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**Modeling the impacts of selective logging on tropical
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L'arbre est un organisme tellement
généreux qu'il offre son ombre à ceux
qui viennent l'abattre.

Francis Hallé

*Les opinions émises par les auteurs sont personnelles et n'engagent ni EcoFoG, ni le CNRS.
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RÉSUMÉ

Les forêts tropicales abritent la moitié de la biodiversité terrestre mondiale, fournissent d'importants services écosystémiques à l'humanité, et sont un important réservoir de carbone. Ces forêts font face à de nombreuses menaces, dont la déforestation à des fins agricoles, et l'exploitation forestière sélective. Cette dernière a affecté ou affectera la majorité des forêts tropicales, et a longtemps été une pratique incontrôlée [Nasi and Frost, 2009]. La Gestion Forestière Durable a été mise en avant pour tenter de résoudre ce problème, s'appuyant notamment sur les principes de l'Exploitation à Faible Impact [EFI, Putz et al., 2008] et des incitations financières, comme le programme REDD+. Cependant, certains auteurs ont remis en question la durabilité réelle d'une telle exploitation [Zimmerman and Kormos, 2012, Pearce et al., 2003]. Évaluer l'impact des pratiques forestières est une tâche difficile, au vu des échelles de temps impliquées. En complément des efforts de suivi, la modélisation peut s'avérer utile pour fournir un aperçu des effets de l'exploitation forestière à plus long terme. TROLL est un modèle spatialement explicite, individu-centré, qui simule un grand nombre d'espèces d'arbres. TROLL offre d'intéressantes perspectives en écologie théorique et appliquée [Maréchaux and Chave, 2017, Chave [1999]]. Nous avons exploré le potentiel de ce modèle pour simuler l'exploitation sélective, et explorer la durabilité de plusieurs scénarios. Nous avons commencé par paramétrer 547 espèces à partir de la base de données BRIDGE [Baraloto et al., 2010], pour simuler d'importantes étendues de forêt, et avons ensuite essayé de réaliser une évaluation et calibration des trajectoires post-coupe simulées, en partant de données réelles. La calibration fut impossible à cause d'une mortalité exagérée dans les forêts d'entrées, pendant les premières années de simulation. Nos analyses suggèrent que TROLL a une structure spatiale différente de celle de vraies forêts, peut être à cause d'une sur-estimation de la compétition pour la lumière, le rendant inadapté à simuler à partir de vraies données pour le moment. Nous avons adapté la version existante du module simulant l'exploitation dans TROLL, pour implémenter plusieurs pratiques et paramètres sylvicoles. Nous avons réalisé un premier jeu de simulations sur deux forêts ayant des volumes de départ contrastés, durant 5 rotations. Nos résultats indiquent que l'exploitation sélective, telle qu'elle est pratiquée en Guyane Française, pourrait mener à un épuisement des volumes totaux d'espèces commerciales, ainsi qu'à une baisse du stock de carbone au fil des récoltes, et cela même pour des rotations de 65 ans, avec des intensités de $20m^3$ et les techniques de l'EFI. Ces résultats sont cependant préliminaires et manquent de réplication, ils doivent donc être interprétés avec précaution. Des analyses plus poussées sur des scénarios plus nombreux sont requises afin de confirmer et affiner nos résultats. TROLL, combiné avec le modèle d'exploitation que nous avons mis à jour, présente un potentiel prometteur pour explorer différents scénarios sylvicoles, et répondre à des problématiques appliquées.

ABSTRACT

Tropical forests shelter half the terrestrial biodiversity worldwide, provide important services to humanity and are a major reservoir of carbon. These forests face numerous threats, among others deforestation for agriculture and selective logging. Selective logging affected or will affect the majority of tropical forest outside protected areas, and has long been an uncontrolled predatory practice [Nasi and Frost, 2009]. Sustainable Forest Management (SFM) has been promoted to answer this issue, relying on Reduced Impact Logging [RIL, Putz et al., 2008], and financial incentives such as REDD+. However, some authors asked whether these techniques are sustainable [Zimmerman and Kormos, 2012, Pearce et al., 2003]. Assessing the sustainability of Forest Management is a difficult task, because of the efforts needed by field studies, and time scales involved. To complement monitoring efforts, the use of models can provide valuable insights of longer-term effects of selective logging. TROLL is an individual-tree-based, spatially explicit forest model that uses functional traits to simulate the life cycle of a wide range of tree species. TROLL offers promising perspectives in studying ecological theories and applied problems [Maréchaux and Chave, 2017, Chave [1999]]. We explored the potential of this model to simulate selective logging and assess the sustainability of different scenarios. We preliminarily parametrized 547 species from the BRIDGE dataset [Baraloto et al., 2010] to simulate large forest plots, and we attempted to evaluate and calibrate the simulated post-logging trajectories inputting real forest censuses in the model. The calibration was impossible because of exaggerated mortality in the inputted forests during the first years of simulation. Spatial structure analysis suggests that TROLL has a different spatial structure than real forests, maybe due to overestimation of competition for light, thus making unadapted the use of real data inputs for now. We adapted the existing version of the module that simulates selective logging in TROLL, to implement cutting cycles, conventional logging, and designation based on timber interest ranks. We did a preliminary set of simulations on two forests that had contrasted timber volumes, to assess the importance of silviculture parameters over five cutting cycles. Our results indicate that selective logging, as applied in French Guiana and neighboring countries, may lead to a depletion of total timber stocks and high-grade species, along with a decrease of carbon stocks over harvests, even for 65 years cutting cycles with $20m^3$ harvested and RIL techniques. However, our results are preliminary, lack replication, and thus have to be interpreted carefully. Further, extensive analyses are needed to confirm and refine our findings. TROLL, combined with the logging model we updated, has a promising potential to explore a wide range of silviculture scenarios, and address applied problematics.

INTRODUCTION

Tropical forests shelter over half the terrestrial species present on Earth and provide numerous goods and services, many of which have essential 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 [Houghton et al., 2012]. Recently, Pearson et al. [2017] estimated a yearly total of 8.29 Pg carbon loss from deforestation and forest degradation worldwide. Although 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 [Herold et al., 2011]. Selective logging is the targetted harvest of a reduced number of individuals, belonging to high value timber species. Selective logging is an important cause of forest disturbance. It affected or will affect the majority of tropical forest outside protected areas [Putz et al., 2012]. 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 (regarding the area) at which these forests are selectively logged approaches 20 times those of deforestation. It is especially 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 severely 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 [Kalamandeen et al., 2018]. In the Brazilian Amazon, selective logging impacted *ca.* 2 Mha.y¹ between 1999 and 2002 [Asner et al., 2005], raising resulting in emissions of about 90 TgC.y¹, *i.e.* 15-19% higher than reported from deforestation alone over the same period [Huang and Asner, 2010].

Selective logging has long rimed with irresponsible cutting [Zimmerman and Kormos, 2012], and poorly regulated harvesting. Governmental and global policies, more than two decades ago, engaged in a collective endeavor to limit this trend with the introduction of Sustainable Forest Management [SFM; United Nations, 1992]. Later on, projects 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. In parallel, aset of techniques and planning guidelines were introduced to mitigate the adverse effects of conventional selective logging, under the name “Reduced impact logging” (RIL). RIL is increasingly implemented and promoted as a cornerstone to achieving both ecologically and economically viable forest management [Putz et al., 2008]. It is somehow seen as a reasonable compromise between clearcutting and outright protection [Putz et al., 2012]. Some authors argue in favor of RIL’s potential to sustain essential ecosystemic and services, such as the ecosystem’s conservation value, above-ground biomass, and timber yields [Putz et al., 2012]. Conversely, Others insist on the apparent non-sustainability of current practices, and affirm that they

are only leading to depletion of timber volumes, carbon stocks, and biological diversity, due to mismatches between minimum economic viability, and subtle ecosystem functioning - on timescales far beyond ours [see [Nasi and Frost, 2009](#), and [Zimmerman and Kormos \[2012\]](#)].

There is no available dataset for more than two cutting cycles. We have insights that resource use-up is ensured at the second or third cutting cycle [[Zimmerman and Kormos, 2012](#); but see [Putz et al., 2012](#)]. Data on forest biomass recovery has also intensively been studied, yielding contrasted conclusions worldwide. Likely, carbon stock 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 (and mature forest trees) are long-lived, shade-tolerant species, rely on complex pollination and dispersal strategies to maintain viable population sizes, and occur low concentration of individuals per spatial unit. They are, in many cases, outcompeted by pioneers, light-responsive species, which contribute carbon stocks transiently and may slow others regeneration [[Nasi and Frost, 2009](#)].

These observations are for short time-scales. To 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. Most simulation studies on selective logging focused on carbon [[Piponiot et al., 2016](#), [Rutishauser et al., 2015](#), [Huang et al., 2008](#)] with more or less large-scale approaches. Up to now, relatively few simulation studies addressed the sustainability of selective logging at the plots' scale, especially for long timescales. [Sist and Ferreira \[2007\]](#) and [Dauber et al. \[2005\]](#) simulated growth and mortality of remaining stands on logged plots, in the Eastern and Western Amazon, respectively. In the Paragominas (Brasil), [Valle et al. \[2007\]](#) used individual-based models to assess timber yields over cutting cycles, but used only 10 species groups, which is somehow restrictive [see [Marechaux, 2017](#)] [Huth and Ditzer \[2001\]](#), did a relatively complete assessment of cutting cycle durations and target volumes on Malaysian dipterocarp forests, further discussed in [Huth and Köhler \[2003\]](#), but again using only 10 species groups to model hyper-diverse forests. [Gourlet-Fleury et al. \[2005\]](#) also used an individual-based model to simulate timber stocks recovery for *Dicorynia guianensis*, the principal harvested species in French Guiana [[Guitet et al., 2011](#)]. There is a need for models either enabling simulation of selective logging for large time scales (over centuries) and integrating fine-scale processes and species diversity. Individual-based and spatial-explicit models are thus offering a perspective to address this need.

TROLL is an individual-based forest simulator that jointly simulates species diversity and carbon dynamics [[Maréchaux and Chave, 2017](#)], over time scales ranging from years to centuries. It explicitly accounts for the influence of species-specific functional traits and competition for light on individuals life cycle (growth, mortality, recruitment, reproduction). We used TROLL to bring a first contribution to the assessment of selective logging sustainability in French Guiana.

Our aims were: * to get as close as possible to the actual logged forests in terms of diversity; * to model selective logging realistically, given field reality and the model limits; * to preliminary explore of possible scenarios for the wood industry in French Guiana; * to make

a generic tool that allows testing more scenarios.

To match these goals, we followed four steps. We first inferred a new species input dataset to simulate more species in French Guianese forests. We then attempted a validation and calibration of post-logging recovery with TROLL, using real censuses from logged and undisturbed plots of the Paracou disturbance experiment. Subsequently, we updated the existing selective logging module to include features such as multiple cutting cycles, conventional logging, designation with species interest ranking, and continuous monitoring of merchantable trees. Finally, we did a pilot-experiment, simulating two cutting cycles, two target volumes, three diversification scenarios, RIL and CL, on two primary forests with contrasted initial timber stocks.

TROLL MODEL

Overview

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 [Pacala et al., 1996, Uriarte et al., 2009] and FORMIND [Fischer et al., 2016]. 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 tridi-mensional (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 1).

