the simulated environment at the next time step, which defaults to one month. Seeds and seedlings are not explicitly modeled and are considered part of a seedling/seed pool. Every tree belongs to a species through a species label, and thus shares common species features that are inherited from the mother tree through the seed. The species label established the correspondence between a tree and species-specific parameters, i.e. trait values obtained from field measurements (and inference). Currently, soil processes and topography are not explicitly modeled. Their overall influence on a real forest at a plot's scale is implicit, partly accounted for when using site-specific species datasets (see after).

# Including more species in TROLL simulations

## Summary

We included more species to the existing dataset used for TROLL simulations. This choice was motivated by both theoretical and practical reasons. The aims were either to enhance the coverage (in number of trees) for Paracou simulations (see next section) and to have enough species to simulate large plots, for the logging experiment. We hierarchically inferred species-specific means for leaf traits, stem traits and allometric parameters, with the BRIDGE dataset. We estimated maximum diameters from the whole Guyafor dataset, pooled with BRIDGE. We used Predictive Mean Matching to complete the dataset beforehand, due to a variable -Pmass- that considerably limited our possibilities.

## Introduction

The importance of biodiversity (in its most generic assertion) in ecosystem functioning[add ref] is well recognized. It affects most of the ecosystemic characteristics, among others productivity [**?**], stability [**?**], resistance to invasion [Lyons and Schwartz, 2001]. Recent advances in Functional Ecology suggest that the most relevant component of communities decription to study ecosystem functioning is its functional composition, that can be assessed using functional traits. Functional traits are formally defined as morpho-physio-phenological traits that indirectly impact fitness via their effect on growth, survival, and reproduction [Violle et al., 2007].

Accounting for functional traits and their effects on processes, instead of overall rates, is necessary to model forest dynamics with a finer accuracy. Classical models often use a limited number of species groups defined according to restrictive criteria. TROLL directly uses 5 functional traits (LMA, Nmass, Pmass, and wsg) and 2 allometric parameters at the species-specific level. All were obtained from real data,. TROLL is one of the few models that depicts forests' functional compositions with such finesse and accuracy, thus allowing finer-scales investigation (Marechaux [2017], **?**, also see **?** for a continuum-based approach).

The two primary goals of this work were to assess TROLL's capacity to simulate post-logging ecosystem trajectories from real censuses, and to simulate silviculture as currently done in French Guiana. For the first, we used real forest censuses from the Paracou Disturbance Experiment site. For the second, we simulated forests *in silico*. Given the number of species present at Paracou (>800), and in French Guianean forests in general, we wondered whether the 163 species included in TROLL's current list were numerous enough to achieve our goals. The actual need to include more species emerged when we explored Paracou individual plots

(6.25 ha), that had a variable but generally large (20-50%) proportion of individuals belonging to species not included in TROLL's list (hereafter referred to as *missing species*).

We used the BRIDGE and Guyafor datasets to include new species for our simulations. Because the dataset had few non-missing values of Pmass, we infered missing values with an approach based on Predictive Mean Matching, taking advantage of the correlations between traits. We then used hierarchical models to infer species means for Nmass, Pmass, LMA, and wsg, including all complete observations. Maximum diameters (dmax) were the 99th percentiles taken from both BRIDGE and Guyafor datasets. For allometric parameters, we used a Michaelis-Menten version of the same hierarchical models. The model blueprints were generously provided by Fabian Fisched (EDB, Toulouse).

# Context and Problem

## The initial species list

TROLL's current species-specific trait dataset contains 8 variables: $LMA$, $Nmass$, $Pmass$, $wsg$, $hmax$, $dmax$, $ah$, and $Freg$ (see table 1, in the previous section). We decided to let apart Freg (the regional frequency of a species) which are adapted for each simulation depending on the forest composition and simulation aims.

The actual maximum height a tree can reach in TROLL model depends on both its maximum diameter, and the H-dbh allometry at the species level.It is given by: $h_{max[real]} = \frac{1.5*h_{max}*d_{max}}{(1.5*d_{max}+ah)}$. With hmax and ah, the parameters of a Michaelis Menten equation (for details, see corresponding inference section). These parameters are highly correlated [Schmitt, 2017]. Although its name may be quite confusing, hmax corresponds to an asymptotic height, which rigourously means that this height will never be reacher by any tree of a given species.

## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.

# Can we represent Paracou plots composition with TROLL's species list ?

Paracou plots display a high proportion of species that are absent of TROLL dataset (Figure 2). These species are mainly less common ones, and may be absent either because they were not present in the plots sampled for BRIDGE or because their number of observations did not allow including them with the inference procedure that was followed. Based on preliminary exploration of the Paracou dataset, we noticed that the proportion of individuals belonging to missing species is slightly reducing over time. This may be linked with an increase in botanical determination reliability. This proportion is rather low compared to the proportion
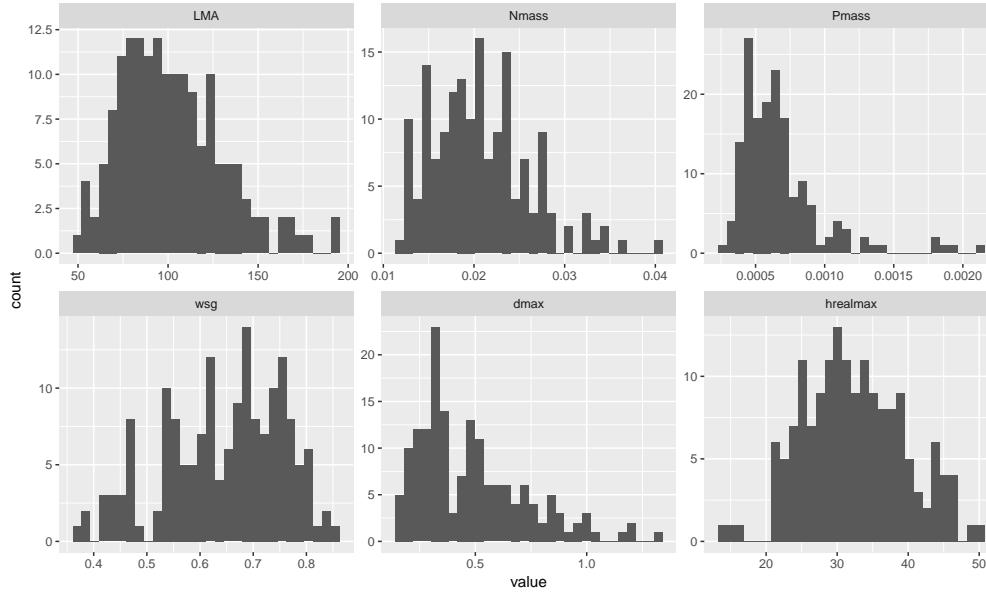
Figure 1: distributions of six functional traits in TROLL species list: LMA, Nmass, Pmass, wsg, dmax, and hmax(real), this one being the outcome of both allometries and maximum diameters. Details on the traits are available in the model description section.

of missing species. However, such proportion was deeply questioning the *a priori* validity of our intent to simulate real forest plots. table **??** shows the observed proportions of missing and simulable species with the initial dataset.

### *Missing species and individuals*

### *Representativity of the subsets*

# How to parametrise more species with the same amout of data ?

## The BRIDGE trait database

We used the BRIDGE trait database (Baraloto et al. [2010], Baraloto et al. [2012]) which was further completed by the Toulouse EDB team (**?**, **?** XXX REF). The BRIDGE dataset contains measurements for ten leaf and stem traits, with a total of 4709 individuals. One of the strengths of BRIDGE is that nine plots were sampled exhaustively, thus providing an exceptional representation of the French Guianean forests functional composition for >10cm dbh trees. However, another feature of the BRIDGE dataset is that the plots sampled are tropical rainforest: the dataset contains numerous species with a majority of rare (>4
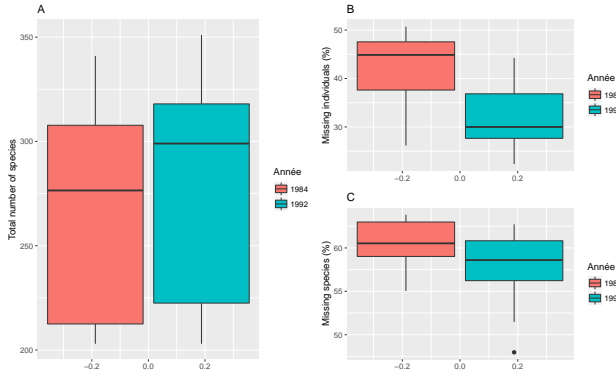
Figure 2: Summary: total number of species and proportions of missing species and individuais in two censuses (1984,1992) for twelve Paracou Plots (1-12). A: Total number of species in the plots, at the plot scale, B: Proportion of individuals belonging to missing species, C: Proportion of missing species, at the plot scale. Colors represent the census years (red: 1984, blue: 1992)

observations) and a minority of highly dominant ($> 200$ observations) species.We used six individual-level traits and characteristics, namely: LMA, Nmass, Pmass, wsg, H, d (**?**). Trait distributions are shown in **??**.

| Trait | Full name | Unit | N (complete) | Missing data |
|-------|-----------|------|--------------|--------------|
| LMA | leaf mass per areaa | g.cm^{2} | 4460 | 265 |
| Nmass | leaf nitrogen content per dry mass | mg.g^{-1} | 2928 | 1797 |
| Pmass | leaf phosphorous content per dry mass | mg.g^{-1} | 931 | 3794 |
| wsg | wood specific gravity | g.cm^{-3} | 2875 | 1850 |
| Height | tree height | m | 4399 | 326 |
| dbh | diameter at breast hight | m | 4597 | 128 |
| Total | complete observations | - | 651 | - |
| LMA, N, wsg | complete observations (Pmass excluded) | - | 1726 | - |
| The dataset w | e used contains large amounts of missing | data, as the | majority of fu | nctional trait |
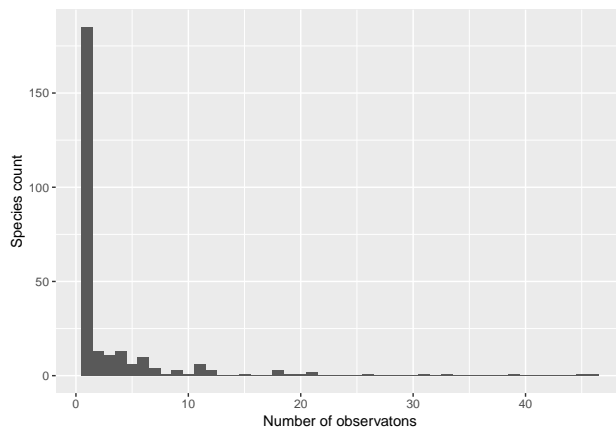


Figure 3: Histogram of the number of observations per species for Pmass. Most species are singletons.

according to taxonomical levels: Imputations were performed at the genus level if more than 30 complete observations were available. If not, imputation was made at the family level, with the same threshold. Monogeneric and underrepresented families were treated at the overall level. The aim of this separation was to reduce the errors due to using overall relationships to infer values. We assumed that functional strategies were more accurately captured by grouping according to taxonomical position than using a global, unique set of relationships between trait. This however can be a source of errors: intergeneric and intrageneric variation is high in tropical trees, be it regarding morphological characteristics, light response and trade-offs.

We obtained a completed dataset of 4245 observations (**??**, with a total of 599 represented species, which is less than the original species number for LMA and wsg. This is due to the fact that individuals belonging to indeterminated genera and species were discarded (except the ones present in Paracou, for example *Symphonia sp.1*), as well as idividuals which had only one trait measured, or with high taxonomic uncertainty, thus having to be excluded according to BRIDGE metadata. In the end, Pmass have more inferred values than actually measured values in the completed dataset.

## Hierarchical modeling framework

We used a simple but efficient modeling framework, which principle was suggested and blueprinted by Fabian Fisher (*pers. comm.*), to hierarchically infer species means and take advantage of every available observation.

The idea is quite simple: for a trait (or an allometric parameter), the value observed in individuals depends on a species mean (modulo a variance, assumed homogen across species), which is itself related to an higher-level grouping entity mean. For example, we can consider that species mean depends on genus mean, that is itself related to the family mean, and so on up to the overall observed mean (*i.e.* regardless to grouping entities). The most critical choices here are the number of grouping entities, an appropriate distribution, and informative priors for the target parameters.

After testing several configurations, we decided to stick with only two layers, namely species and overall levels. The main reason of this choice was parsimony. Genera means, variance, and species raw/actual deviation from its genus mean represented a high number of extra parameters, which is excessive compared to the predictive power enhancement it represents. This was estimated by a quick comparison using the WAIC criterion, that confirmed our intuition (data not shown)

# Leaf and stem traits

To infer species mean traits, we used two types of hierarchical models. Both accounted for two layers only, for reasons of parsimony: adding grouping variables (Genus or Family) did not bring significant improvement considering the number of parameters added.

We used the following model:

$$X_{sp} \sim \mathcal{N}(\mu_{sp}, \sigma_{intra}) \tag{1}$$

Where, for individuals belonging to species $s$, and a given trait of log-transformed trait $X$, the $X$ attribute of these individual follows a *Gaussian* prodability distribution, of parameters $\mu_{sp}$, a species-level trait mean, and $sigma_{intra}$, the intraspecific variance (here assumer to be homogen among species). Moreover:

$$\mu_{sp} \sim \mathcal{N}(\mu_{tot}, \sigma) \tag{2}$$

The species mean $\mu_{sp}$ itself is normally distributed, depending on an overall mean $\mu_{tot}$ and an overall variance $\sigma$.

# Michaelis-Menten hierarchical model

In TROLL model, the allometries used to model trees height/dbh relationship is a Michaeli-Menten form, defined as:

$$\hat{h} = log\left(\frac{1}{\left(\frac{1}{h_{max_{sp[i]}}} + \frac{1}{\beta_{sp[i]}*dbh[i]}\right)}\right) \tag{3}$$

Originally, the model provided by Fabian has the form:

$$[log(h_i)|sp_i; dbh_i] \sim \mathcal{N}([\hat{h}_i|sp_i; dbh_i], \sigma) \tag{4}$$

Where $h$ is the observed height for tree $i$, which varies lognormally around $\hat{h}_i$, the expectation of its height knowing its species $sp_i$ and diameter $dbh_i$, with variance $\sigma$. $\hat{h}_i$ is computed with:

$$[\hat{h}_i|sp_i; dbh_i] = log\left(\frac{1}{\left(\frac{1}{h_{max_{sp_i}}} + \frac{1}{\beta_{sp_i}*dbh_i}\right)}\right) \tag{5}$$

Where $h_{max_{sp_i}}$ is the asymptotic height of species $i$, and $\beta_{sp_i}$, a shape parameter of the model.

$$\beta_{sp[i]} \sim \mathcal{N}(\bar{\beta}, \sigma_\beta) h_{max_{sp[i]}} \sim \mathcal{N}(\bar{h}_{max}, \sigma_\beta) \tag{6}$$

with

beta_species = beta + beta_dev_species ; hmax_species = hmax + hmax_dev_species ;

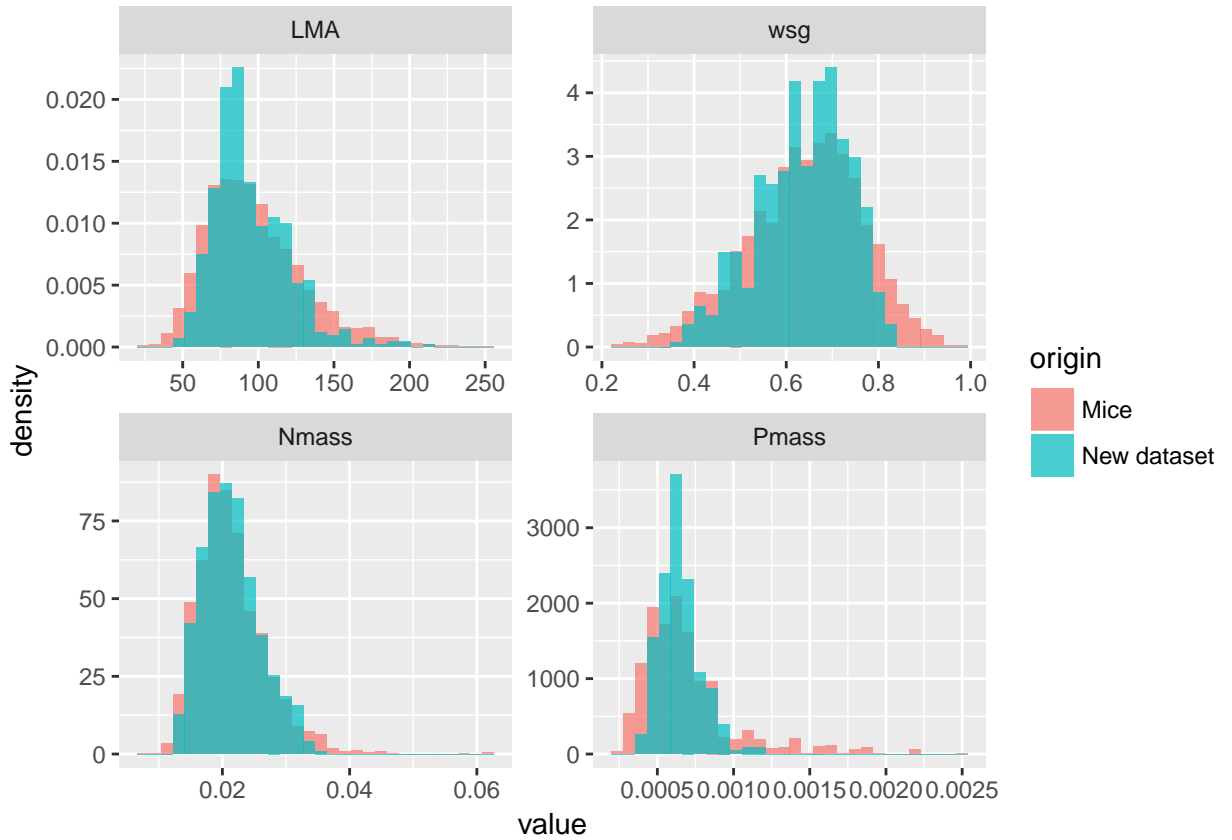Which can be rewritten to the classical Michaelis-Menten form:

$$\hat{h} = log\left(\frac{h_{max_{sp[i]}} * dbh[i]}{dbh[i] + \frac{h_{max_{sp[i]}}}{\beta_{sp[i]}}}\right) \tag{7}$$

Thus, with $\frac{h_{max_{sp[i]}}}{\beta_{sp}}$ corresponding to $a_h$ in equation (3)

# More species for TROLL

We obtained a new set of 599 species means for Nmass, Pmass, wsg and LMA.

## `stat_bin()` using `bins = 30`. Pick better value with `binwidth`.



What appears obvious here is that the range of estimated species means is more narrow that the one of raw species means, estimated on the dataset we performed the inference from. This is due to shrinkage of the distributions by estimating hierarchically the species means distribution, to keep only punctual estimators (the mean of the MCMC sampled species means) as a final output. In more poetic terms, what happens here is an illustration of the

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precaution principle: species with extreme and with very few observations are attributed more reasonable estimates, because of the uncertainties.

# Discussion

The hierarchical models used here, species means are derived from the general trait mean,and thus depend on both the number of observations for each species and the observed trait values. If a species is observed very few (or one) time, its inferred mean is "attracted towards the overall mean value because of the poorly informative value of a low number of observations. Thus, singleton species with"extreme" trait values will be attributed more reasonable means, leveraged by the rest of the data due to high incertainty around the actual observed value. On the contrary, abundant species have narrow confidence intervals around their deviation to the overall mean, thus, a reliably *distinct* trait mean, even when close to the global mean value.

This is consistent with the arguable assumption that measuring only one extreme value can be the outcome of picking one very special tree by chance, and that this is barely more informative than attributing it the community mean. These models thus allow to account for uncertainties due to scarce observations. Even further, considering the number of rare species in tropical plant trait databases such as BRIDGE, and given that each of them contribute to the overall mean, it is wise to include them and as low weight, but numerous contributors to the overall distribution, instead of setting an arbitraty cutoff: why would a species mean computed with 5 observations more reliable than one computed with 4 measurements ?

The adjustment of an extreme estimate to a more moderate one is termed shrinkage, and is inherent to many hierarchical models. It can either be considered a advantageous phenomenon or a real problem (see Rouder et al. [2005], Mould and Upton [2013], Savic and Karlsson [2009]). The main drawback of this approach is that shrinkage effect leads to an overestimation of traits distribution densities around the overall mean, for it ponderates maybe excessively the the whole dataset (*i.e.*, the sum of each individual contribution) in front of any single individual. This is also due to the fact that our final output is a table of species means, the uncertainties around these means -thus a part of the diversity of possible trait value- being ignored.

The validity of this approach is not jeopardized by these considerations. Using hierarchical modeling and the underlying shrinkage as a "precaution principle" to work with scarce species-specific observations, and datasets such as Bridge, is advisable. The main perspective of improvement on this inference is the use of a new feature of TROLL, recently implemented by Fabian Fischer: intraspecific, normal or lognormal trait variability, constrained by between-trait covariance. This approach allows both to recreate continuums such as those observed in real forests, by conserving at least the overall links between every trait. This has been also tested by **?**(2014). We did not have the time to adapt our study to this feature, for it came out a very few months ago.

# Can TROLL simulate real forests and post-logging trajectories ?

## Overview - PRESQUE OK

Tree reproduction (pollination, dispersion, germination) and recruitment (seedling and sapling dynamics) are key points to understand the response of forests to disturbances such as selective logging. Due to our whopping lack of knowledge concerning autecology oftimber species and their competitors (*e.g.* pioneers), we may question the accuracy of the conclusions drawn with models in general. Field studies on < 10 *cmdbh* trees are scarce and often focus on a few species, making it difficult or impossible to correctly evaluate and calibrte models on the whole plot scale with it.

The original goal of this section was to evaluate TROLL's aptitude to simulate post-logging trajectories by using real data. Preliminary comparison of the model understoreys with seedling and sapling censuses in Paracou (from the Mariwenn Database), showed TROLL underestimates seedling **abundances**, due to discrete space assumtions (data not shown). It however reliably depicts diameter structure for higher *dbh* categories (**?**). We thus compared simulated ecosystem trajectories with regular censuses (> 10 *cm dbh*), after adapting the data to the model input format and simulating the understorey stratae. Since the obtained results showed anomalies, this yielded another question: is TROLL adapted to simulate forests from real data ? We used a spatial statistic approach, comparing real censuses with mature forests simulated with comparable species composition.

## Methods

### Handling missing species

We used our new species dataset to simulate post-logging trajectories at Paracou. Overall, 347 Paracou species matched with our dataset, resulting in higher yet still disturbing proportions of individuals belonging to missing species. The number of species matching at a plot's scale was enhanced with the new dataset, but stimm low (100 to 200), compared to the 250-350 species that can occur in a single plot (4. We had about three missing species out of five but representing only 15-30% of the total number of individuals at the plot scale. The representativeness of these subsets was assessed, and was overall correct (see XXX ANNEXE). To handle species that were still missing, we replaced the individuals belonging to missing species by individuals of parametrized species, by diameter class: 10-20, 20-30,30-45,45-60,>60.
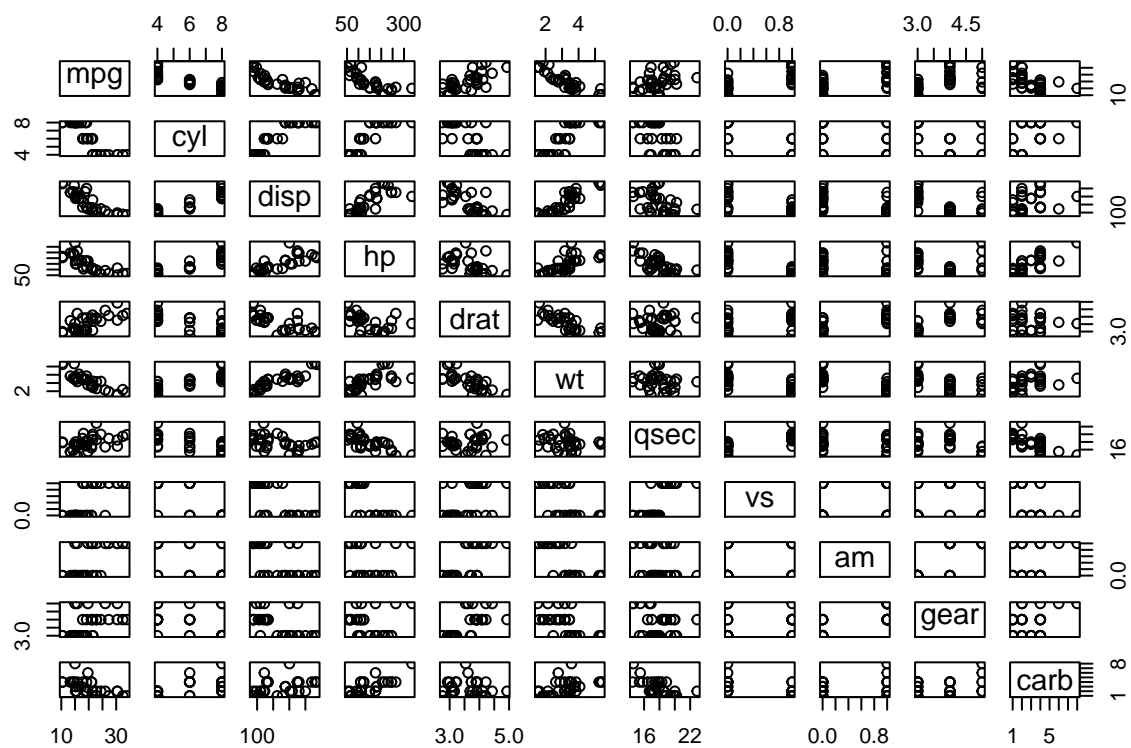
Figure 4: a caption for a figure yet to add

We graphically explored the representativeness of our species subset comparing it to the whole BRIDGE database. Pioneer species were slightly under-represented, but generally, the parametrized species subset was representative of the functional diversity of the whole BRIDGE data (see Appendix X).