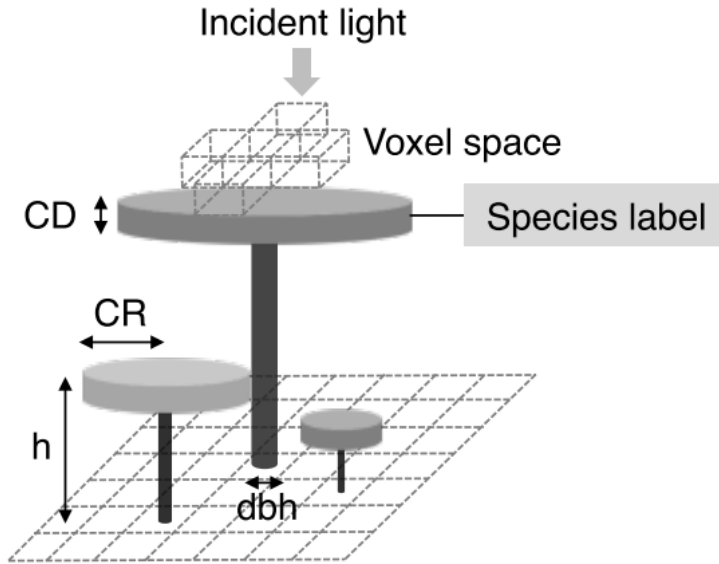


Figure 1: Individuals tree inside TROLL explicit spatial grid from @Marechaux2017a. Tree geometry (crown radius CR , crown depth CD , height h , diameter at breast height dbh) is updated at each timestep (1 months) using allometric relationship with assimilated carbon allocated to growth. Each tree inherits a species label linking to its species-specific attributes. Light is computed explicitly at each timestep for each voxel, and trees are asymmetrically shading each-other.

The firsts encompass tree age, diameter at breast 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 Maréchaux and Chave [2017]. 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 breast height threshold	m
h_{lim}	asymptotic height	m
a_h	parameter of the tree-height-dbh allometry	μ

Tree geometry is derived from its diameter according to allometric relations, 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, 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.

INCLUDING MORE SPECIES IN TROLL SIMULATIONS

Introduction

Biodiversity affects most of the ecosystemic characteristics, among others productivity, stability, resistance to invasion [Lyons and Schwartz, 2001, Huston et al., 2001]. Recent advances in Functional Ecology suggest that the most relevant approach to study ecosystem functioning is through 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 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 [Maréchaux and Chave, 2017]. TROLL directly uses 5 functional traits (*LMA*, *Nmass*, *Pmass*, and *wsg*) and 2 allometric parameters at the species-specific level. All are obtained from real data.

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 the 99th quantiles of species diameter 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. The model blueprints were generously provided by Fabian Fischer (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 the regional frequency of a species, which are adapted for each simulation depending on the forest composition and simulation aims.

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). Based on preliminary exploration of the Paracou dataset, we noticed that the proportion of individuals belonging to missing species is slightly reducing over time, possibly linked with an increase in botanical determination reliability. This proportion is rather low compared to the proportions of missing species. However, such proportions were questioning the *a priori* validity of our intent to simulate real forest plots. These species are mainly less common ones and may be absent either because they were not present in the plots sampled in BRIDGE or because their number of observations did not allow including them.

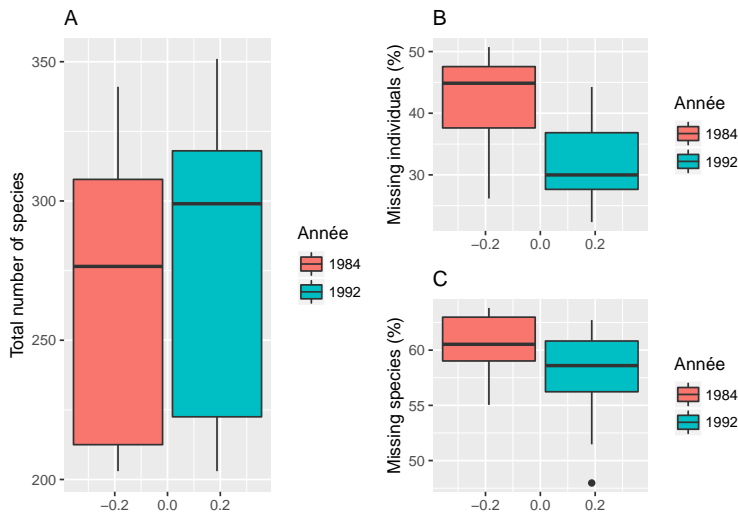
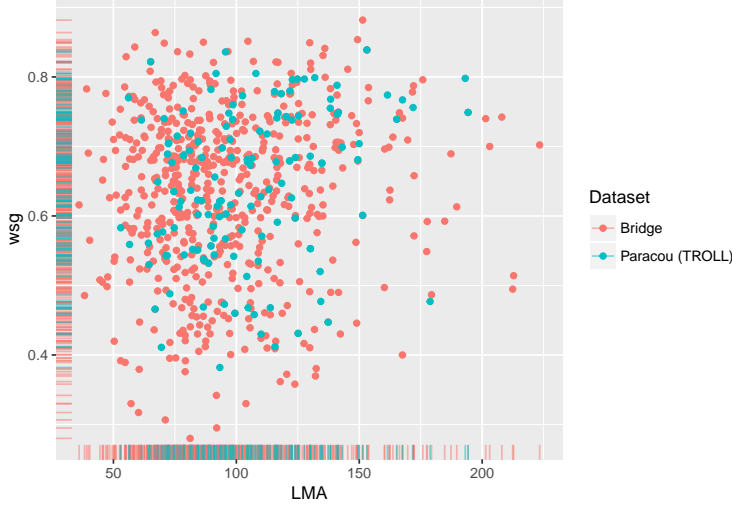


Figure 2: Total number of species, proportions of missing species and individuals in two censuses (1984,1992) for twelve Paracou Plots (1-12). A: Total number of species in the plots, at the plot scale; B: Proportion of individuals belonging to missing species; C: Proportion of missing species; All are computed at the plot scale. Colors represent the census years (red: 1984, blue: 1992)

Missing species and individuals

Functional representativity Figure ?? compares the distribution of LMA and wsg for BRIDGE and species from TROLL's list that occur in Paracou. These traits are linked to construction costs for the trees and are part of the leaf and wood economics spectra [Wright et al., 2004, Chave et al., 2009]. According to Baraloto et al. [2010], both spectra are decoupled and represent two components of the plants' strategy. In TROLL, LMA is linked to leaf lifespan, photosynthesis In Figure ??, the fraction of TROLL species list that matches with Paracou (137 species) is rather representative of the bridge dataset (which we assume

to be itself well representative of the real forests' functional traits ranges). However, each plot had from 70 to 115 species matching with those of TROLL, out of 300 species present. As explained above, not only the number of species matching those of TROLL was low, but also, the corresponding number of individuals was problematic. We thus decided to perform a new trait means inference to reach a better representativity, and to simulate Paracou plots.



How to parametrise more species ?

Datasets

We used the BRIDGE trait database [Baraloto et al., 2010, 2012] which was further completed by Marechaux [2017], to infer leaf, stem and allometric parameters. We used both BRIDGE and Guyafor datasets to estimate d_{max} , as the 99th percentile of species diameters. 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 Guianese 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 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 (see `tab:traits`).

Table 2: Summary table of the trait data obtained from the BRIDGE database. The two last rows “Total” and “LMA, N, wsg” are the complete observation for all traits and with P excluded, respectively.

Trait	Unit	N (complete)	Missing data	Species
LMA	g.cm^2	4460	265	642
Nmass	mg.g^{-1}	2928	1797	537
Pmass	mg.g^{-1}	931	3794	270
wsg	g.cm^{-3}	2875	1850	630
Height	m	4399	326	645
dbh	m	4597	128	663
Total	-	651	-	251
LMA, N, wsg	-	1726	-	505

The dataset we used contains significant amounts of missing data, as the majority of functional trait databases [Taugourdeau et al., 2014]. Still, we can infer a high number of species means for LMA, Nmass, wsg and height-diameter allometries. For Pmass, however, very few observations are available compared to other variables. It is by far the most limiting variable. Indeed, out of the 270 species, the overwhelming majority of them are singletons (see Figure 12 in the second Appendix section). Maréchaux and Chave [2017] have further completed this dataset, probably with TRY database [Kattge et al., 2011] to achieve parametrization for 163 species in TROLL.

Preliminary completion with Predictive mean matching

We used a Predictive Mean Matching algorithm (described in the third Appendix), implemented in the R-package mice [van Buuren and Groothuis-Oudshoorn, 2011]. We used the default $k = 5$ (the number of matched cases per iteration) proposed in the mice package and repeated the imputations ten times, then pooled the datasets and averaged the obtained proposals for missing values. To improve predictive power based on inter-trait correlation, we included additional variables that were correlated with our target variables, and selected with an automatic, stepwise linear model comparison procedure: leaf toughness, leaf thickness, SPAD (a proxy of chlorophyll content), and leaf carbon content. Palms were excluded from the analysis beforehand since there are not currently modeled with TROLL. Individuals belonging to indeterminate genera and species were discarded (except those present in Paracou, for example, *Symphonia sp.1*), as well as individuals with only one trait measured or high taxonomic uncertainty. Moreover, we clustered the observations 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. This separation aimed at reducing the errors due to using overall relationships to infer values.

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. Pmass have more inferred values than actual measures in this completed dataset.

Hierarchical modeling framework

We used a simple but efficient modeling framework, which was 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 homogenous 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 for 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 confirmed 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:

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

Where, for individuals belonging to species s , and a given trait (or log-transformed trait) X , the X attribute of these individual follows a *Gaussian* probability distribution, of parameters μ_{sp} , a species-level trait mean, and σ_{intra} , the intraspecific variance (here assumed to be homogen among species). Moreover:

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

The species mean μ_{sp} itself is normally distributed, depending on an overall mean μ_{tot} and an overall variance σ .

Michaelis-Menten hierarchical model

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

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

Originally, the model provided by Fabian has the form:

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

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 σ . \hat{h}_i is computed with:

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

Where $h_{max_{sp_i}}$ is the asymptotic height of species i , and β_{sp_i} , a shape parameter of the model. Both are define by:

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

Equation (7) can be rewritten to the classical Michaelis-Menten form:

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

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

More species for TROLL

We obtained a new set of 599 species means for Nmass, Pmass, wsg and LMA using the inference procedure. Allometric parameters and $dmax$ limited the final dataset for TROLL to 547 species. 347 of those species matched with Paracou species. Figure 3 shows that the new species set has a better coverage of wsg and LMA distributions. The histograms for each trait are available in the second Appendix sections. Overall, the inferred species set allowed to better represent trait distributions in TROLL, and enhanced the coverage for Paracou.