# Residual mortality after logging: where to start from ?

Residual mortality after selective logging is a well observed phenomenon, which have been documented for seven sites in the Amazon [five in Brazil, one in Suriname, and Paracou - see Blanc et al., 2009, for summary table and references]. During six to sixteen years after disturbance, logged stands undergo a high persistent mortality which is due to several factors:

- Many trees are hurt during operations. They do not die immediately, but rather a few years after being hurt. This is especially true when poison girdling is applied to the plots.
- Soil modifications (compaction, degradation, and ultimately erosion) can also stress the trees located neer the main or secondary tracks.
- Changes in abiotic environment due to gap opening can be detrimental to some trees.

We used Paracou data and Geraldine Derroire's mortality function (unpublished) to check the annual mortality rates in the 12 plots of the Disturbance Experiment (REF XXX). Paracou plots have undergone different treatments, consisting in conventional selective logging (T1), additional Timber Stand Improvement (TSI - thinning by poison girdling: T2, T3), and additional fuelwood harvest (T3). Control plots (natural forests, T0) are also included. The annual mortality rates observed at logged plots to go back to levels comparable to control plots about ten years after logging (Figure 5, and see Blanc et al. [2009]), althought there is no neat transition. Still, for treatments 1 to 3, the mortality levels 6 years after logging are reasonable compared to rates observed in the first 3 years following disturbance.

Considering that 1. the number of botanical indeterminations decreased, and the "coverage" by TROLL species list increased over time at Paracou; 2. residual mortality decreases between 6 and 8 years after logging in this dataset; and 3. we want to model as much as possible the entire trajectory following logging; we started the simulations from 1992, which is an acceptable compromise.

# Coordinates and duplicates: moving, or removing

Paracou inventories are real forest data at a $0.5m * 0.5m$ resolution and TROLL simulates forests with horizontal cell size set to 1mš. Other resolutions are technically possible, but were not further explored, and increase computation time. As TROLL supports only one tree per cell, we handled cells containing several trees: the solution was either to keep only the most prominent tree in each conflicting cell, or to replace the smallest trees in a randomly
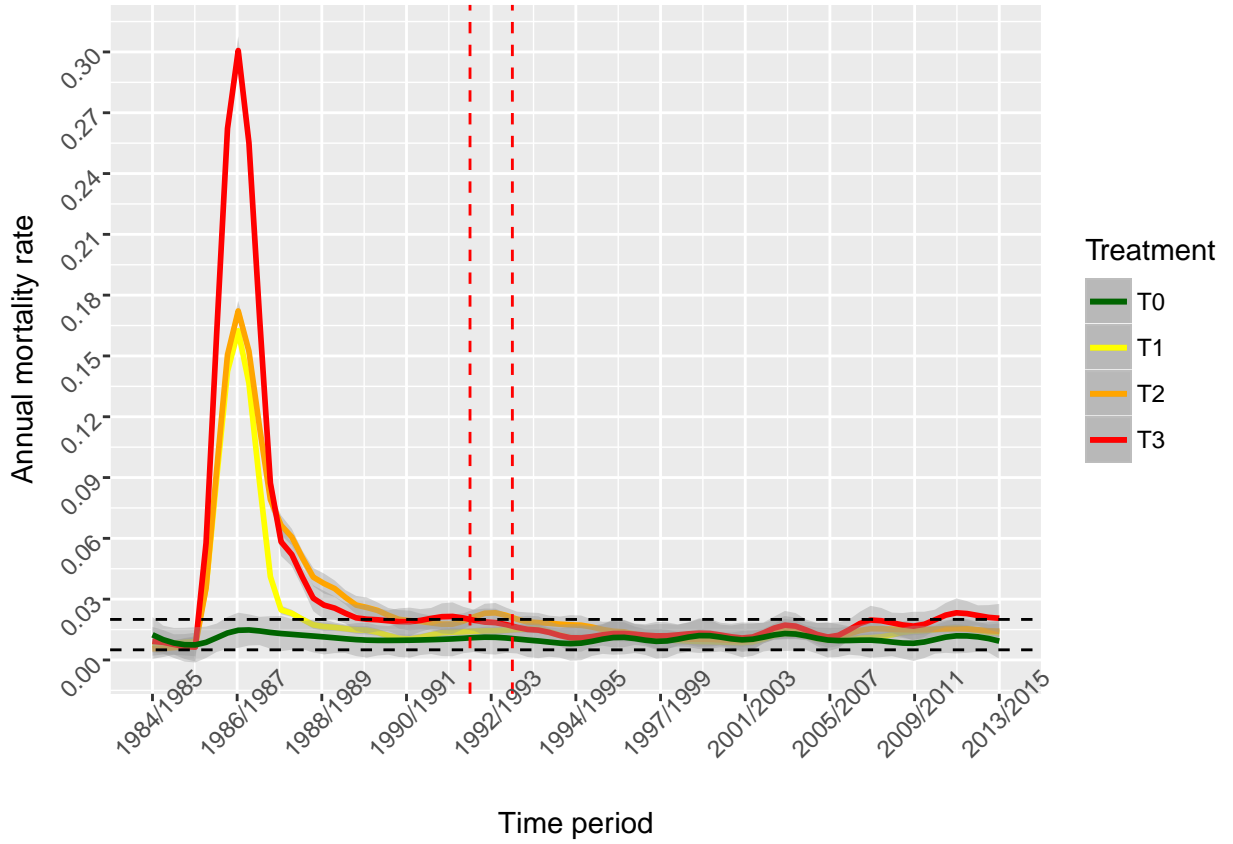
Figure 5: Annual mortality rates at Paracou plots, pooled by treatment. T0 are control plots, T1 are conventionally logged plots, T2 are logged plots with additional Stand Improvement treatment (thinning by poison girdling), T3 are plots logged for timber and additional fuelwood, having also undergone Stand Improvement treatments (cf XXX REF). Grey bands around the curves are pseudo-confidence intervals generated with geom_smooth (package ggplot2). The plots were logged in 1986/1987.

sampled, nearby free cell with an algorithm (details available on demand). Both introduce some bias, as it consists in direct modification of the raw data. Deleting trees is, in our opinion, worse than moving them of 1 or 2 meters, because it has more impact on canopy structure, thus on competition for light, which is the central process modeled with TROLL.

# Missing understoreys

Paracou censuses only include trees over 10 cm dbh, whereas TROLL simulates trees from 1 cm dbh (or 1m height). Direct similation from Paracou censuses, without any tree under 10 cm dbh initially present, is highly erroneous. The regeneration of the understorey strata from scratch would inducs a latency between the beginning of the simulation and the first "recruitment" events(*sensu* reaching 10 *cm dbh*). In reality, recruitment happens continuously and new trees over 10 *cm dbh* are registered every year. We thus had to dodge this problem the most reasonably as can be: We first simulated the forests' understoreys, that we re-injected in the initial maps.

We considered the following simplifying assumptions:

- Even thought we can question TROLL realism to simulate the regeneration strata, this is still the best option for we have nearly no data for trees under 10cm dbh. We assumed that TROLL can be realistic enough to use it in this purpose.
- To simulate an understorey with TROLL in order to simulate a plot with TROLL is than using another solution (for consistency).
- TROLL simulates explicitly competition for ligth: thus the upper-stratae spatial structure impact the lower-stratae.
- Paracou was a mature forest before the logging experiment.
- Mature trees project their seed on the ground. If they do so for long enough, the frequency of the seeds on the plots should be close to the frequencies of the upper strata.
- Even if logging damages (as represented on the map in Appendix XXX) let part of the >10cm trees survive, the understorey must have been more impacted in the corresponding areas : skidders and bulldozers tend to avoid big trees, but slaughter small trees.
- Thus, the understorey of a logged plot is heterogeneously impacted, and is finally a spatial mixture of "mature state" and "early stage" understoreys.
- Areas outside the damaged zones have been relatively few impacted during 5 years after logging, so the understorey may have the same structure and compositions as in 1986.
- Few trees over 10cm dbh have been recruted between 1987 and 1992, because of understorey damages.

We derived modeling choices considering these assumptions:

- The final understorey we use to inject to the >10dbh census for logged plots is constructed from two distinct TROLL simulations of two different censuses, and spatially

consistent with the geographic data available for the plots and the upper strata structure.

- For undamaged zones in disturbed plots, we simulated the understoreys from the last Paracou prelogging census during 30 years, which was a compromise between a "mature state" understorey and having initial (real) trees still alive, for spatial consistency.

- For areas located within damaged zones (see map XXX), we simulated an understorey from the 1992 censuses for 5 years, to obtain a youg understorey [6] that has undergone high enlightenment in opened areas (cf pictures in XXX REF PARACOU BIBLE)

- For control plots, a single understorey was simulated for 30 years and reinjected in the census. We used packages XXXX and data XXXX

## Simulation parameters

The simulation parameters were all TROLL default parameters (calibrated in **?**, adapted for the new version by Fabian Fischer, *pers. comm.*), except the seedrain scaling constant and the mortality rate parameters.

We initlally tested a wide range of seedrain parameters to determine the values that gave realistic results, to use if for our subsequent *in silico* experiment. This constant can have a strong influence on commercial tree species regeneration, of which depends directly the conclusions we can draw from logging experiments. TROLL's default to simulate forests from bare ground is C_seedrain = 50000 seeds/ha, and certainly overestimates the importance of this process in our framework. We tested 100%, 50%, 25%, 10% and 5% of the default value.

Mrtality parameters were first let to default values (i.e. the minimum mortality rate, m0 = 0.025; and the slope, m1 = 0.025), but we tested softer mortality rates *a posteriori*, decreasing from 0.020 to 0.010 since the results were highly unrealistic.

## Spatial structure analysis

After seeing the first outputs, we simulated mature forests corresponding to each plot in terms of species composition (regional frequencies set to plot frequencies and default seedrain scaling constant). Simulations lasted 600 years, which is assumed to be the time needed to reach ecosystem maturity in TROLL for high seed-rain constant values [**?**].

Spatial statistical analyses were performed with the help Stéphane Traissac, using the ads R-package (XXX REF). We compared the spatial structure of TROLL and Paracou forests using classical spatial indices, based upon Ripley's K function [Ripley, 1977], namely g(r) and L(r). The first is the linearised version of K proposed by **?**, thas has the advantage to be readily interpreted. The second is the derivative of Ripley's K function, and is proportional

to the expected number of neighbours present between two consecutive circles at a distance r, for a randomly choosen point in the map.

# Results and discussion
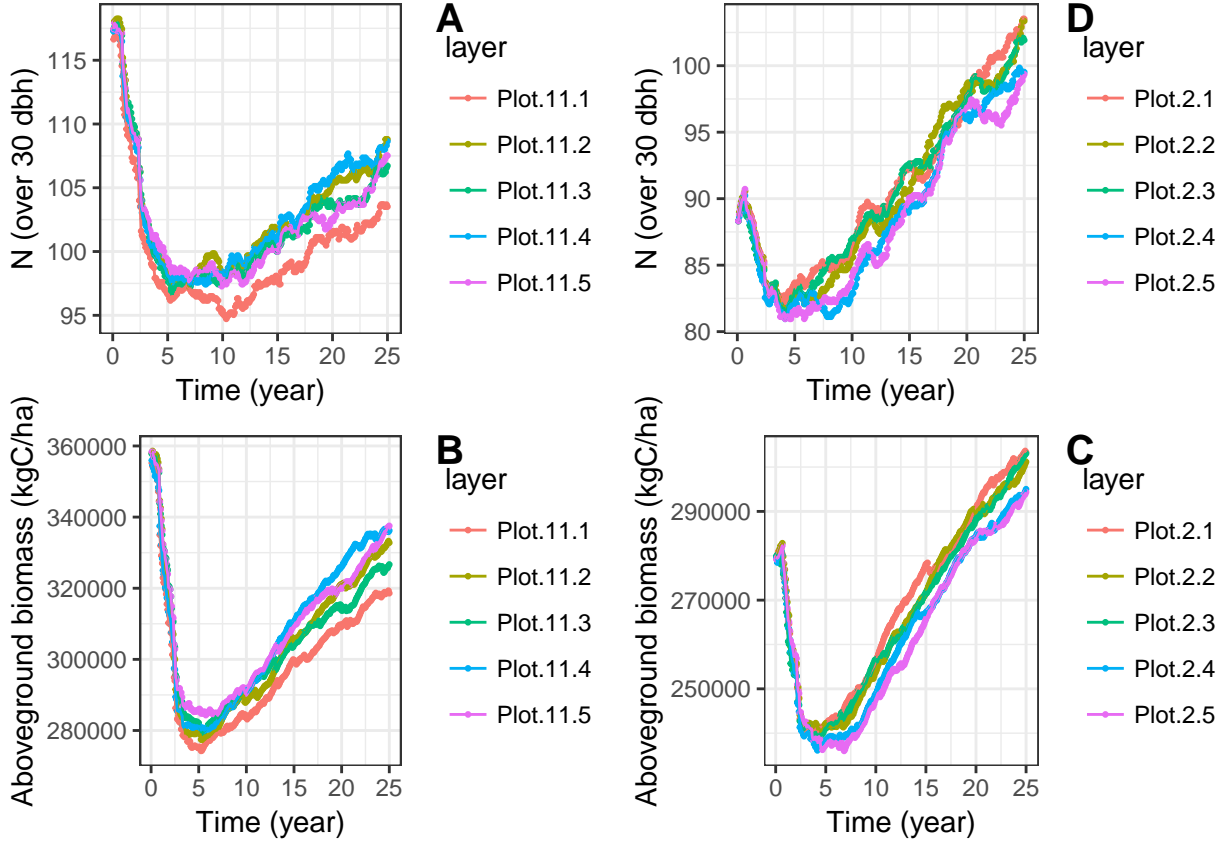
## Simulated trajectories



Figure 6: Trajectories obtained with TROLL, using real data as an input. A and B are outputs obtained with the plot number 11 (undisturbed). D and C are the results obtained with plot 2 (selectively logged). A and D show tree density per hectare for individuals above 30 cm dbh over time. B and D display the evolution of above-ground biomass over time. Each curve is a distinct simulation. Simulations lasted 5 years.

Figure 6 shows the trajectories obtained for a control plot (T0) and a logged plot (T1), in terms of above-ground carbon biomass (AGB, $kgC.ha^{-1}$) and densities of canopy trees ($dbh > 30$,N30,$ha^{-1}$). In every plot and for every simulation, we observed an anormal decrease in AGB and N30. This pattern holded at every mortality rate tested, although high mortality lead to stronger decreases in AGB and N30. This surprinsing behavior is not likely to be linked to the way we simulated the understorey, because it affects trees over 30 dbh. To

understand these results, we adopted a spatial analysis approch, wich results are presented hereafter.
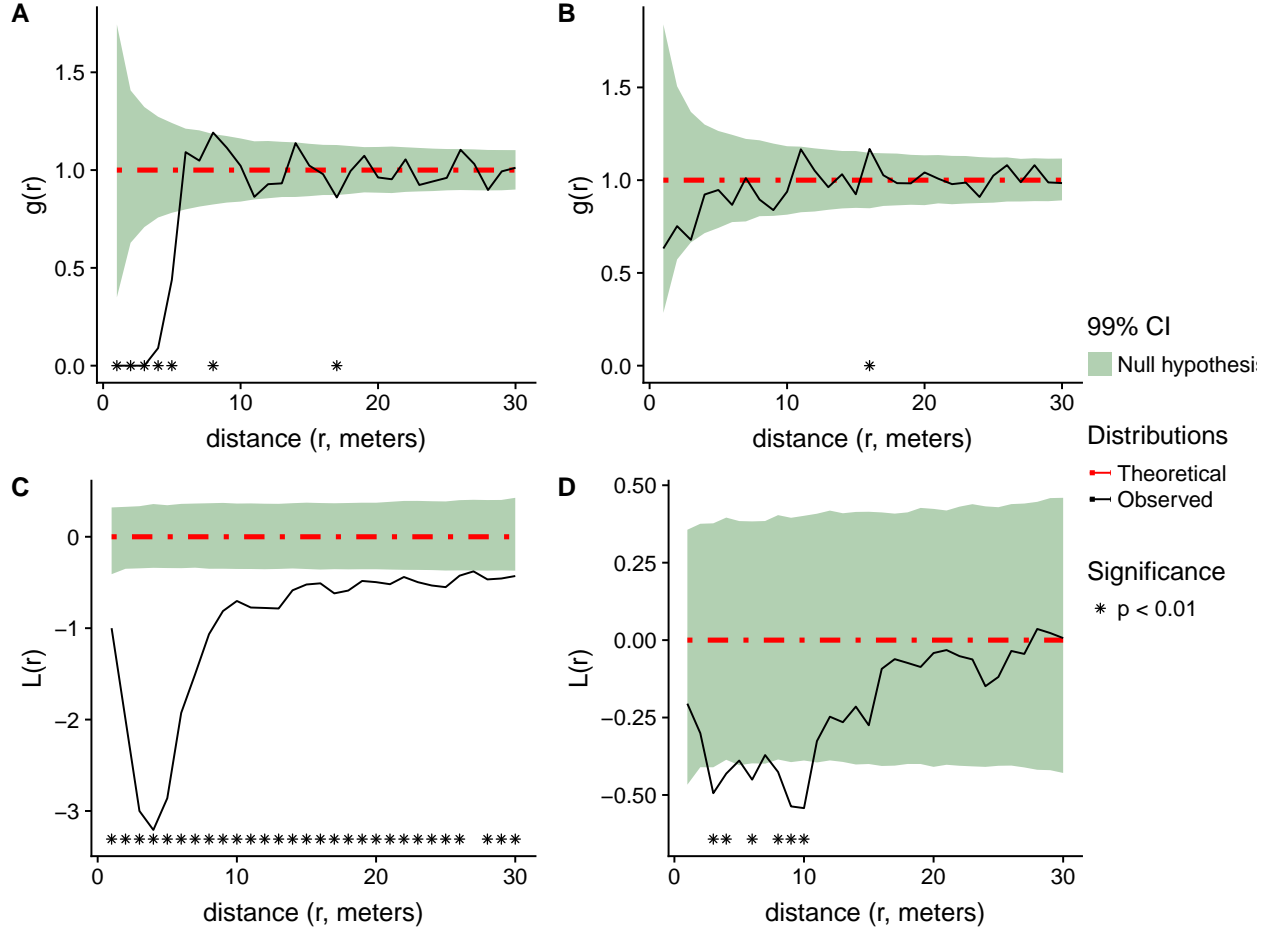
## Spatial statistics



Figure 7: Spatial structure of simulated (A and B) and real (C and D) forests for Paracou plot P1 (undisturbed). A and B show the distribution of g(r), the pair density function. C and D show the distribution or L(r), a linearization of Ripley's K. Both were computed for 30 radii ranging from 1 to 30 meters. Solid black lines are the observed distributions, dotted red lines represent the expected mean distribution under null hypothesis (Complete Spatial Randomness, CSR). Green areas are 99% confidence intervals (CIs) around the CSR null distribution means (for each radius), that were obtained by resampling randomly trees coordinates (1000 simulations). Parts of the curves that are out the CIs, for a given radius, violate the assumption of CSR for this radius. Values under the CIs indicate an overdispersed repartition, and values over the CIs, a clustered repartition
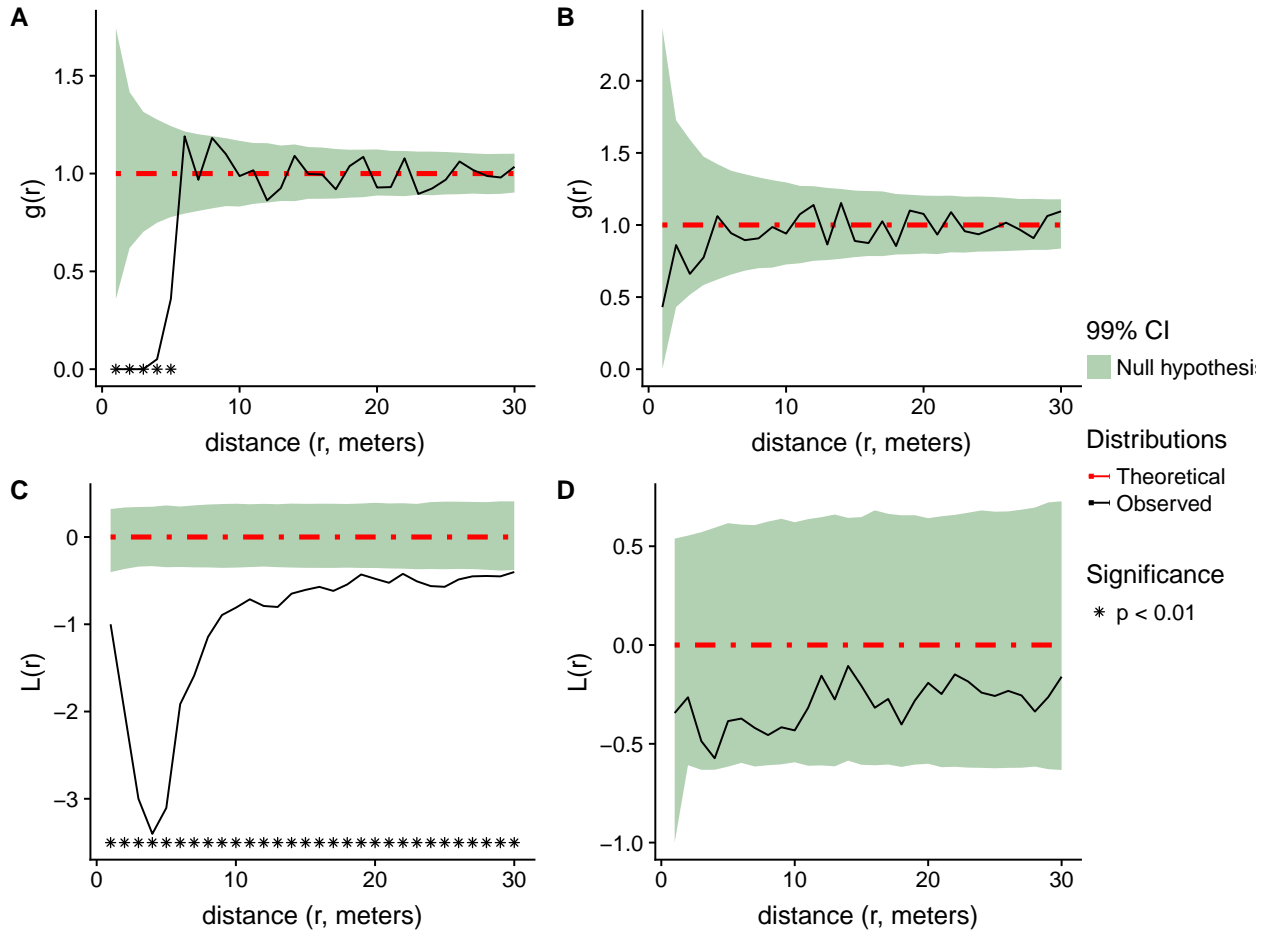
The spatial distribution of trees over 30 cm dbh differed greatly between real forests (year 1992) and mature simulated forests, regardless if real plots have been logged or are undisturbed (Figures 7 and **??**). This pattern holds for every plot (Annexe XXX to see the rest of the graphs). The $L(r)$ function (C and D, on both) curves slightly differ for logged and disturbed plots, with a slightly overdispersed spatial structure for radii between 3 and 10 meters in control plots. In simulated mature forests, $L(r)$ reaches extremely low values for radii up to 10 meters. The rest of the curve probably stays out of the confidence interval because of the autocorrelation inherent to $L(r)$: it is computed for concentric circles, so the deficit in points observed for low radii impacts the rest of the distribution. The $g(r)$ function curves bring more reasonable results, yet still showing an enormous overdispersion in simulated mature forests, for radii between 1 and 5 meters. The $g(r)$ curves are computed for consecutive crowns (the inner-most circle is eliminated). This yields more reasonable, autocorrelation-free results, yet loosing discrimination power.

These result show that TROLL severely overdisperses trees over 30 cm dbh compared to real forests at relatively small scale (radius $< 5$m).

# Synthesis

There are several possible reasons to the results of the simulations from real data. First, it might an inaccurate parametrization of the model, but this seems very unlikely since **?** intensively calibrated TROLL. Another can be an overestimated basal mortality rate, we tested a wide range of values, and the lowest (0.001) attenuated the phenomenon (not shown). However, the mentioned mortality event was always conspicuously displayed in the output graphs, for . A factor also influencing the results may be our data pre-treatment, consisting in replacing trees which had duplicated coordinates. The observed pattern is however homogen for all simulations, that were led with different random seeds. Our last hypothesis is that the observed result are due to a difference in spatial structure between TROLL and real forests, influencing the modeled light competition effects.

It may seem difficult, at first sight, to disentangle the effects of light competition and discretisation (cells of 1mš) on TROLL's spatiallisation. We are comparing two structurally different objects. TROLL is constrained to homogen spatial structure at fine scale (say, from 1-2 m radius) because of its fundamental assumption of a discrete space, with maximum 1 tree in each cell, while natural forests are spatially continuous. Whilst the same analysis for saplings or poles (*sensu* $< 10$ and $< 20$ cm dbh) might only reveal the obvious effects of TROLL's design, focusing on big trees (over 30cm dbh) brings interesting clues to explain the results observed with simulations from real data.

Light competition is the principal ressource-limiting process modelled in TROLL, which reproduces realistic forests in terms of global variables and floristic composition [see **?**]. Other factors, possibly contributing a proportion of the overall mortality rate in real forests, are not all accounted for. This might lead to an overestimation of the detrimental effects of competition for light in TROLL, althought our experience of TROLL is still insufficient to affirm it confidently. Still, it seems likely that TROLL underestimates trees' tolerance to shade or vicinity with other big trees, thus making simulation from real data irrelevant for structural reasons.