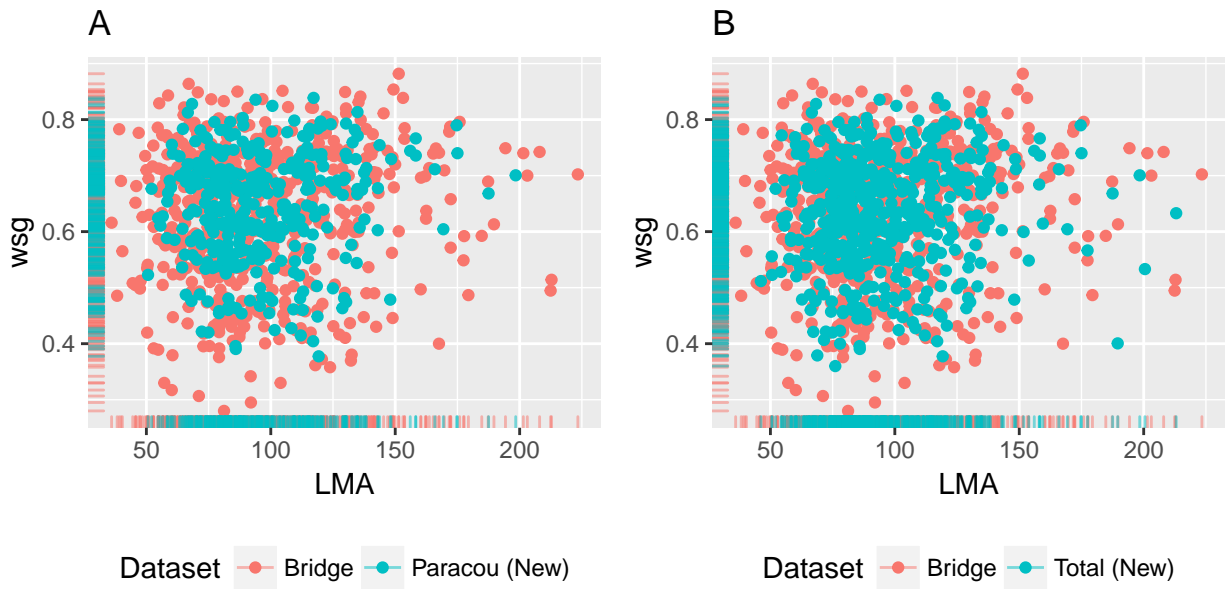


Figure 3: Joint representation of LMA and wsg distributions for A: the 347 new species set for Paracou, B: the 547 species set used for the selective logging experiment; Compared to the distribution of the same traits in the total BRIDGE dataset. Colors indicate whether points belong to bridge (red) or to the inferred species set (blue). Marginal rugs help to visualise each trait distribution, and highlight the coverage of their distribution in BRIDGE (red) by the new species set (blue).

Discussion

In the hierarchical models used here, species means are derived from the general trait mean. They thus depend on both the number of observations for each species and the observed

trait values. These models allow to account for uncertainties due to scarce observations: The inferred mean of a species with few data but extreme trait values is attracted towards the overall mean, because of high uncertainty due to a low number of observations. 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 idea that using only one measure for a species is barely more informative than attributing it the community means, due to sampling stochasticity. Considering the number of rare species in tropical plant trait databases such as BRIDGE, and given that each of them contributes to the overall mean, it is arguably to include them instead of setting an arbitrary cutoff: why would a species mean computed with five observations more reliable than one computed with four 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 an advantageous phenomenon or a problem [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. A solution to reduce this bias would be to account for the inferred distributions of every means: we only used punctual estimations, and thus ignored a part of the information. This can be enhanced for subsequent works thanks to a new feature of TROLL, recently implemented by Fabian Fischer: a species parametrization simulating intraspecific trait variability constrained by between-trait covariance. This allows to recreate continuums such as those observed in real forests, by conserving at least the overall links between every trait. Fyllas et al. [2014], for example, used this approach. We could not adapt our study to this feature, for it was released a few months ago.

CAN TROLL SIMULATE REAL FORESTS AND POST-LOGGING TRAJECTORIES ?

Overview

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 that TROLL underestimates seedling *abundances*, due to discrete space assumptions (data not shown). It however reliably depicts diameter structure for higher *dbh* categories (Marechaux [2017]). We compared simulated ecosystem trajectories with regular censuses ($> 10\text{ cm dbh}$), after adapting the data to the model input format and simulating the understorey strata. 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 high proportions of individuals belonging to missing species. The number of species matching at a plot’s scale was enhanced with the new dataset, but still low (100 to 220), compared to the 200-350 species that can occur in a single plot (4). The representativities of these subsets was overall correct (data not shown). To handle species that were still missing, we replaced the individuals belonging to missing species by individuals of parametrized species, by diameter class.

Residual mortality after logging: where to start from ?

Residual mortality after selective logging is a well-observed phenomenon, which has been documented for seven sites in the Amazon [five in Brazil, one in Suriname, and Paracou - see Blanc et al., 2009, for a summary table and references]. During six to sixteen years after disturbance, logged stands undergo 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, especially when poison girdling is carried out.

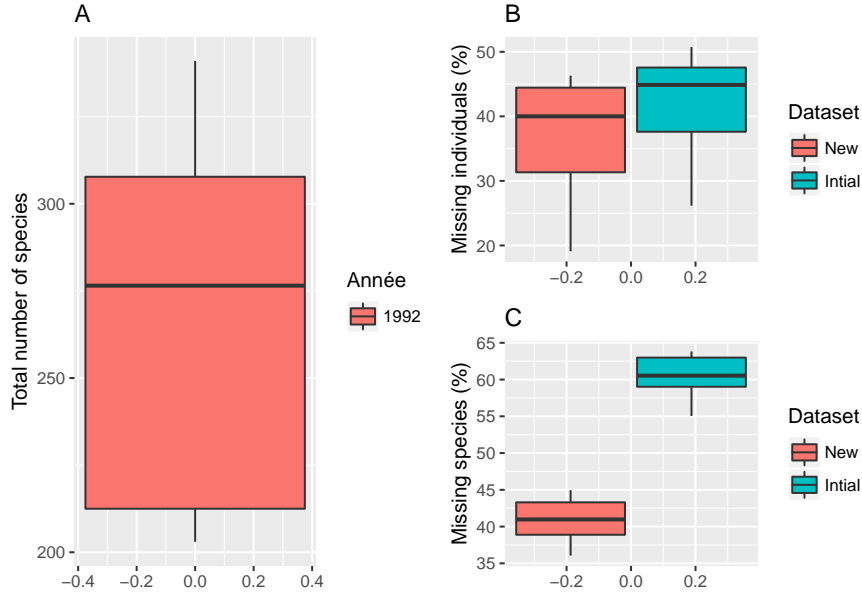


Figure 4: Comparison of the coverage (species and individuals) between the initial and new dataset. A: Total number of species in the plots. B: Proportion of missing (uncovered) individuals. C: Proportion of missing species. Colors indicate the dataset used: blue for the initial set, red for the new one.

- Soil modifications (compaction, degradation, and ultimately erosion) can also stress the trees located near the main or secondary tracks.
- Changes in the 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 at Paracou. 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 15 in appendix 5, and see [Blanc et al. \[2009\]](#)), although there is no neat transition. Still, for treatments 1 to 3, the mortality levels six years after logging are reasonable compared to rates observed in the first three 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 sampled, nearby free cell with an algorithm (details available on demand). Both introduce some bias, as it consists of 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 simulation from Paracou censuses, without any tree under 10 cm dbh initially present, is highly erroneous. The regeneration of the understorey strata from scratch would induce 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:

- 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 light, so the upper-stratae spatial structure impact the lower-stratae.
- Even if logging damages 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 finally a spatial mixture of “mature state” and “early stage” understoreys.

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, we simulated an understorey from the 1992 censuses for 5 years, to obtain a young understorey that has undergone high enlightenment in opened areas
- For control plots, a single understorey was simulated for 30 years and reinjected in the census.

We used damaged areas shapefiles obtained from <https://paracoumaps.cirad.fr>.

Simulation parameters

The simulation parameters were all TROLL default parameters (calibrated in [Marechaux \[2017\]](#), adapted for the new version by Fabian Fischer (*pers. comm.*), except the seedrain scaling constant and the mortality rate parameters.

We initially 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.

Mortality 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 [[Marechaux, 2017](#)].

Spatial statistical analyses were performed using the *ads* R-package [[Pelissier, 2015](#)]. We compared the spatial structure of TROLL and Paracou forests using classical spatial indices, based upon Ripley’s K function [[Ripley, 1977](#)]: $L(r)$, a linearization of Ripley’s K [[Besag, 1977](#)]; and $g(r)$, the pair density function;. The first (L) is linked to the expected number of neighbours present in a circle of radii r and centered on each point of the map. The second (g) is linked to the mean number of neighbours present between two consecutive circles at a distance r and $r+dr$, for all the points in the map.