We can question the validity of the model, because in natural forest, certain demographic and successional processes rely on trees vicinity, for example what we can call *substitution*, a successful strategy some trees, consisting in thriving close to bigger "pairs" to benefit additional water and nutrients (Stéphane Traissac, *pers. comm.*). However, the fact that TROLL might overestimate competition for light, and makes forest with overdispersion of big trees, certainly does not take away its numerous strengths. TROLL is still an valuable tool for various purposes, such as jointly simulating carbon and biodiversity (**?**), exploring the impact of forests composition on ecosystem resilience (Schmitt [2017]), or simulate selective logging with unequalized spatial resolution. Modelling real forest with TROLL is just not what it is meant to... for now. Future developments may enable to do it.

# Modelling silviculture with TROLL: from reality to simulations

## Introduction

To model silviculture in French Guiana with TROLL, we used the first version of the logging module, which we updated according to bibliographical infoormation [mostly in Guitet et al., 2011] and numerous communications with Laurent Descroix, head of the RD pole of the National Forels Office (ONF).

Silvicultural practices *largo sensu* encompass selective logging with or without cutting cycle, tree plantation, and stand improvement, such as enrichment planting or tending operations [REF]. Nowadays in French Guiana (FG), silviculture operations mainly consist in selective logging. Tree plantations are not yet a practice to generate timber incomes, but promising experiments are ongoing [Project ForesTreeCulture; Nicolini and Morel, 2016]. Stand improvement often consisted in thinning by poison-girdling, but this practice has been left apart in agreement with the results of the Paracou Disturbance Experiment (Guitet et al. [2011])[XXX ref]. Currently, Sylviculture in French Guiana is oriented towards reduced impact logging (RIL). It is called "silviculture" for the care that is taken in the operations. Part of the aim is to destroy as less future trees as possible, and optimize natural regeneration processes by reducing damages and canopy opening during operations. Notwithstanding these remarks, we mostly refer to "silvicultural treatments in FG" as "selective logging" in this whole report.

Forest management focused on selective logging is currently divided into three fundamental parts: Tree choice, Harvesting, and Monitoring. Both encompass different steps and effects:

- Areas and tree choice:
    - Definition of the harvestable areas and main track planification
    - Designation of the harvestable trees by the ONF
    - Minor selection from the loggers
    - Tree probing
- Harvesting operations:
    - Tree Felling
    - Main tracks opening
    - Secondary tracks opening
    - Bole skidding
    - Post-logging, residual damages

Each of these processes is modeled either explicitly or implicitly. Hereafter, we detail these processes and effects in two parts:

- What currently happens with RIL implementation, or used to with "conventional"[1] practices
- The way we model the process in TROLL

The modified version of the code will be stored in a public Github Repository.

[2]What is referred to as "conventional logging" may be equivocal. Laurent Descroix (ONF, Cayenne center) insisted several times on how "RIL2" and "conventional" are both ends of a continuum. Conventional logging was characterized by no controlled tree designation, no resource spatialization, and even less optimization of skidding tracks planning. These factors generally led to higher damages due to unoptimized tracks network, for equal target volumes, but a lower quantity of harvested timber (due to selection or lack of organization). This definition probably holds for every selectively logged tropical forest [Zimmerman and Kormos, 2012].

# Choosing area and trees

## Harvestable areas

**_Reality_**  The ONF subdivides forest areas into plots or sampling units. Their surface area is variable (from 20 to 250 hectares; Laurent Descroix, unpublished data), but often somewhere between 20 and 50 hectares. Mechanical and "floristic" constrain the choice of harvestable areas. Bottomlands and swamps are avoided. They generally display poor stands, and engines do not circulate well in flooded areas. Steep slopes are also avoided due to mechanical constraints. Lateral slopes are especially restricting because they increase the risk of "sweeping effect" (when the bole, tied to a cable, slips laterally) or engine fall, and thus can cause accidents and considerably increase the damages. Because of such constraints, sampling units are nearly always located on plateaus or smooth slopes around hill crests.

In conventional logging, the definition of harvestable areas follows approximately the same rules. Perhaps the guidelines mentioned above are not carefully respected as in RIL, because of prevailing profit interests and untrained crew, but it is as least comparable concerning human and mechanical safety: this is about common sense.

Moreover, the rules (XXX WHICH ONES) stipulate that these zones may not be crossed by engines, to avoid jeopardizing the integrity of freshwater ecosystems. Additionally, a buffering space (XXX WHICH DIMENSIONS) have to be left intact around creeks and waterlogged areas, for the same reasons.

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[1]The maps shown in the precedent chapter are actually made with the coordinates of destroyed stems, for which the cause of the death is registered.

[2]The maps shown in the precedent chapter are actually made with the coordinates of destroyed stems, for which the cause of the death is registered.

**_Model_**   Topography is not yet implemented in TROLL model, which implicitly assumes a flat environment. Thus, we consider the whole simulated plot as a harvestable area. We simulated 24 $ha$ plots ($400 * 600 \ m^2$), thus making a compromise between simulating realistically big plots, and computational costs.

# Designation

**_Reality_**   high rank species are "protected" by additional designation rules, that depend on stand spatial structure. For example, one individual of Dicorynia guianensis is marked as "reserve" every 100 meters in large aggregates. This is supposed to let enough reproductive individuals to ensure the stock in the next rotation. #### Model Designation was deeply modified in the new version of the module. For consistency with field reality, the designation process is now tailored to depend the interest loggers have for the different species present on the plot, in a simple way.

There are a myriad of methods to model choice and preference (REF CHOICE MODELLING), and this is a huge theoretical field of statistics and mathematics. A choice basically depends on which entities that are confronted, which are the preferences of the actor who choose, and the presence of other entities of contextual factors (covariables that modulate choice along with preference relationships). The preference relationship between two entities (say, $A$ and $B$) can be direct and unvariant , variable , or neutral . In the first case, $A$ is always preferred over B, in the second, the outcome has a certain dependance on the context, and int the latter, there is neither a preference for A nor for B)

To model designation oriented by the neat preferences of loggers for some timber species, we splitted species into categories and established simple rules to choose which trees to harvest. In concrete terms, the categories are interest ranks and the contextual variable is the individual's diameter. We defined the following relationships inside and between categories : * The preference between two individuals of different ranks is direct and unvariant. Preference is oriented toward the lowest rank number regardless to diameters (provided it matches the minimum cutting diameter). * The preference between equal rank ndividuals depends on their diameter. The biggest one is picked, because it yields more timber. * If diameters and ranks are equal, both can be indifferently be picked.

We use three interest ranks in to match the 3 overall categories of species : * Always harvested and highly demanded (all Principal Major Commercial Species - ECMP, and _Bagassa guianensis_) * Species harvested if the first are not abundant enough (most of the Other Major Commercial Species - ECMA) * Species nearly never harvested, but sometimes [3] if the two others are really unsufficiently abundant.

In the model, the relashionships between these categories a fixed. To simulate harvesting

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[3]In reality, loggers often harvest less than the target volume if the stand is not commercially interesting enough, but this is not what we wanted to simulate here.

diversification, we made species interest ranks vary (*cf* next section), but not the way ranks interact with each other. Our modelling framework is simplified : Additional protection rules and the "reserve" designation are not implemented yet.

# Tree Probing

***RIL and conventional*** Generally, 20% of the trees matching commercial criteria (species and diameter) have redhibitory defaults and are considered "rotten" by the lumberman after probing (*i.e.* after burying a chainsaw inside the trunk to check if it is hollow). The causes of these defaults are partially mysterious. The observed symptoms are generally: the presence of holes on the trunk or the basis; the break of a big fork that has not cicatrized; or a hollow sound of the trunk. The probability for a tree to be rotten depends on its diameter, because big trees are likely to be older than small trees. They thus had more time to be exposed to wood consumers such as fungi (REF GUIDE) or Coleoptera (personal observations), or events inducing crown damages (causing a vulnerability) due to neighboring treefalls.

The ONF "encouraged" the loggers to harvest all trees, including rotten ones, during an experimental campaign and gathered data on the probability to be probed rotten, the actual rotten volume, and the characteristics of the trees (Laurent Descroix, pers. comm.). According to this data, around half the designated trees probed rotten by lumbermen are intact on a *ca.* 90% of their bole volume. This is good news, because an exciting perspective is to valorize those trees. Conversely, these trees may better be let on the plot, because they can survive and keep producing seeds. If the fuelwood demand is expanding during the next years, harvesting rotten trees could be advantageous even for high rotten volume trees.

***Model*** We used **?**'s models, calibrated on the mentioned dataset, to describe the probability for a tree to be rotten, and the proportion of intact wood in rotten trees. The first is already implemented in the module :

$$probbed\ rotten \sim \mathcal{B}(P(probbed\ rotten))$$
$$P(probbed\ rotten) = logit^{-1}(\beta_0 + \beta_1 * dbh) = \frac{e^{\beta_0 + \beta_1 * dbh}}{1 + e^{\beta_0 + \beta_1 * dbh}} \tag{8}$$

[XXX values] The probability for a tree to be *probbed rotten*, noted $P(probbed\ rotten)$, follows a *Bernoulli* probability law. The odds for a tree to be probed as rotten is the sum of a basal odd $\beta_0$, and a diameter dependent odd proportional to $\beta_1$. The probability for a tree to be probbed as rotten $P(probbed\ rotten)$ is the inverse logit ($logit^{-1}$) of the odd (see Schmitt [2017] for the detailed model design).

We implemented the rotten volume model as well, to compute the volume of energy wood potentially valuable from rotten trees.

$V_{intact} = 8.9 dbh \check{s} (1 - (0.4 * dbh^2))$

# Then, harvesting

## Felling trees

***Reality*** In RIL, directional felling is theoretically implemented to avoid damaging leave ("reserve") trees. The basic treefall direction is considered random, but in fact depends on the trees' natural orientation and crown aspect. In fact, four orientations characterize an optimally felled tree (see figure 1). Oriented treefall aims at orienting logs at *ca* 30° in relation to the closest track (main or secondary), to reduce damages when skidding and to handle the logs with more ease. Unfortunately, very few harvesters currently apply this technique in French Guiana, at least for now. Its implementation is ongoing, being part of the ONF's goals.

In conventional logging, few care is taken in felling the trees. The orientation is not controlled, and future trees are not accounted for at all. It makes it more dangerous for workers, and the damages in the understorey are expected to be higher.

***Model*** The complexity and computational costs involved with directional felling implementation are too high regarding the gain that it represents. A fully functional oriented treefall function would do it by assessing, for each harvested tree, what orientation fits with the closest track and involves the minimum damage for future merchantable trees, which would have to be preliminarily marked. We hope that further developments of the module will bring an easy and computationally efficient way to implement this feature.

In the current implementation, trees are felled at random, and gap dimensions are kept in memory to subsequently compute post-logging damages.

## Main Track

***Reality*** Foresty roads and tracks are split in three categories: truck roads, main tractor track, and secondary track (*cloisonnement*). In each plot, the main track is designed following the crest line (using digital elevation models). The main track extent within the sampling unit generally depends on the quantity of wood available in the plot. If more than 100 cubic meters of wood are transiting on a segment of forest track, the main track must be built up to there, probably to avoid excessive damages to the soil (that cause compaction, erosion and ultimately, infrastructure destruction). Wood quantity can be assessed directly, or using using surface as a proxy. This second option is often used, but assumes an isotropic distribution of harvestable trees, which is often violated to some extent.

***Model*** Given TROLL's assumption of a flat environment, the main track is opened from the midle of one side of the plots with a width of 6 meters, and traced untill reaching the point corresponding to a volume threshold. The extent of the main track is foreseen using the targetted volume and the dimensions of the plot, and the surface uncovered by the main track correspond to the volume threshold, approximately.

We choosed to use a threshold of 250 $m^3$, instead of the 100 $m^3$ used by the ONF. This adaptation was specific to the size and shapes of our plots, and is partly wrong. However, with 100m3, the main track always reached very close to the other edge of the plot, and this was conceptually disturbing.

## Secondary tracks

***Reality*** One of the major improvement in RIL is the mapping of felled trees and the usage of topographical relevés to optimize the secondary tracks network. The National forest office currently uses these tools to trace the tracks manually (being careful with inclinations and slopes) the secondary tracks in a way that more wood is extracted for a reduced track area. Software developed by the CIRAD and ONF is also used to optimize the tracks automatically but is currently still improved, to become fully functional. Recent improvements, such as the use of a nylon cable to skid the logs, also allow reducing the damage, because the tracks do not have to go up to every tree. Thus, tracks are designed to go between trees, approaching them to a distance of 30 meters maximum.

Conventional logging was primarily characterized by the absence of GPS mapping and topographical relevés. Skidding tracks were designed "on the heap," directly in the field. Thus, some trees were omitted and the track network used to be everything but optimal. There is no evident way to describe how tracks were typically traced. Bulldozers were used to go up to every felled tree, following the (somewhat imprecise) approximations of lumbermen. According to the information I received (I never attended a conventional logging project !), the trajectories were partly random, with many errors, and shortcut (the bulldozer sometimes was coming back by another way that the one it came with). Overall, this could be more related to visual-based skidding, from close to close.