Results and discussion

Simulated trajectories

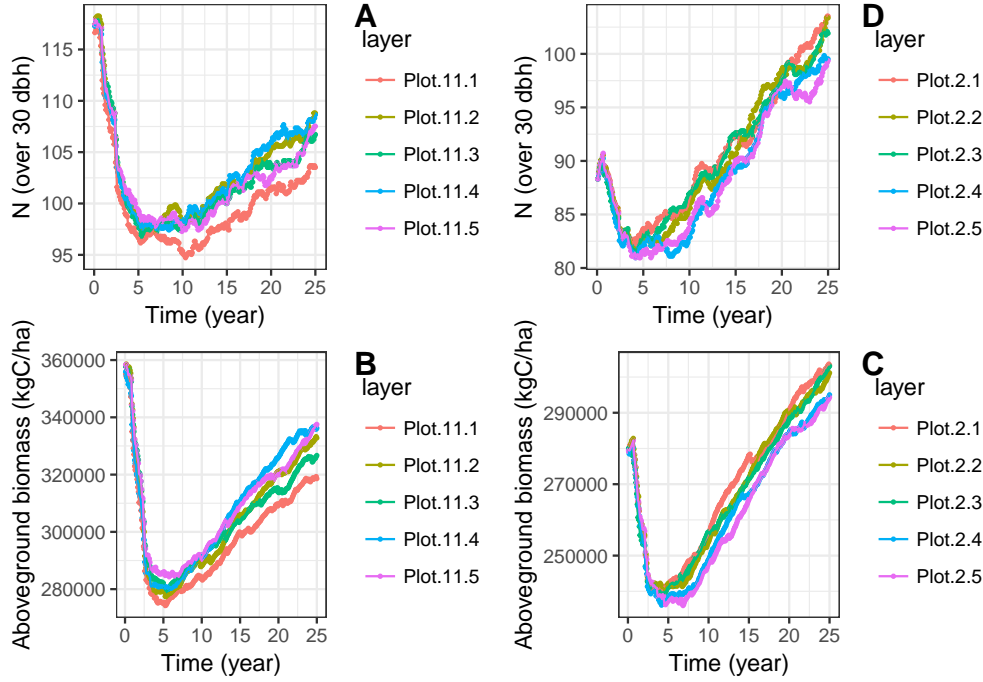


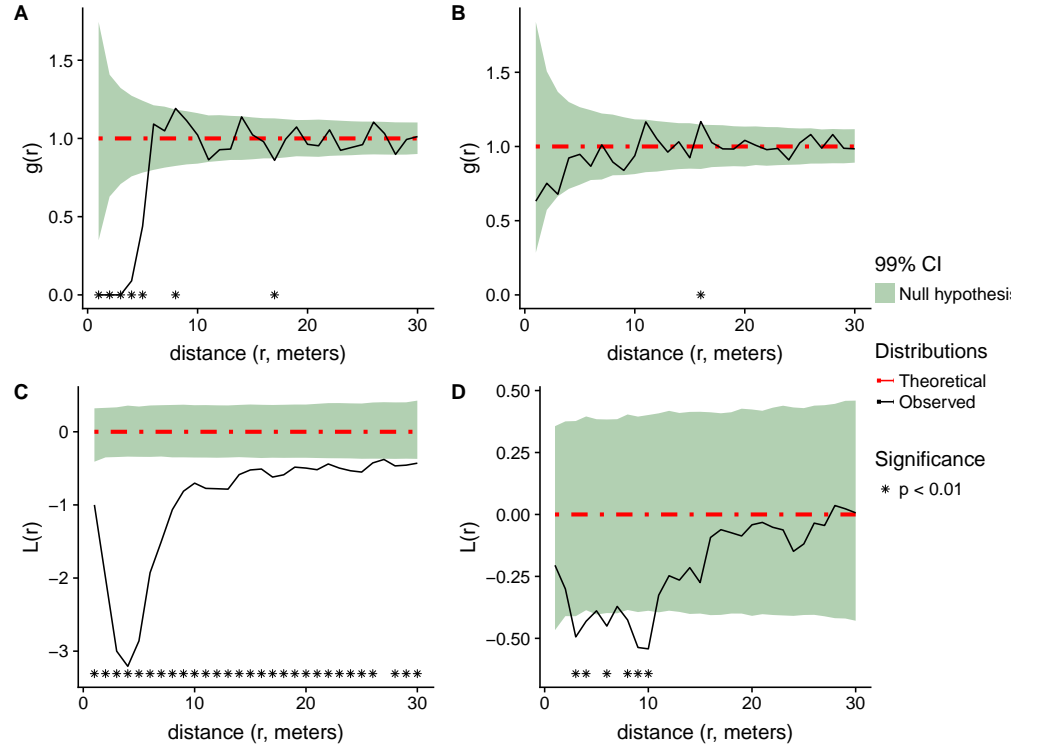
Figure 5: Trajectories obtained with TROLL, using real data as an input. A and B are outputs obtained with the plot number 11 (undisturbed). D and C are the results obtained with plot 2 (selectively logged). A and D show tree density per hectare for individuals above 30 cm dbh over time. B and D display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

Figure 5 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 ($dbh > 30, N_{30}, ha^{-1}$). 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 surprising 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 approach, wich results are presented hereafter.

Spatial statistics

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 undis-

turbed (Figures and 6). This pattern holds for every plot (not shown). 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 well-known autocorrelation inherent to $L(r)$. The $g(r)$ function curves bring more reasonable results, yet still showing an strong significant 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 losing discrimination power. These results show that TROLL severely overdisperses trees over 30 cm dbh compared to real forests at relatively small scale (radius < 5m).



\begin{figure}

\caption{Spatial structure of simulated (A and C) and real (B 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 of $L(r)$, 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}

\end{figure}

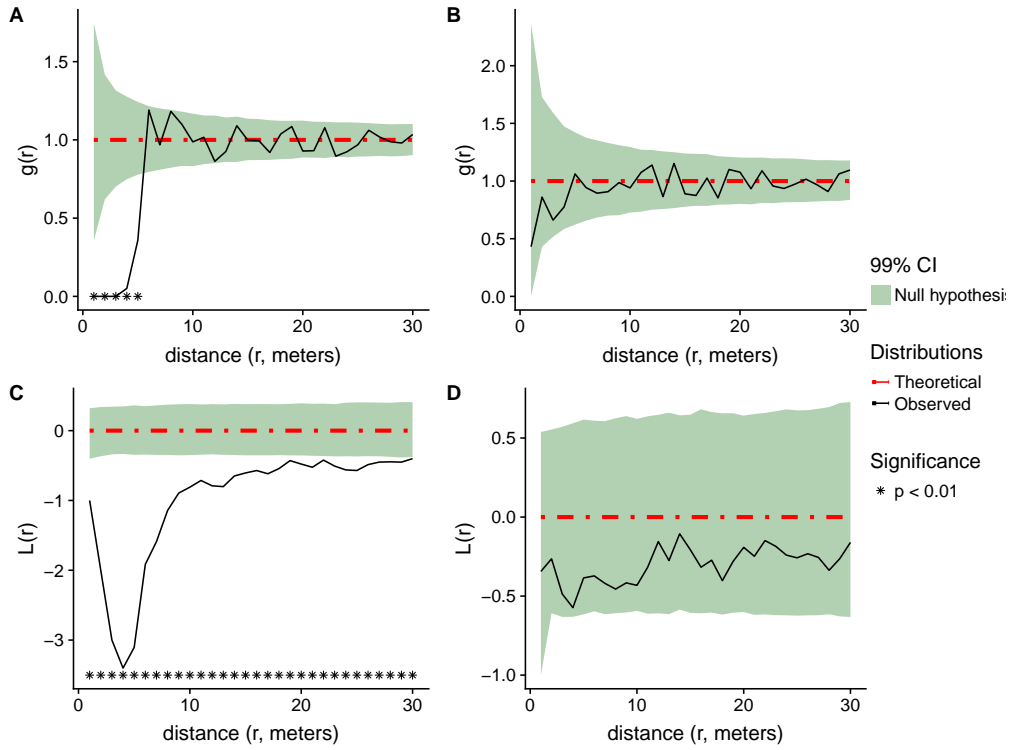


Figure 6: Spatial structure of simulated (A and B) and real (C and D) forests for Paracou plot P1 (logged). These graphics correspond rigourously to the figure, please refer to its label for description and interpretation tips.

Synthesis

There are several possible reasons to the results of the simulations from real data. First, it might be an inaccurate parametrization of the model, but [Maréchaux and Chave \[2017\]](#) 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, this 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 with 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 to disentangle the effects of light competition and discretisation (cells of 1mš) on TROLL’s spatialisation. 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 assumption of a discrete space, with maximum 1 tree per cell, while Paracou plots are mapped with a 0.5m resolution. 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.

Competition for light is the principal resource-limiting process modelled in TROLL, which reproduces realistic forests in terms of global variables and floristic composition [see [Marechaux, 2017](#)]. 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 ([Marechaux \[2017\]](#)), 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 information [mostly in [Guitet et al., 2011](#)] and numerous communications with Laurent Descroix, head of the RD pole of the National Forests 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. 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 [[Guitet et al., 2011](#)]. Currently, Silviculture 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.

Selective logging is currently divided into three fundamental parts: Tree choice, Harvesting. 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” practices * The way we model the process in TROLL

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

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. 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 at least comparable concerning human and mechanical safety.

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 ($400 \times 600 \text{ m}^2$), thus making a compromise between simulating realistically big plots, and computational costs.

Designation

Reality Designation was implemented with RIL by the ONF in 2007 [Guitet et al., 2011]. It consists in mapping trees and tag trees to be harvested for the current harvest, future trees to keep for the next harvest, and “reserve” trees (ecologically important, or threatened species). The designation is made in order to meet the target volume, and the preference of the loggers: the ONF does not designate trees that will not be sold. 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. In CL, there were no designation. The loggers used to choose the trees, and generally focused on a few species, and big individuals.

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, and this is a huge theoretical field of statistics and mathematics [Kaci, 2011]. 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 or contextual factors.

To model designation oriented by the preferences of loggers for some timber species, we split 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 individuals 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 ¹ if the two others are really unsufficiently abundant.

In the model, the relationships between these categories are fixed. To simulate harvesting 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. 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.

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. If the fuelwood demand is expanding during the next years,

¹In 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.

harvesting rotten trees may be advantageous. Conversely, these trees may better be let on the plot, because they can survive and keep producing seeds.

Model We used [Schmitt \[2017\]](#)’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 :

$$\begin{aligned} \text{probbed rotten} &\sim \mathcal{B}(P(\text{probbed rotten})) \\ P(\text{probbed rotten}) &= \text{logit}^{-1}(\beta_0 + \beta_1 * dbh) = \frac{e^{\beta_0 + \beta_1 * dbh}}{1 + e^{\beta_0 + \beta_1 * dbh}} \end{aligned} \quad (8)$$

The probability for a tree to be *probbed rotten*, noted $P(\text{probbed rotten})$, follows a *Bernoulli* probability law. The odds for a tree to be probbed as rotten is the sum of a basal odd β_0 , and a diameter dependent odd proportional to β_1 . The probability for a tree to be probbed as rotten $P(\text{probbed rotten})$ 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, given by:

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

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. Oriented treefall aims at orienting logs at *ca* 30° in relation to the track (main or secondary), to reduce damages when skidding and to handle the logs more easily. Unfortunately 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 angle, and gap dimensions are kept in memory to subsequently compute post-logging damages.

Main Track

Reality Forestry 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 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 middle of one side of the plots with a width of 6 meters, and traced until 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 chose 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 100 m^3 , the main track always reached very close to the other edge of the plot, and this was conceptually disturbing.

Secondary tracks

Reality A 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 manually 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 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. Overall, this could be more related to sight-based skidding, and getting trees from close to close.

Model We modeled both conventional and RIL skidding fashions. RIL skidding was already implemented in the first version of the modules [see Schmitt, 2017]. CL was modeled using the simple assumption that the closest tree is first harvested, and the next ones, from close to close. Figure 7 shows maps generated with both options, at two different harvest intensities. Note the difference in track extent, and the dependence to target volume.

Residual mortality

Reality Logging operations have immediate and secondary damages on tree stands. Secondary damages are way less conspicuous than immediate damages and cause residual mortality during the first years after logging. These damages can be due to direct hurts of the remaining trees during felling or skidding (uprooted stems, stem wounds, and bark scrapes), or due to 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 Herault et al. [2010] based on a disturbance index into:

$$\begin{aligned} Death &\sim \mathcal{B}(P(Death)) \\ P(Death) &= \text{logit}^{-1}(\theta + \beta * e^{\alpha * d_{gaps}}) = \frac{e^{\theta + \beta * e^{\alpha * d_{gaps}}}}{1 + e^{\theta + \beta * e^{\alpha * d_{gaps}}}} \end{aligned} \quad (9)$$

Death of a tree follows a *Bernoulli* law of probability $P(Death)$. The odds for a tree to die are calculated with the sum of the natural tree death odd θ 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.

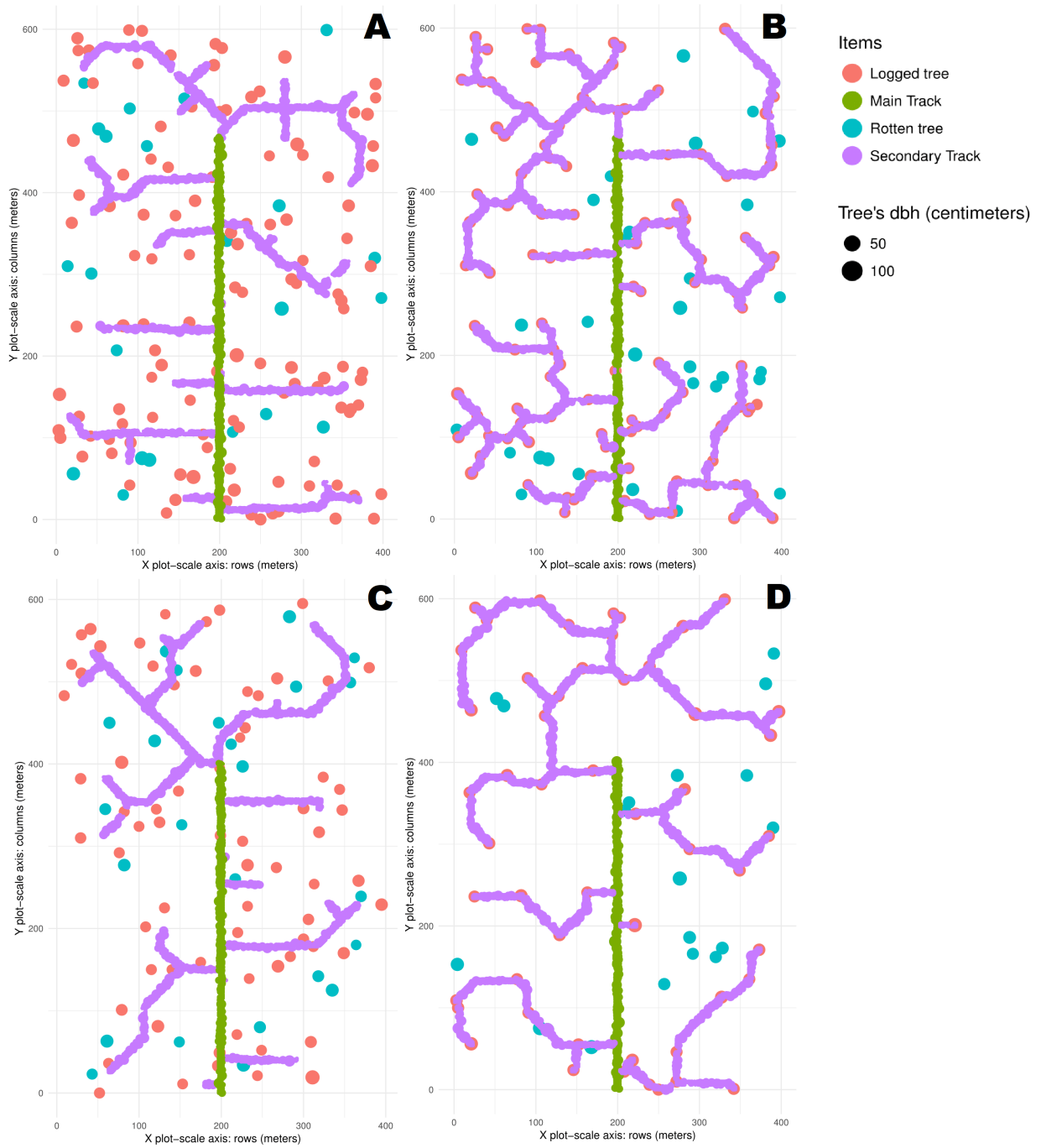


Figure 7: Maps generated by the selective logging module. A and B are maps obtained with a target volume of 30 cubic meters. For C and D, target volumes were 20 cubic meters. A and C were simulated with the RIL configuration. B and D were simulated with the conventional logging configuration.

SELECTIVE LOGGING EXPERIMENT

Experiment design

In French Guiana, 77% of carbon emissions would be due to deforestation and selective logging would account for 5% of these emissions, although uncertainties are high [Cabon et al., 2015]. 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 lead 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.

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 implementation of fuelwood outputs in TROLL was motivated by this need, because the quantities that can be obtained from logging wastes are still uncertain.

Simulated forests

Diversification of the harvested species

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 the majority the overall extracted timber volume [every information on timber species is in Guitet et al., 2011]. 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 and one ECMA (*Bagassa guianensis*) are subject to designation to be harvested. On the one hand,

the ONF insist on the need to diversify the set of harvested species, without what current choices can only lead to resource 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 between 30 and 45 years. French Guiana is 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 adverse effects on these animals [Zimmerman and Kormos, 2012]. 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 has an impact on the simulation outcome.

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. It is not adapted to simulate regeneration from 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.

Results

Model features

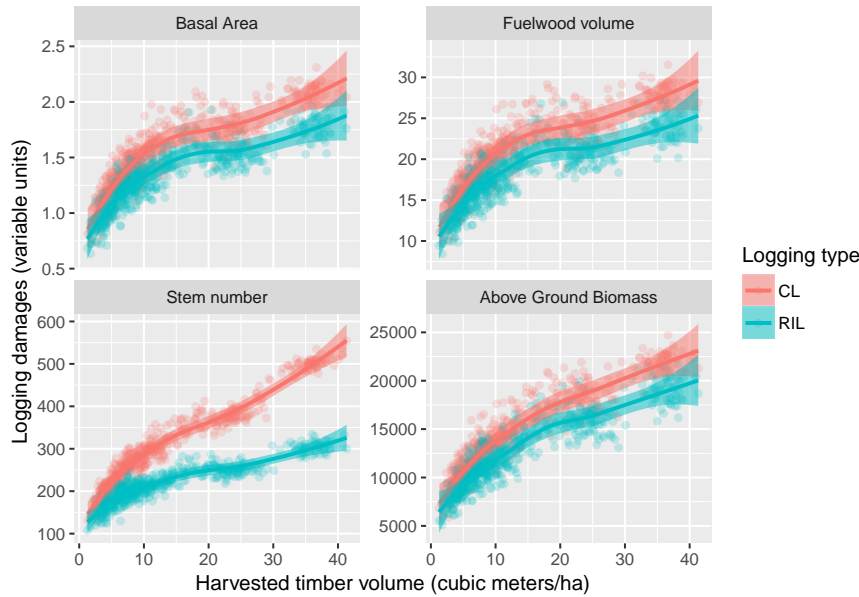


Figure 8: Summary of the logging damages caused by main and secondary tracks opening in our simulations (logged and rotten trees are excluded), plotted against the corresponding actual harvested timber volume: removed Basal area (mš), damaged stem count, removed Above Ground Biomass (kgC/ha), and Fuelwood 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 8). The most discriminant indicator, for the two logging techniques, is the number of damaged stems (over 1 cm dbh), which is equally unsurprising because it is an excellent proxy of the tracks area², that strongly differ between CL and RIL. For BA

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

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. 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 bias in estimating main track damages for the first cutting cycles (after which regeneration occurs 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 the high harvest intensities in our simulations. Thus, we pooled these simulations and decided to emphasize on cutting cycle, target volume, and initial forests.

Our two simulated forests started from 48.5 m³ or 74.3 m³ of harvestable timber. This initial difference did not have a significant effect on the final outcome over 5 rotations. Total timber volumes importantly decrease over harvests. The volumes available before the second harvest strongly differ according to target volumes, and initial timber stocks: they are higher in the initially rich forests for the lowest harvest intensity. Cutting cycle length has a marginal influence on timber volumes for the second rotation. Likely, the initially present and uncut trees are logged at the second harvest. Trajectories seem to be stable after 3 of 4 cutting cycles. From there onwards, timber volumes available at harvest time barely reach 5 and 10 m³ for 35 and 65 years cutting cycles, respectively.

Diversification

Diversification was simulated by making vary the equitability of interest ranks for merchantable species. Figure 10 shows the merchantable volume for ECMPs, which are the actual most valuable timbers. The relaxation of the loggers' preferences has nearly no effect on the proportion of ECMP (10), that decreases, probably because of high harvested volume. In each case, the proportion of this category of commercial timbers (the most valued) sinks drastically over rotations. In our forests, the majority of the timber species (in term of volume) initially belong to this category, but we simulated a weak external seed-rain, thus letting the regeneration be more influenced by trees that are in the plot.

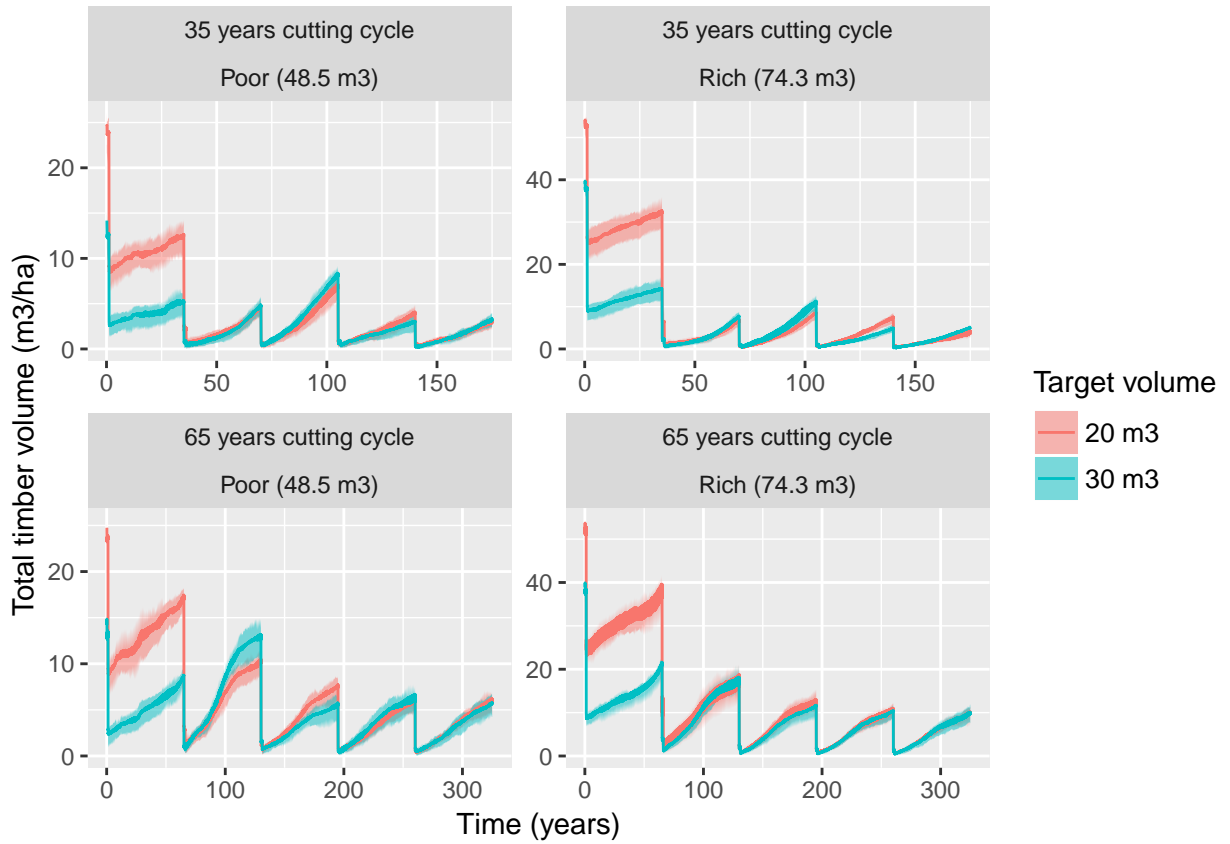


Figure 9: Simulated evolution of the timber stocks over 5 complete cutting cycles, for two contrasted (rich and poor) initial forests -in terms of initial timber stock, cf. the facets labels-, with cutting cycles of 35 and 65 years, and target volumes of 20 (red) and 30 (blue) cubic meters. Lines represent the mean trajectory of 30 simulations each, and color bands, confidence intervals delimited by the 1st and 99th percentile computed for the 30 observations at each timestep.