*Model* We decided to model both conventional and RIL skidding fashions. RIL skidding was already implemented in the first version of the modules. CL was modeled using the simple assumption that the closest tree is first harvested, and the next ones, from close to close.

Figure 8 shows maps generated with both options, at two different harvest intensities. Note the difference in track extent, but also the dependence to target volume.
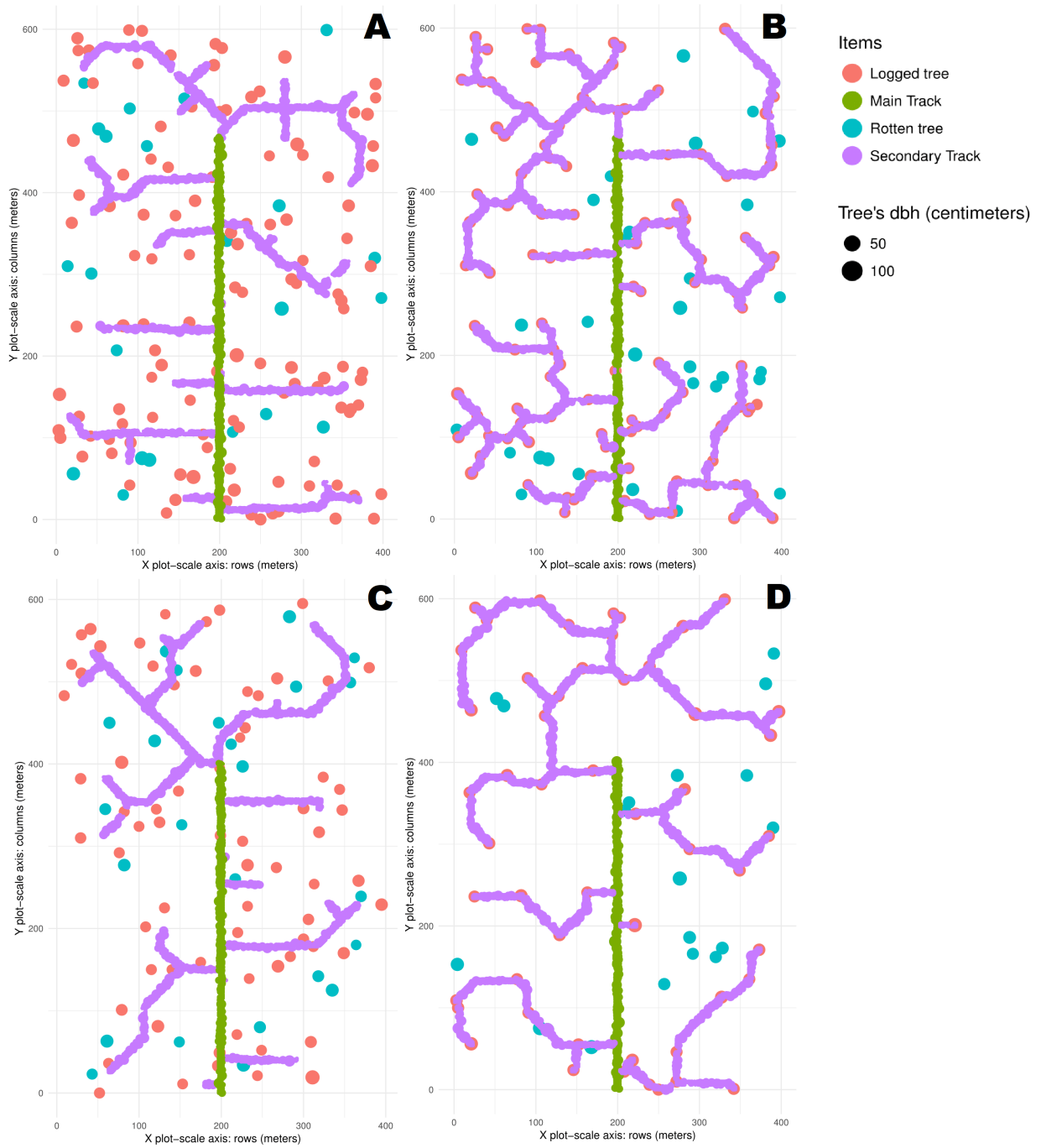
Insert Image

Figure 8: Maps generated by the selective logging module. A and B are maps obtained with a target volume of 30 cubic meters. For C and D, target volumes were 20 cubic meters. A and C were simulated with the RIL configuration. B and D were simulated with the conventional logging configuration.

# Residual mortality

***Reality*** Logging operations have immediate and secondary damages on tree stands. If the cause of the immediate damages is easy to guess, secondary damages are way less conspicuous and cause residual mortality during the first years after logging operations. These damages can be due to direct hurts underwent by the remaining trees during felling or skidding (uprooted stems, stem wounds, and bark scrapes), or due to consequences of the induced habitat changes. As exposed in section 4 of the thesis, mortality rates are higher at Paracou during the first years following logging, from 1987 to 1994.

***Model*** Generally, long term damages due to selective logging are modelled with a 10 years increased mortality [Huth et al., 2004, **?**, **?**]. We used the model developed by Schmitt [2017] last year, who gathered data from Paracou censuses between 1988 and 1992 on harvested plots and adapted the model from **?** based on a disturbance index into:

$$Death \sim \mathcal{B}(P(Death))$$
$$P(Death) = logit^{-1}(\theta + \beta * e^{\alpha * d_{gaps}}) = \frac{e^{\theta + \beta * e^{\alpha * d_{gaps}}}}{1 + e^{\theta + \beta * e^{\alpha * d_{gaps}}}} \tag{9}$$

*Death* of a tree follows a $\mathcal{B}ernoulli$ law of probability $P(Death)$. The odds for a tree to die are calculated with the sum of the natural tree death odd $\theta$ and a perturbation index $\beta * e^{\alpha * d_{gaps}}$. The perturbation index depend on the distance $d_{gaps}$ of the tree $i$ to the closest logging gap. The probability for a tree to die $P(Death)$ is finally calculated by taking the inverse logit $logit^{-1}$ of the odd.

# Model output files

# Selective Logging experiment

## Experiment design

### GFClim scenarios: Adaptation to the study scale

Currently, the GFClim project tackles the problematics of climate change and its interrelation with tropical forests in GF. The second Work Package of the project aims at defining scenarii regarding forest management and timber industry in the region, and examine their potential impact in this context, among others carbon emissions and required forest area.

Nowadays, about 80 000 m3 of wood are harvested by selective logging each year in French Guiana. This quantity slowly increases year by year. Current demographic growth in French Guyana is at a level which arguably can lean to a double increase of the population by 2030. Given this estimate, and a general aim to develop wood industry (the only possibly sustainable lucrative activity in French Guiana, opposed to gold mining), current projections aim at 200 000m3 of timber harvested per year, to be reached by 2025, along with a substantial quantity of fuelwood to supply biomass-fueled power station. This involves either an increased need to designate areas for logging, or an increase in harvest intensities. Moreover, public policies and the international context are supposed to give a rising importance to biodiversity preservation and carbon-accounting problems. Whilst neotropical forests are possibly no longer an important carbon sink (XXX REF BRUNO) [**?**] [Brienen et al., 2015], thy still represent an important stock (200-400 T.ha) of carbon (XXX REFS STOCK).

In French Guiana, 77% of carbon emissions would be due to deforestation (XXX FIND REF : "CIRAD GEC 2016"??), and selective logging would account for 5% of these emissions, although uncertainties are high [Cabon et al., 2015].

The fuelwood supply is a problematic of growing interest in the region. Three solutions could answer the increasing demand of wood for energy supply : Valorize the wastes that are usually left on the ground during timber extraction Dedicate plots for this particular activity Take advantage of plantation wood and local species to minimize pressure on natural forests. The scenarii defined in the GFClim wp3 are the following:

### Simulated forests

### Diversification of the harvested species

Primary neotropical rainforests are hyperdiverse. The main point of studying selective logging is to determine how these mixed-age, mixed-species stands, recover from the occasioned

disturbance and damages to ensure the production of timber and the maintenance of ecosystemic services. Most of the harvested primary forest tree species are non-pioneer, long-lived tree species with dense and imputrescible hardwood, low number of individuals per surface area, and which growth is supposed to be extremely slow [**?**]. It is critical to define the best way to manage the stands to ensure ecosystem resilience, that is in this context a synonymous with long-term, sustainable incomes.

The choice of harvested trees is essential to allow for regrowth of merchantable timber species instead of pioneer trees. The diversification of harvested species has long been proposed as a solution to mitigate the adverse demographic impacts of logging of these species [Guitet et al., 2011].

In French Guiana, more than 100 tree species are recognized for their technological qualities, and are referred to as commercial species. However, only a handful of species constitute over a 70% of the overall extracted timber volume [add graph XXX]. Commercial species are classified according to 4 categories: * Principal Major Commercial Timbers (ECMP) * Other Major Commercial Timbers (ECMA) * Precious Timbers (BP) * Other Commercial Timbers (AEC) Currently, only every ECMPs (*Peltogyne sp., Sextonia rubra, Dicorynia Guianensis*)[XXX names] and one ECMA (*Bagassa guianensis*) are subject to designation to be harvested. One the one hand, the ONF insist on the need to diversify the set of harvested species, without what current choices can only lead to ressource depletion within a few cutting cycles. On the other hand, they have to collaborate with logging companies to ensure the operations economical viability, which is impossible if too much non-demanded timbers, that can't be sold in the current market context, are designated.

We simulated three situations of preferences starting from the actual preferences to ideal, total diversification, resulting in three cases which we refer to as "realistic", "intermediate" and "diverse". Diversification is modelled with a species-specific interest variable, and our 3 modalities correspond to three cases:

- Species interest are split into three rank levels :
- 1: the few species that are overharvested in reality
- 2: species that are occasionally harvested as a complement of the firsts
- 3: species that are generally avoided, *i.e.* the majority.
- Species interest are split into two rank levels
- 1: the previous first and second categories, i.e. the diversification occurs on the species that loggers currently accept only.
- 2: the often-avoided species set
- Every commercial species have the same rank
- This is the ideal diversification, the case where every technically usable species would be valorised.

## Silvicultural parameters

**_Both types of selective logging_**  We simulated both Reduced Impact Logging and "improved" conventional logging, as implemented in the new version of the silviculture module. The reason of this choice is that both logging types can still happen in French Guiana: logging companies undergo a rapid turnover, and the degree of collaboration with the ONF is not constantly ideal. Careless operations, yet supposed to follow EFI guidelines, can lead to unoptimized skidding tracks opening and be, in terms of damages, relatable to conventional logging (Laurent Descroix, pers. com.).

**_Target and designated volumes_**  Current harvests in French Guiana target timber volumes of 25m3 per hectare in average, and the actual quantity of wood that is extracted is generally around 20 m3 due to rotten trees that are not yet valorised. This can however have advantages, such as conserving carbon stocks and seeding trees.

In the present regional and international contexts, harvest intensity is a central element of forest management, and can be influenced by two adverse forces: human needs or ecological concern. A growing body of evidence suggests that harvests must be regulated at low intensities, to make selective logging less harmful to the ecosystem. However, in a region such as French Guiana, experiencing high demographic growth and with ambitions relative to timber valorisation, there is a pressure to either uprise logging intensities, or log more forest areas.

We thus tested two target harvesting intensities:

- 20 $m^3$, which is in agreement with the current practices
- 30 $m^3$, which may be a future target according to GFClim scenarii

Since the overall proportion of rotten trees is about one third of the total designated trees, we parametrized the module accounting for this. The total designated volumes thus were uprisen to 30 and 45 $m^3$, to obtain the target volume at the first rotation, in average.

**_Cutting cycles_**  The cutting cycle duration is equally a key parameter in sustainable management. It varies widely in the Tropics depending on the continent, region, or even the country. In the Amazon, most of the cutting cycles are currently set to 40 approximately (XXX check exact values). French Guiana is somehow an exception, with cutting cycles fixed at 65 years for the moment. This exception is thought to be the minimum time that should elapse between two cutting operations, but this is often inadequate considering economic and development purposes. This situation may change in French Guiana someday, if logging is to be intensified in the region.

We tested two durations for a complete cutting cycle: 35 years, which is the duration that matches most current practices in neighboring countries (for example Brasil); and 65 years, the choice currently adopted by the ONF in French Guiana. To assess the alleged sustainability of such cutting cycles, we simulated logging operations, and stopped the simulations just before the sixth. This resulted in 175 years of simulation for the short cycle, and 325 years for the long one.

***Seed-rain scaling: personal choices*** Most of tree species rely on animal pollinators and dispersers to perpetuate their lineage. Selective logging has certainly adverse effects on these animals, be it directly (changes in forest structure, depletion of ecologically important trees) or indirectly (increased hunting pressure subsequently to road opening) [XXX REF]. The remaining reproductive adult trees are probably the major dispersers of seeds in logged plots. Since regeneration processes and timber species autecology remain mysterious, the way we model seed dispersion may have a wide range of impacts on the results obtained with logging simulations.