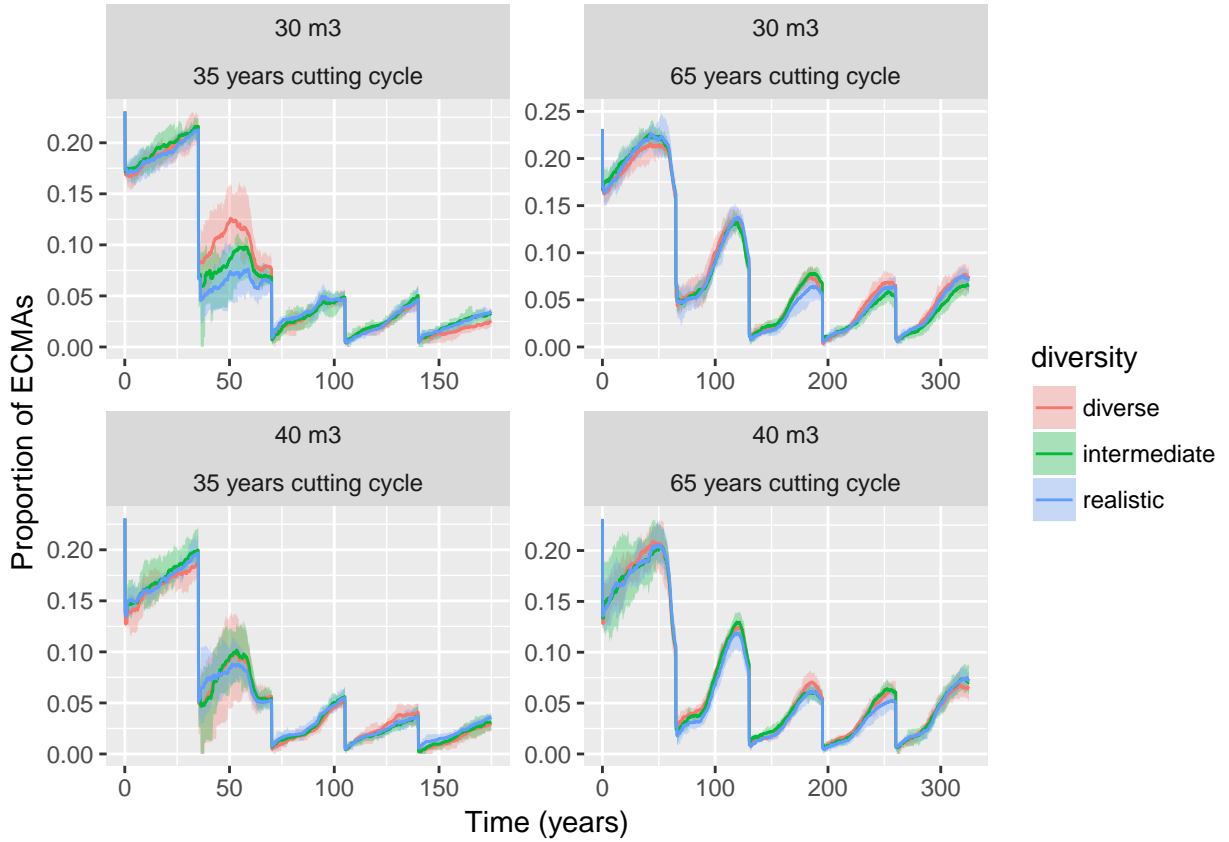


Figure 10: Total proportion of the merchantable volume (trees over 55 cm dbh) for Major Principal Commercial Timber species (ECMPs) over time (years). Diversity corresponds to our 3 designation choice scenariii: Diverse - all species have equal interests; Intermediate - ECMP and ECMAs are preferred over BPs and AEC; Realistic - ECMPs are preferred over every other categories, ECMAs are preferred over BPs and AECs. Color bands are confidence intervals obtained by pooling replicates

Carbon

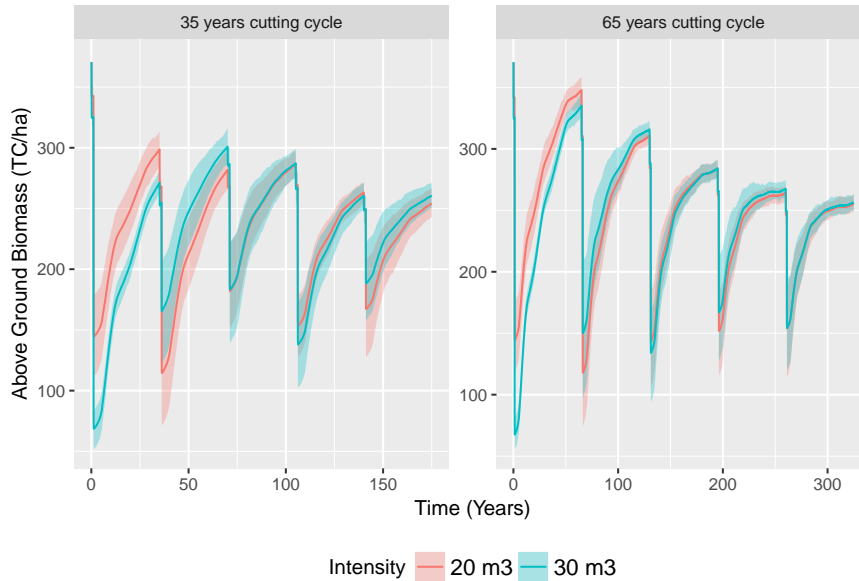


Figure 11: Simulated effects of selective logging on Ecosystem carbon stocks over time with 5 complete cutting cycles. Simulations are pooled to focus on two keys variables - Cutting cycle, and target volume.

Logging, and post-logging mortality applied one year post-harvest, cause considerable loss in AGG in any case. 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 severely logged ones, once again for both cycles duration, yet this effect is of unlikely to be significant. From the third harvest onwards, the differences in harvest intensity is insufficient to change the ecosystem fate: both trajectories converge towards a maximum value of $250 TC/ha$ at the very end of the last cutting cycle, *i.e.* around 30% less than the original *ca.* $350 TC/ha$. The carbon loss is more progressive for plots harvested each 65 years than those cut every 35 years. The last regrowths, for both, seem likely to stabilize AGB at a lower level than the initial $350 TC/ha$, although longer regrowth simulation would be needed to confirm this trend.

Discussion

Timber volumes are not sustained

Our *preliminary* results indicate that selective logging, as currently carried out, is unsustainable in terms of timber yields. Ecosystem fates were similar in that every treatment led to a depletion of timber stocks. Short cutting cycles considerably accelerate this phenomenon.

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. This dependence on the initial conditions is explained by insufficient regeneration of timber stocks, that fails to compensate for the harvest intensities we simulated. At the second cut, plots were left with no remaining timber stock in every scenario. Diversification of the harvested species had a low impact on the stock of first grade timbers, which reduced over years in any case. This is probably due to high harvest intensities. Moreover, elementary protection rules are currently applied in the field to protect seeding trees for valuable timbers [Guitet et al., 2011]. We did not include it in our model. Our preliminary results match previous findings from simulation studies. In his most optimistic scenarios, Sist and Ferreira [2007] predicted a recovery of 50% the initial timber stocks at the second harvest for 30 years cycles, starting from an intensity of $20\text{m}^3/\text{ha}$. They also estimated an average $10\text{-}14\text{ m}^3/\text{h}$ for available timber after 40 years of regrowth. Dauber et al. [2005] estimated that 4 to 28% the initial total timber volume is recovered before the second cycle, with similar intensities and duration to those we simulated. In a case study on *Dicorynia guianensis*, by far the most harvested timber species in French Guiana, Gourlet-Fleury et al. [2005] estimated a maximum 60% of volume recovered in any case they tested. Valle et al. [2007] presented more optimistic results, estimating to 30-40 and 60 years the time needed to recover commercial volumes for CL and RIL, with similar intensities. They however concluded that selective logging is unsustainable without adapted silvicultural treatments.

Carbon stocks decrease

Simulated forests undergo a spectacular above-ground biomass (AGB) loss because of logging and the simulated post-logging mortality. It is difficult to estimate if this effect is overestimated or not: in reality, logging damages do not cause an immediate decrease in AGB, but rather yields extra mortality for several years, less visible because buffered by regrowth [see Piponiot et al., 2016]. In our model, post-logging mortality is simulated 1 year after logging, and integrates damages for a 10-year period. This should be revised in the next version of the model. The total AGB globally decreases over time and harvests (11), and the AGB recovery is decelerating after each harvest. This may be due to a shift in community composition from shade-tolerant, slow growing tree species to heliophilous, fast growing stands. Huth and Köhler [2003], as well as Valle et al. [2007] observed this effect in their own simulations. We did not study the evolution in species composition and diversity, but this shift is likely to happen, because we simulated low external seed incomes. Thus, we gave more importance to the surviving trees for reproduction, which seems more reasonable than a constant, huge arrival of seeds in the plot. However, our simulations indicate that AGB stocks are partly retained, and recover faster than other attribute, consistently with other authors findings [Rutishauser et al., 2015]. Sist et al. [2015] suggested that AGB can be fully recovered 125 after logging, but they did not assess the effect of multiple harvests.

In a nutshell

Our preliminary simulations indicate that selective logging may be unsustainable in many aspects. Current practices may allow neither to sustain overall timber stocks nor high value timber yields, nor fundamental services such as holding carbon stocks. Current cutting cycles are too short, even in French Guiana, to allow for sufficient timber species recovery. Harvested volumes are too high, and guarantee substantial decrease in commercial trees that are not compensated by remaining trees growth, recruitment, and external seed incomes. However, our results lack replication and may been interpreted with precaution.

CONCLUSIONS AND PERSPECTIVES

We inferred seven traits means for 547 species, resulting in better coverage of Paracou species, needed to address our goals. Post-logging trajectories were not reproducible starting from real censuses because of abnormally high mortality during the five first years of simulation. We hypothesized that this could be related to the model’s structure and assumptions. We verified this hypothesis using spatial statistics and found an overdispersion of canopy trees (>30 cm dbh) in TROLL, not observed in real data. Our results indicate that calibration of post-logging recovery with TROLL requires another approach than inputting real data into the model. We implemented new generic functionalities to simulate selective logging in two different ways (CL and RIL) and test variations of essential silviculture parameters such as cutting cycle duration, target volume, minimum cutting diameters, and preferences among timber species. This enables to investigate a wide range of scenarios with TROLL.

Finally, we did a preliminary set of simulations, testing 24 scenarios in two different forests. Preliminary results indicate that ecosystem damages are both sensitive to the target volumes, and the logging techniques used. In the model, the gain of RIL regarding damages is mitigated by high harvest intensities. Every scenario we tested to similar long-term trajectories. Current cutting cycles seem inadequate with Sustainable Forest Management, no matter what exactly one wants to sustain: carbon stocks and timber volumes undergo a long-term decreased in our simulations. Above-ground biomass trajectories are consistent with forest secundarisation. We did not test the impact of logging on species diversity and composition in the long term, but it is likely that pioneer species take advantage of the repeated disturbances caused by multiple harvests. The majority of the extractible fuelwood volume, over two rotations, concern trees damages during secondary tracks opening. The results suggest that TROLL could be useful to explore scenarios and provide first estimates of the quantity of fuelwood that could be valorized from damaged trees during operations.

Our experiment, however, lacked replication: we used only two different forests and did only five replicates per scenario and forest. These **preliminary** results must not be overinterpreted. Instead, they give a clue of what else to test, and which effects to separate to further use this model. Moreover, the external seed arrival may have been underestimated by our parametrization, and the bias it causes regarding merchantable species recovery yet has to be evaluated.

TROLL is a model and thus has limits. TROLL is based on some simplifying assumptions that have significant implications for silviculture modeling. For example, the topography is not yet included in the model, although it is the most limiting constraint during planifications and harvests. Belowground processes and soil characteristics are not yet included. Additionally, the external seed rain is difficult to tune in order to have realistic results, yet it influences strongly the results of simulations [Schmitt, 2017]. The logging model needs refinement and optimization, and relies on simplifying assumptions. The output generated also need a proper calibration to assess their realism, which we did not succeed to do from real censuses.

Still, TROLL has a promising potential to assess the impacts of selective logging. Its spatialisation and finesse offer more realism than many models previously used. Future updates of the model will bring interesting improvements, such as the explicit integration of water fluxes [Marechaux, 2017]. The implementation of silvicultural treatment in the logging module are also a potential perspective, because many authors advise their use, but insights of their efficiency on large time scales are simply inexistant. We hope that this study is only the first step of a longer-term work, that will bring interesting results and help improving forest management.

APPENDIX 1: TROLL MODEL

This appendix provides a description of the model, adapted from [Marechaux \[2017\]](#) and [Schmitt \[2017\]](#).

Abiotic environment

The abiotic environment is explicitly modelled in a voxel space, with a resolution of 1 m^3 . For each tree crown, leaf area density is calculated assuming a uniform distribution across voxels occupied by the crown. Leaf area density is computed within each voxel summing all tree crowns inside the voxel v , and is noted $LAD(v)$ (leaf area per voxel in $\text{m}^2.\text{m}^{-3}$). The vertical sum of LAD from voxel v to the soil is $LAI(v)$ (leaf area index; $\text{m}^2.\text{m}^{-2}$) :

$$LAI(v) = \sum_{v'=v}^{\infty} LAD(v') \quad (10)$$

Daily variations in light intensity (taken as photosynthetic photon flux density PPFD in $\mu\text{mol}_{\text{photons}}.\text{m}^{-2}.\text{s}^{-1}$), temperature (T in $^{\circ}\text{C}$), and vapor pressure deficit (VPD in kPa) are computed to assess carbon assimilation within each voxel for a representative day per month. Variation of PPFD within the canopy is calculated with a Beer-Lambert extinction law:

$$PPFD_{\text{max},\text{month}}(v) = PPFD_{\text{top},\text{max},\text{month}} * e^{-k*LAI(v)} \quad (11)$$

The daily maximum incident PPFD at the top of canopy $PPFD_{\text{top},\text{max},\text{month}}$ is an input variable. The extinction rate k is assumed as constant. Only vertical light diffusion is considered. Intra-day variation at half-hourly time steps t , for a representative day per month, are used to compute $PPFD_{\text{month}}(v, t)$, $T_{\text{month}}(v, t)$ and $VPD_{\text{month}}(v, t)$. Water and nutrient process both in soil and inside trees are not simulated, for now (but water fluxes are going to be implemented soon)

Photosynthesis

Theory

Troll simulates individual's carbon uptake of each with the Farquhar, von Caemmerer and Berry model for C3 photosynthesis [[Farquhar et al., 1980](#)]. Gross carbon assimilation rate (A in $\mu\text{mol CO}_2.\text{m}^{-2}.\text{s}^{-1}$) is limited by either Rubisco carboxylation activity (A_v) or RuBP regeneration (A_j):

$$A = \min(A_v, A_j) \mid A_v = V_{cmax} * \frac{c_i - \Gamma^*}{c_i + K_m} ; A_j = \frac{J}{4} * \frac{c_i - \Gamma^*}{c_i + 2 * \Gamma^*} \quad (12)$$

V_{cmax} is the maximum carboxylation rate ($\mu mol CO_2.m^{-2}.s^{-1}$). c_i is the CO_2 partial pressure at carboxylation sites. Γ^* is the CO_2 compensation point in absence of dark respiration. K_m is the apparent kinetic constant of Rubisco enzyme. J is the electron transport rate ($\mu mole^-.m^{-2}.s^{-1}$), and depends on the light intensity with $PPFD$:

$$J = \frac{1}{2 * \theta} * [\alpha * PPFD + J_{max} - \sqrt{(\alpha * PPFD + J_{max})^2 - 4 * \theta * \alpha * PPFD * J_{max}}] \quad (13)$$

J_{max} is the maximal electron transport capacity ($\mu mole^-.m^{-2}.s^{-1}$), θ is the curvature factor and α is the apparent quantum yield of electron transport ($mole^-.mol photons^{-1}$).

Carbon assimilation by photosynthesis are limited by CO_2 partial pressure at carboxylation sites. Stomata control this through stomatal transport:

$$A = g_s * (c_a - c_i) \quad (14)$$

g_s is the stomatal conductance to CO_2 ($mol CO_2.m^{-2}.s^{-1}$).

TROLL simulates g_s with the model from [MEDLYN et al., 2011]:

$$g_s = g_0 + (1 + \frac{g_1}{\sqrt{VPD}}) * \frac{A}{c_a} \quad (15)$$

TROLL model assume $g_0 \approx 0$ (empirically tested and considered as reasonable), and g_1 is given as an input.

Parametrization

DOMINGUES et al. [2010] suggested that V_{cmax} and J_{max} were both limited by the leaf concentration of nitrogen N and phosphorus P ($mg.g^{-1}$):

$$\log_{10} V_{cmax-M} = \min \left(\begin{array}{l} -1.56 + 0.43 * \log_{10} N - 0.37 * \log_{10} LMA \\ -0.80 + 0.45 * \log_{10} P - 0.25 * \log_{10} LMA \end{array} \right) \quad (16)$$

$$\log_{10} J_{max-M} = \min \left(\begin{array}{l} -1.50 + 0.41 * \log_{10} N - 0.45 * \log_{10} LMA \\ -0.74 + 0.44 * \log_{10} P - 0.32 * \log_{10} LMA \end{array} \right) \quad (17)$$

V_{cmax-M} and J_{max-M} are the photosynthetic capacities at $25^\circ C$, for mature leaves and per leaf dry mass (respectively, $\mu mol CO_2.g^{-1}.s^{-1}$ and $\mu mole^-.g^{-1}.s^{-1}$). LMA is the leaf mass

per area ($g.cm^{-2}$). V_{cmax} and J_{max} are calculated by multiplying V_{cmax-M} and J_{max-M} by LMA . V_{cmax} and J_{max} variation with temperature are calculated with [BERNACCHI et al. \[2003\]](#).

TROLL computes leaf carbon assimilation A_l combining equations from (12) to (17), for each crown voxel within each crown layer l :

$$A_l = \frac{1}{n_v * t_M} * \sum_v \sum_{t=1}^{t_M} A(PPFD_{month}(v, t), VPD_{month}(v, t), T_{month}(v, t)) \quad (18)$$

$PPFD_{month}(v, t)$, $VPD_{month}(v, t)$, and $T_{month}(v, t)$ are derived from site-specific climatic data; n_v is the number of voxels within crown layer l ; And the sum is calculated over the t_M half-hourly intervals t of a typical day.

Autotrophic respiration

A large fraction of plants carbon uptake is actually used for plant maintenance and growth respiration. The autotrophic respiration can represents up to 65% of the gross primary productivity but varies strongly among species, sites, and environnements.

TROLL uses [Atkin et al. \[2015\]](#) database of mature leaf dark respiration and associated leaf traits to compute leaf maintenance respiration:

$$R_{leaf-M} = 8.5431 - 0.1306 * N - 0.5670 * P - 0.0137 * LMA + 11.1 * V_{cmax-M} + 0.1876 * N * P \quad (19)$$

R_{leaf-M} is the dark respiration rate per leaf dry mass at a temperature of $25^\circ C$ ($nmolCO_2.g^{-1}.s^{-1}$). The other terms are in equations (16) and (17).

TROLL assumes leaf respiration during the day to be 40% of leaf dark respiration, and computes total leaf respiration by accounting for the length of the daylight.

TROLL model stem respiration (R_{stem} in $\mu molC.s^{-1}$) with a constant respiration rate per volume of sapwood:

$$R_{stem} = 39.6 * \pi * ST * (dbh - ST) * (h - CD) \quad (20)$$

dbh , h , CD and ST are tree diameter at breast height, height, crown depth and sapwood thickness, respectively (m). TROLL assumes $ST = 0.04 m$ when $dbh > 30 cm$ and an increasing ST for lower dbh .

TROLL computes fine root maintenance respiration as half the leaf maintenance respiration, and coarse root and branch maintenance respirations as half the stem respiration.

Growth respiration (R_{growth}) is assumed to account for 25% of the gross primary productivity minus the sum of maintenance respirations.

Net carbon uptake

Net primary production of carbon for one individual NPP_{ind} (gC) is computed with gross primary production GPP_{ind} and respirations R :

$$NPP_{ind} = GPP_{ind} - R_{maintenance} - R_{growth} \quad (21)$$

TROLL separates total leaf area LA , for each individual, into three pools corresponding to different photosynthesis efficiency (young, mature and old leaves with LA_{young} , LA_{mature} , and LA_{old} respectively). Growth primary production for one individual is thus computed as as:

$$GPP_{ind} = 189.3 * \Delta t * \sum_{l=[h-CD]+1}^{\lfloor h \rfloor} [A_l] * \left(\frac{LA_{young}}{2} + LA_{mature} + \frac{LA_{old}}{2} \right) \quad (22)$$

With h and CD the tree height and crown depth(m). $\lfloor x \rfloor$ is the rounding function. Δt is the duration of a timestep ($year$).

Carbon allocation to wood is computed as an increment of stem volume ΔV (m^3):

$$\Delta V = 10^{-6} * \frac{f_{wood} * NPP_{ind}}{0.5 * wsg} * Senesc(dbh) \quad (23)$$

f_{wood} is the fixed fraction of NPP allocated to stem and branches. wsg is the wood specific gravity ($g.cm^{-3}$, see 1). TROLL assume large trees to undergo a size-related growth decline with function $Senesc$ after a specific diameter at breast height threshold dbh_{thresh} :

$$Senesc(dbh) = \max(0; 3 - 2 * \frac{dbh}{dbh_{thresh}}) \quad (24)$$

Allocation to canopy is computed with canopy NPP fraction, f_{canopy} decomposed into leaf, twig and fruit production. Carbon allocation to leaf results in a new young leaf pool, whereas other leaf pools are updated as follow:

$$\begin{aligned} \Delta LA_{young} &= \frac{2 * f_{leaves} * NPP_{ind}}{LMA} - \frac{LA_{young}}{\tau_{young}} \\ \Delta LA_{mature} &= \frac{LA_{young}}{\tau_{young}} - \frac{LA_{mature}}{\tau_{mature}} \\ \Delta LA_{old} &= \frac{LA_{mature}}{\tau_{mature}} - \frac{LA_{old}}{\tau_{old}} \end{aligned} \quad (25)$$

τ_{young} , τ_{mature} , and τ_{old} are species-specific leaf residence times for each leaf pool (*years*). Their sum is the leaf lifespan $LL = \tau_{young} + \tau_{mature} + \tau_{old}$ (*years*). τ_{young} is set to one month and τ_{mature} is set to a third of leaf lifespan LL . Belowground carbon allocation is not simulated inside TROLL.