We think that the default value of the seed-rain scaling constant -used in TROLL to model external seed arrival- overestimates the actual regeneration potential in the case of logged forests. This default parameter (50000 seeds/ha/month) is convenient to simulate regeneration from bare soil of craft forests with predictible species frequencies, but is not adapted to simulate regeneration from already-established, disturbed, or logged forests, in which we assume a more enclosed demographic functioning.

Moreover, in our experiment, we assume that our simulated logged plots are surrounded by equally logged plots, that thus cannot supply a high number of seeds to neighboring areas. Thus, we believe that it would be safer to underestimate the seedrain than overestimate it. We set TROLL's seed-rain constant on an arbitrary 5% of its value (2500 seeds/ha/mmonth)

***Replication of the experiment*** The experiment is constrained by time and high computational costs. The present experiment design already yields a total of 48 factor combinations. We replicated each simulation 5 times with a distinct random seed, resulting in 240 simulations.

# Grouping effects to analyse the output

With a continuous screening of ecosystem variables by commercial group, and from the damage maps saved at each operation, we produced five different types of outputs.

- Overall damages in relation with the actual harvested volumes, to have an idea of the range of the disturbances we simulated and control for model consistency.
- Timber quantities over time and cutting cycles, to evaluate the sustainability of the practices we testes
- Volumes per merchantable species class, to assess the effects of diversification
- Fuelwood volumes, to estimate the quantities obtainable from colateral damages
- Overal abovegroune biomass, to assess the impact of selective logging on carbon stocks

All the analysis were performed using a 16 cores calculus cluster provided by EcoFog, and marginally, a 32 cores cluster also belonging to EcoFog. Analyses were led using R v3.4.X and rStudio v1.9.X, and many packages, including: tidyverse, ggplot2, ggplotly, Rstan, devtools, BBmisc,cowplot, gridExtra... etc XXX REF

# Results

## Model features
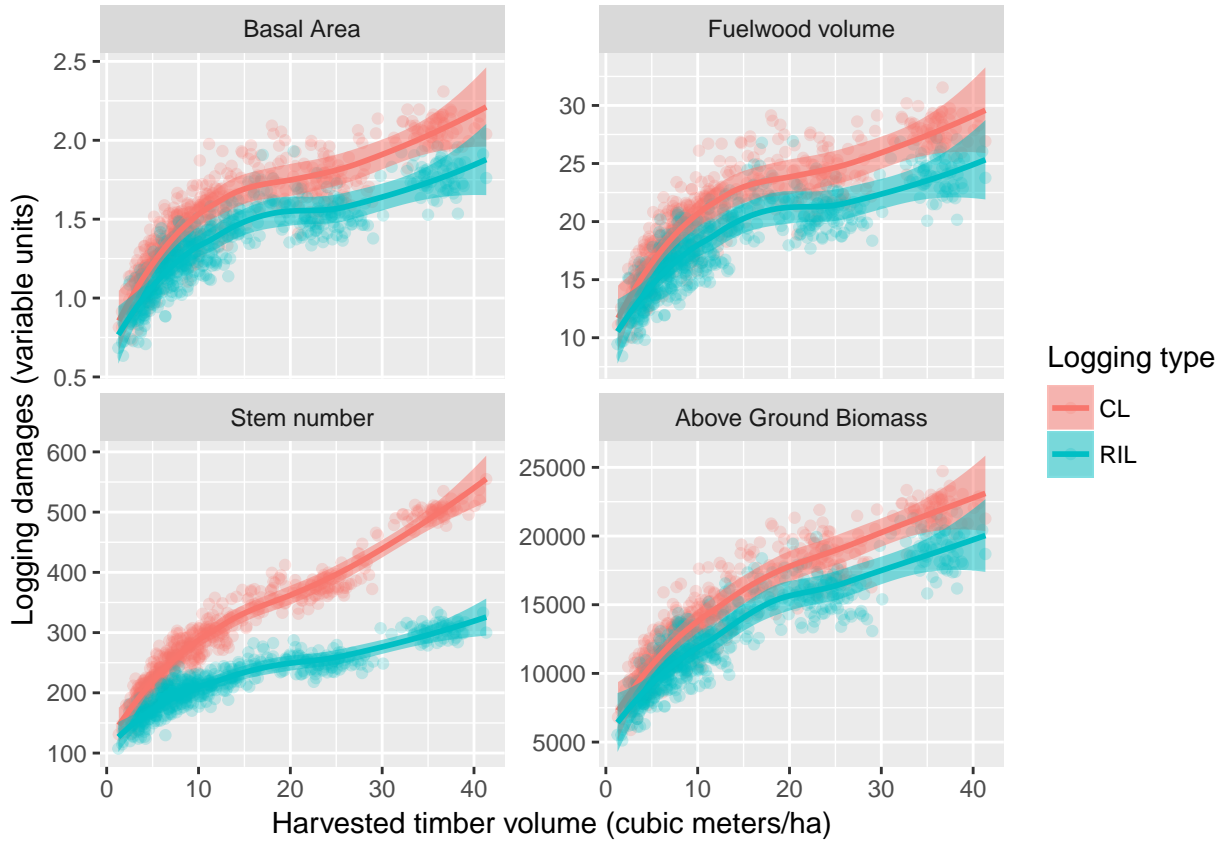


Figure 9: Summary of the logging damages caused by main and secondary tracks opening in our simulations (logged and rotten trees are excluded), plotted against the corresponding actual harvested timber volume: removed Basal area (mš), damaged stem count, removed Above Ground Biomass (kgC/ha), and Fuelwood volume (the volume of damaged trees over 20cm dbh). In the model, every damaged tree is at every cutting cycle. Points are all the observations for every scenario tested and all cutting cycles (1200 observations: 240 simulations - 2 forests, 2 target volumes, 2 cutting cycles, 3 designation modes, and 2 logging techniques; with 5 replicated each).

Unsurprisingly, conventional logging (CL) always caused significantly higher tracks damages than reduced impact logging (RIL), be it in terms of above-ground biomass, basal area or stem number (Figure 9). The most discriminant indicator, for the two logging techniques, is the number of damaged stems (over 1 cm dbh), which is equally unsurprinsing because it is an excellent proxy of the tracks area[4], that strongly differ between CL and RIL. For

---

[4]The maps shown in the precedent chapter are actually made with the coordinates of destroyed stems, for which the cause of the death is registered.

BA and AGB, the difference between CL and RIL is less pronounced. Each of the four variables is strongly related to the actual harvested timber volume. Including logged trees makes this relationship tightly linear, within the range of our harvested volumes, for BA and AGB (see suplementary material S XXX). Averaging the whole simulated dataset, we noticed that about one third of damaged trees died due to the main tracks, and another third due to secondary tracks. The differences observed between both logging types are more strongly related to secondary tracks, because the main track length only depends on the target volume, in our model. Additionally, the absence of replication of the experiment on several other initial forests, simulated with different random seeds, may be a source of biais in estimating main track damages for the first cutting cycles (after which regeneration occurr at random): it is traced at the same place on the map for every simulation,with only variations of length according to target volumes. Thus, differences between CL and RIL might be more marked if examined on a bigger set of simulations

## Selective logging sustainability

Conventional and reduced impact logging only had a marginal impact on wood quantity (not shown), probably due to high harvest intensities in our simulations. Thus, we pooled these simulations and decided to emphasize on cutting cycle, target volume, and initial forests.

All factors contribute to the available wood volume at the second harvest. However, this quantity is best explained by the initial timber stocks and the target volume than by the length of the cutting cycles. Regeneration of timber stocks between two harvests is not of the same order of magnitude than the harvest intensities that we applied our *in silico* forests. At the second cut, plots were left with no remaining timber stock in every case scenarii, which is something predicted by many authors (XXX) Short cutting cycles considerably accelerate the depletion of timber stocks, which may even be overestimated in the model's framework (see discussion XXX).

SImulated forest started from 48.5m3 or 74.3 m3 of harvestable timber. This initial difference did not have a significant effect on the final outcome, and only retarded the total ressource de ### Diversification

Diversification was simulated by making vary the equitability of interest ranks for merchantable species. Figure **??** shows the merchantable volume for ECMPs, which are the actual most valuable timbers.

## Fuelwood volumes

Is it better only to include figure on first rotation ? The average usable fuelwood quantities, over the two first cutting cycles, range mainly between 1 and 5 cubic meters per hectare from rotten trees, and between 2 and 4 $m^3/ha$ from main track damages. Secondary tracks are the
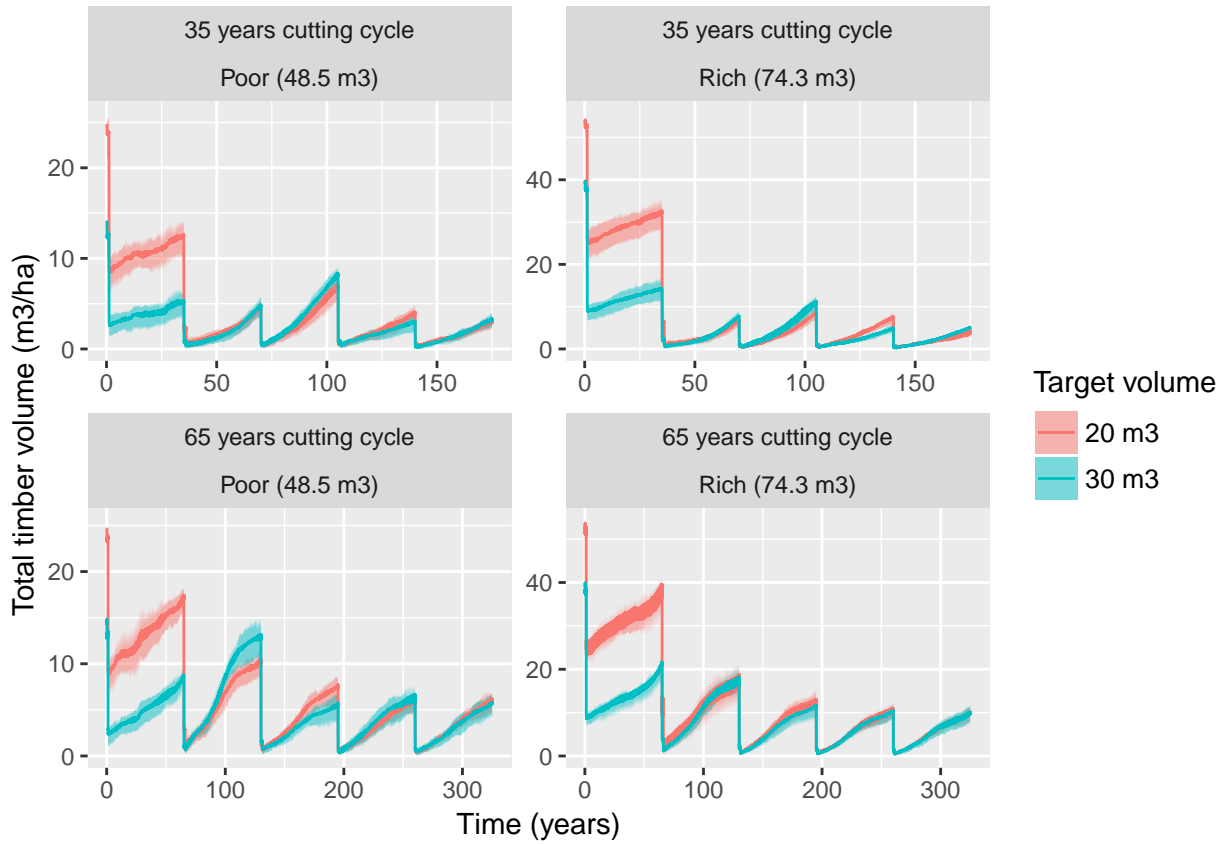
Figure 10: Simulated evolution of the timber stocks over 5 complete cutting cycles, for two contrasted (rich and poor) initial forests -in terms of initial timber stock, cf. the facets labels-, with cutting cycles of 35 and 65 years, and target volumes of 20 (red) and 30 (blue) cubic meters. Lines represent the mean trajectory of 30 simulatons each, and color bands, confidence intervals delimited by the 1st and 99th percentile computed for the 30 observations at each timestep.
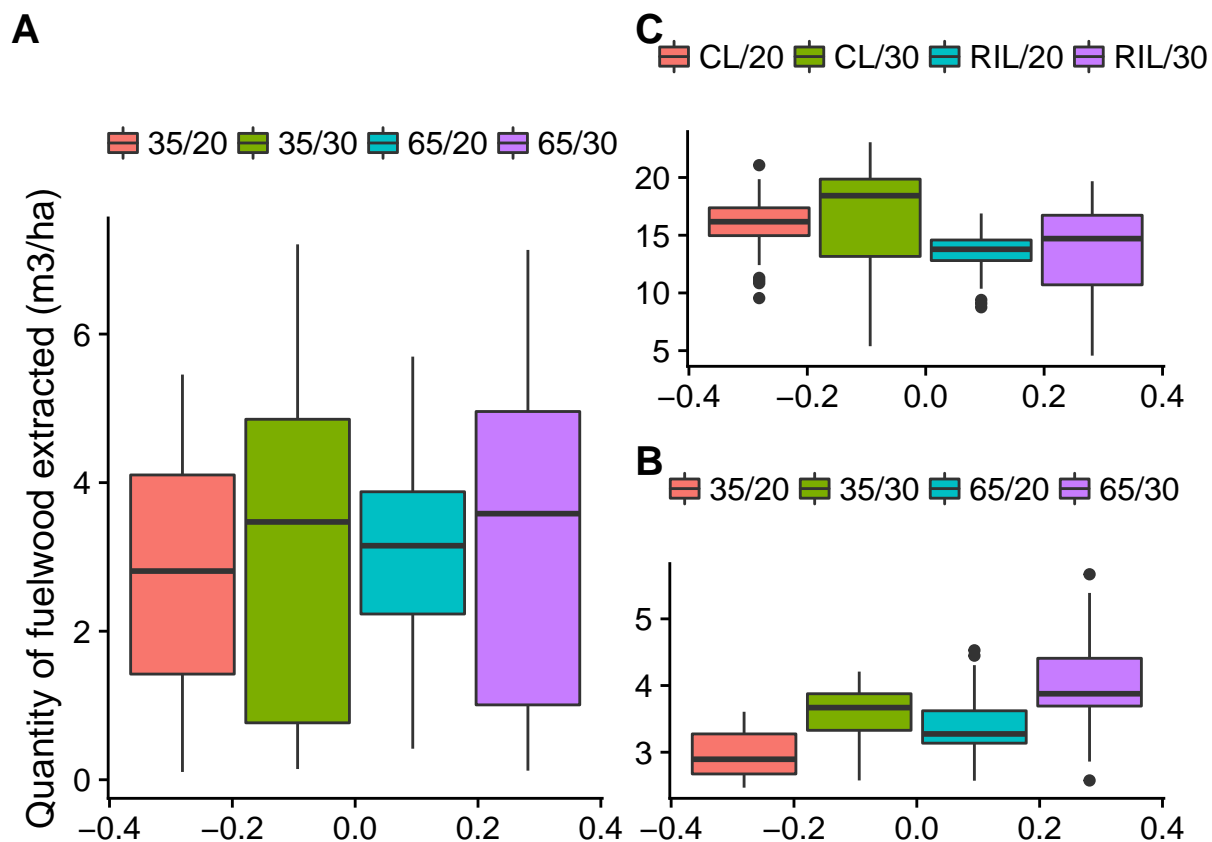
Figure 11: Estimated usable fuelwood volumes during the 2 firsts cutting cycles, originating from : A - Rotten trees, with a comparison between cutting cycle durations (35 or 65), and target volumes (20 or 30); B - Main tracks, with the same label correspondence as A; and C - Secondary track, with separation on logging techniques (CL or RIL) and target volumes (20 or 30); Black horizontal lines point the median of the distributions. Color boxes encompass values between the 1st and 3rd quartile. Black points are extreme values.

main potential source of extractible fuelwood over two cutting cycles, with quantities ranging from 10 to 20 $m^3$ in most cases. The target volume is the principal factor influencing this quantity for the main track, because its extent depends on it. The duration of the cutting cycle has an impact, yet marginal, due to longer regrowth period. Concerning secondary tracks, CL obviously yields more damages than RIL, thus a higher quantity of reusable wastes. No factor apparently influenced the fuelwood quantities from rotten trees over two harvests, because of the quantity of designated trees that vary between both cutting cycles, due to the lack of stock regeneration exposed above. In fact, for the first rotation only it depends directly on the target volume(XXX summplementary). These Theare influenced by both harvest intensities, logging techniques. (Figure @??fig:fuelwood2)) Pooling all cutting cycles, logging type and target volume did not have a significant effect on the harvested quantities of fuelwood. These factor are confused by the differences in timber volumes, thus in actually harvested volumes between the first cutting cycles, and the next ones, leading to reduced secondary track extent and number of rotten trees.

# Carbon
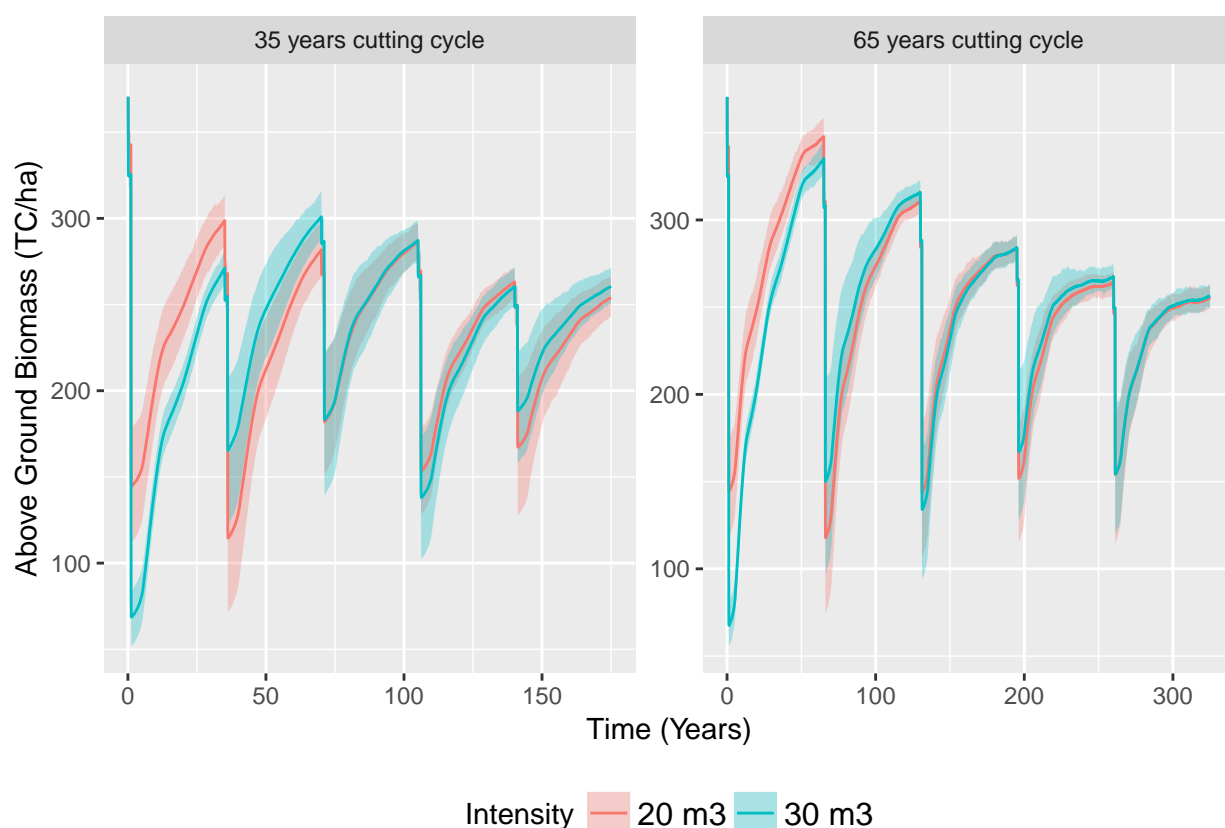


Logging only causes a neat decrease in AGB of about 10-15% for the first harvest in both cases (the detail might be hard to see en the graph), but post-logging mortality, applied one year post-harvest, causes considerable loss in AGG in any case. This effect is, in reality, not instantaneously causing a decrease in AGB but rather causing extra mortality for several

years, less visible because buffered by adjacent regrowth. The total above-ground biomass globally decreases over time and harvests (**??**. For both cutting cycle durations, the regain in AGB is significantly higher for plot logged at the lower intensity ($20m^3$). After the second cut, intensively harvested plots seem to regrow their AGB stock faster than less severly logged ones, once again for both cycles duration, yet this effect is of unlikely to be significant. Still, this would be explainable by a shift in community composition, accentuated by the second cut, from shade-tolerant, slow growing tree species to heliophilous, fast growing stands. From the third harvest onwards, the differences in harvest intensity is insufficient to change the ecosystem fate: both trajectories converge towards a value of 250 $TC/ha$ at the very end of a cutting cycle, *i.e.* around 30% less than the original *ca.* 350 $TC/ha$.

# Final discutiion

Our simulations indicate that selective logging may be unsustainable regarding many aspects. Current practices may allow neither to sustain overall timber stocks nor high value timber yields, nor fundamental ecosystemic services such as holding carbon stocks.

# CONCLUSIONS AND PERSPECTIVES

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***Résumé :*** Les forêts tropicales font face à de nombreuses perturbations qui représentent la troisième source mondiale démission de gaz à effet de serre. La déforestation et la dégradation des forêts tropicales sont responsables de lémission de 8.26 milliards de tonnes de dioxyde de carbone par an (Pearson et al. 2017). La déforestation a retenu lattention mondiale, mais la dégradation des forêts représente 20% des émissions de lAmazonie brésilienne (Asner et al. 2005). La gestion durable des forêts a été proposée comme réponse à la déforestation et la dégradation, malgré la remise en question de la durabilité de lexploitation forestière (Zimmerman & Kormos 2012). Dautre part, les forêts tropicales abritent plus de la moitié de la biodiversité terrestre mondiale (Scheffers et al. 2012). Par conséquent, nous avons décidé détudier le rôle de la biodiversité dans la réponse des écosystèmes forestiers aux perturbations, en reliant diversité et fonctionnement de lécosystème (Loreau 2010). Nous avons utilisé lhypothèse que lors dune perturbation, grâce à une productivité plus forte, une forêt plus diverse aura une meilleure résilience, en se basant sur la relation positive entre biodiversité et productivité. Nous avons relié cette hypothèse aux effets de complémentarité et de sélection (Loreau & Hector 2001b). La complémentarité est la combinaison de la partition des ressources et de la facilitation, alors que leffet de sélection est le résultat de la sélection compétitive. Nous avons ainsi centré létude sur les mécanismes impliqués dans la relation entre biodiversité et résilience des écosystème forestiers par une approche par simulation afin dappréhender les processus à long terme. Nous avons utilisé le modèle TROLL (Maréchaux & Chave) pour simuler 60 forêts matures aux diversités taxonomiques et fonctionnelles croissantes. Nous avons perturbé toutes les forêts et mesuré la résilience de leurs fonctions écosystémiques. En outre, nous avons mesuré la résilience de leffet net de la biodiversité que lon a décomposé en en effets de complémentarité et de sélection. Nous avons trouvé que la diversité améliore la résilience des forêts tropicales, particulièrement au travers de la diversité et léquitabilité fonctionnelle. De plus, nous avons montré que la complémentarité entre les espèces assurait la résilience de la forêt en début de succession avant de laisser place à leffet de sélection. Nos résultats suggèrent la possibilité dune gestion durable des forêts tropicales grâce à une meilleure résilience avec une plus haute diversité. Mais cette conclusion na de sens que si lexploitation sélective est durable (Zimmerman & Kormos 2012). Au contraire, une gestion non durable des forêts tropicales entraînera des rétroactions négatives diminuant lentement la diversité et donc la résilience des forêts, aboutissant ultimement à la dégradation des forêts.


***Mots clés :*** Résilience, Biodiveristé, Exploitation sélective, Fonctionnement de l'écosystème


***Abstract:*** Forest disturbances are the third worldwide source of greenhous gas. Tropical deforestation and degradation emit 8.26 billion of tons of carbon dioxyde per year (Pearson et al. 2017). Deforestation has retained much attention, but degradation from forest represents 20% of emissions in brazilian Amazon (Asner et al. 2005). Sustainable forest management has been promoted as an answer to deforestation and degradation, besides logging sustainability has been questionned (Zimmerman & Kormos 2012). On the other hand, tropical forest host over half of the Earths biodiversity (Scheffers et al. 2012). Consequently, we decided to study the role of biodiversity in forest ecosystem answer to disturbance, linking diversity to ecosystem functionning (Loreau 2010). We used the hypothesis that when a disturbance event happen, due to a higher productivity, a more diverse forest will be more resilient, based on the positive relationship between biodiversity and productivity. We linked that hypothesis to the complementarity and selection effects (Loreau & Hector 2001b). Complementarity is the addition of ressource partitionning and facilitation, whereas selection effect is the result of competitive selection. We thus focused on mechanisms involved in the relationship between biodiversity and forest ecosystem resilience with a simulation approach to assess long term processes. We used TROLL model (Maréchaux & Chave) to simulate 60 matures forests with growing taxonomic and functional diversities. We disturbed all forests and measured the resilience of their ecosystem functions. Additionnally, we measured biodiversity net effect resilience partitioned into complementarity and selection effects. We found that diversity improved tropical forest resilience, particularly through functional diversity and eveness. Moreover, we showed that complementarity between species insured forest recovery in the beginning of the succession before being replaced by selection effect. Our results suggest the possibility for a sustainable management of tropical forest due to an increased resilience with an higher diversity. But this conclusion has meaning only if selective logging meet sustainability (Zimmerman & Kormos 2012). On the contrary, unsustainable tropical forest management will lead to negative feedbacks slowly diminishing diversity and thus forest resilience, resulting ultimately in forest degradation.


***Keywords:*** Resilience, Biodiversity, Selective logging, Ecosystem functionning