Tree growth

With the increment in stem volume ΔV calculated with equation (23), TROLL derives an increment of tree diameter at breast height denoted Δdbh . It infer tree height from dbh using a Michaelis-Menten equation:

$$h = h_{lim} * \frac{dbh}{dbh + a_h} \quad (26)$$

and the trunk volume is $V = C * \pi * (\frac{dbh}{2})^2 * h$, thus:

$$\begin{aligned} \Delta V &= C * \frac{1}{2} * \pi * h * dbh * \Delta dbh + C * \pi * (\frac{dbh}{2})^2 * h \\ \Delta V &= V * \frac{\Delta dbh}{dbh} * (3 - \frac{dbh}{dbh + a_h}) \end{aligned} \quad (27)$$

Then, TROLL uses the new trunk dimension (dbh and h) to update tree crown geometry using allometric equations [Chave et al., 2005]:

$$\begin{aligned} CR &= 0.80 + 10.47 * dbh - 3.33 * dbh^2 \\ CD &= -0.48 + 0.26 * h ; CD = 0.13 + 0.17 * h \quad (h < 5 \text{ m}) \end{aligned} \quad (28)$$

The mean leaf density is finally computed within the crown (LD in $m^2.m^{-3}$) assuming a uniform distribution:

$$LD = \frac{LA_{young} + LA_{mature} + LA_{old}}{\pi * CR^2 * CD} \quad (29)$$

Mortality

Mortality is partitioned in three factors inside TROLL: background death d_b , treefall death d_t and negative density dependent death d_{NDD} . Because density dependent death d_{NDD} is currently at development stage.

Chave et al. [2009] opposed fast growing light wood species species, with high risk of mortality, to slow growing dense wood species, with reduced mortality. In TROLL, background mortality is derived from wood specific gravity wsg :

$$d_b = m * (1 - \frac{wsg}{wsg_{lim}}) + d_n \quad (30)$$

m ($events.year^{-1}$) is the reference death rate for lighter wood species (pioneers). d_n represents death by carbon starvation. If the number of consecutive day with $NPP_{ind} < 0$ (21) is superior to tree leaf lifespan d_n is set to 1 and remains null in other cases.

Mortality by treefall inside TROLL depends on a specific stochastic threshold θ :

$$\theta = h_{max} * (1 - v_T * |\zeta|) \quad (31)$$

h_{max} is the maximal tree height. v_T is the variance term set to 0.3. $|\zeta|$ is the absolute value of a random centered and scaled Gaussian. If the tree height h is superior to θ then the tree may fall with a probability $1 - \theta/h$ [Chave, 1999]. The treefall direction is random (drawn from a uniform law $\mathcal{U}[0, 2\pi]$). All tree in the trajectory of the falling tree will be hurted through a variable denoted $hurt$, incremented by fallen tree height h . If a tree height is inferior than its $hurt$ values then it may die with a probability $1 - \frac{1}{2} \frac{h}{hurt}$. $hurt$ variable is reset to null at each timestep ($month$).

Recruitment

Once the tree became fertile they will start to disperse seeds. TROLL consider tree as fertile after a specific height threshold h_{mature} [Wright et al., 2005]:

$$h_{mature} = -11.47 + 0.90 * h_{max} \quad (32)$$

TROLL is not considering seed directly through a seedbank, instead seed might be interpreted as a seedling recruitment opportunity. The number of reproduction opportunities per mature tree is denoted n_s and set to 10 for all species. This assumption originates from a trade-off between seed number and seed size resulting in equivalent survival and recruitment probability. All n_s events are dispersed with a distance randomly drawn from a Gaussian distribution.

Additionally, TROLL model consider external seedrain through n_{ext} events of seed immigration:

$$n_{ext} = N_{tot} * f_{reg} * n_{ha} \quad (33)$$

N_{tot} is the external seedrain per hectare (number of reproduction opportunities). f_{reg} is the species regional frequency. n_{ha} is the simulated plot size in ha .

The seedrain has important implications in the model, because it influences the equilibrium stats of the model and the regeneration after a disturbance [Schmitt, 2017]

A bank of seedlings to be recruited is defined for each pixel. If the ground-level light reaches a species light compensation point LCP the species will be recruited:

$$LCP = \frac{R_{leaf}}{\phi} \quad (34)$$

R_{leaf} is the leaf respiration for maintenance (see (19)). ϕ is the quantum yield ($\mu mol C. \mu mol \ photon$) set to 0.06. If several species reach their LCP , one is picked at random. Seedlings are recruited with following intial geometry:

$$\begin{aligned} dbh &= \frac{a_h}{h_{max}-1} \\ h &= 1 \ m \\ CR &= 0.5 \ m \\ CD &= 0.3 \ m \\ LD &= 0.8 \ m^2.^{-3} \end{aligned} \quad (35)$$

APPENDIX 2: INCLUDING MORE SPECIES IN TROLL’S LIST - SUPPLEMENTARY MATERIAL

Phosphorous measurements are mainly single-tons

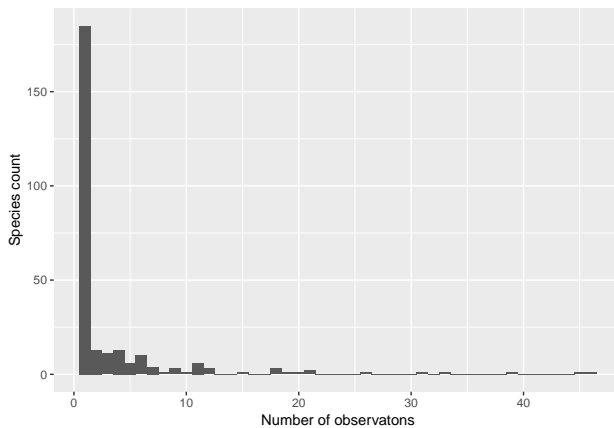
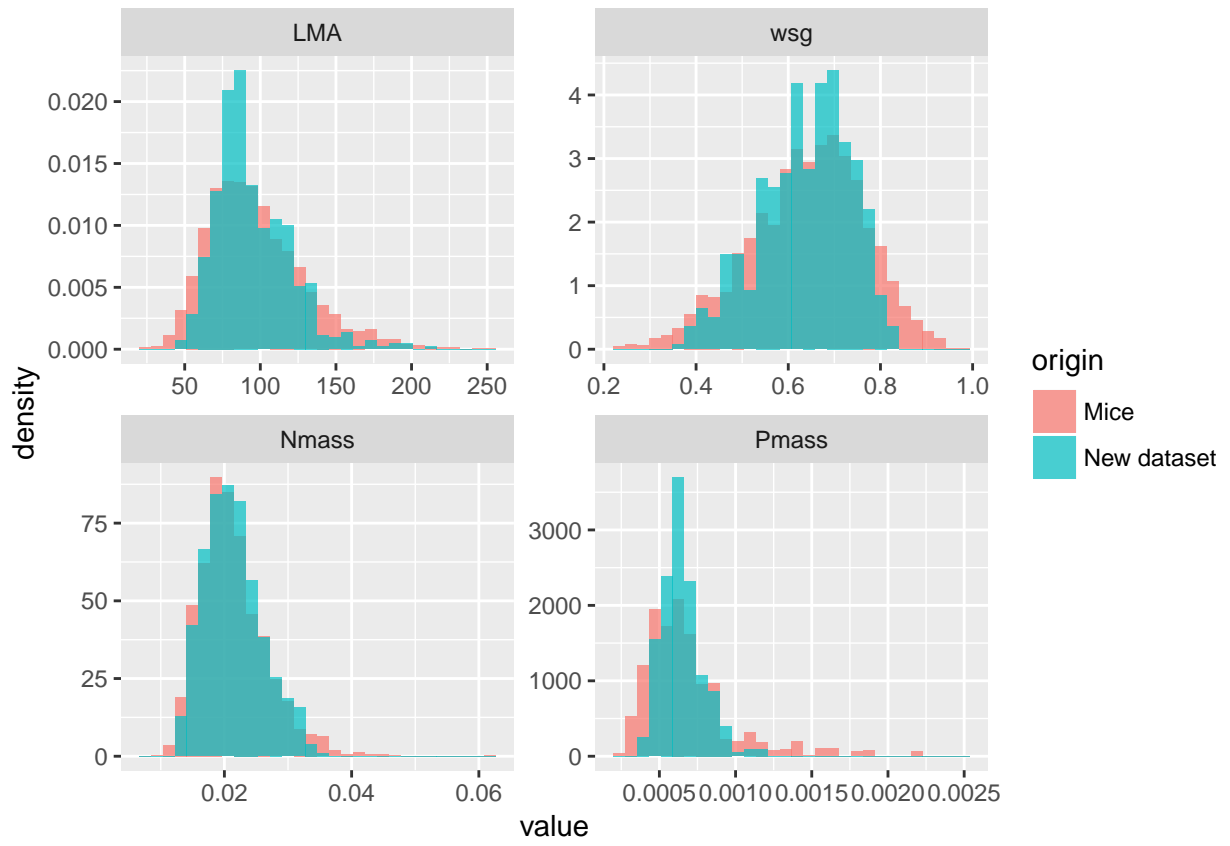


Figure 12: Histogram of the number of observations per species for Pmass. Most species are singletons.

Distribution of traits for the newly inferred species

We obtained a new set of 599 species means for Nmass, Pmass, wsg and LMA. What appears obvious here is that the range of estimated species means is more narrow than 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 precaution principle: species with extreme and with very few observations are attributed more reasonable estimates, because of the uncertainties.



APPENDIX 3: PREDICTIVE MEAN MATCHING (PMM) EXPLAINED

Let X be a single variable that has cases with missing data, and a set of variables Z (with no missing data) that are used to impute x . PMM, as implemented on mice package, follows these steps:

1. For cases with no missing data, it estimates a linear regression of X on Z , producing a set of coefficients β .
2. It then makes a random draw from the “posterior predictive distribution” of β , producing a new set of coefficients β^* . This would typically be a random draw from a multivariate normal distribution with mean β , and the estimated covariance matrix of β (with an additional random draw for the residual variance). This step aims at producing variability in the imputed values, and is common to all efficient methods for multiple imputation.
3. Using β^* , it generates predicted values for x for all cases, both those with data missing on x and those with data present.
4. For each case with missing x , it identifies a set of cases with observed X whose predicted values are close to the predicted value for the case with missing data.
5. It then randomly chooses one and assign its observed value to substitute for the missing value.
6. Steps 2 through 5 are then repeated for each completed data set.

There are several variations to this method. Generally, each case with missing data on X is matched to the k cases (with data present) that have the closest predicted values, of which one is chosen at random and its X value assigned to the case with missing data. We used the default $k = 5$ proposed in the mice package and repeated the imputation 10 times, then pooled the datasets and averaged the obtained proposals for missing values.

APPENDIX 4: COMPLEMENTARY FUELWOOD GRAPHICS

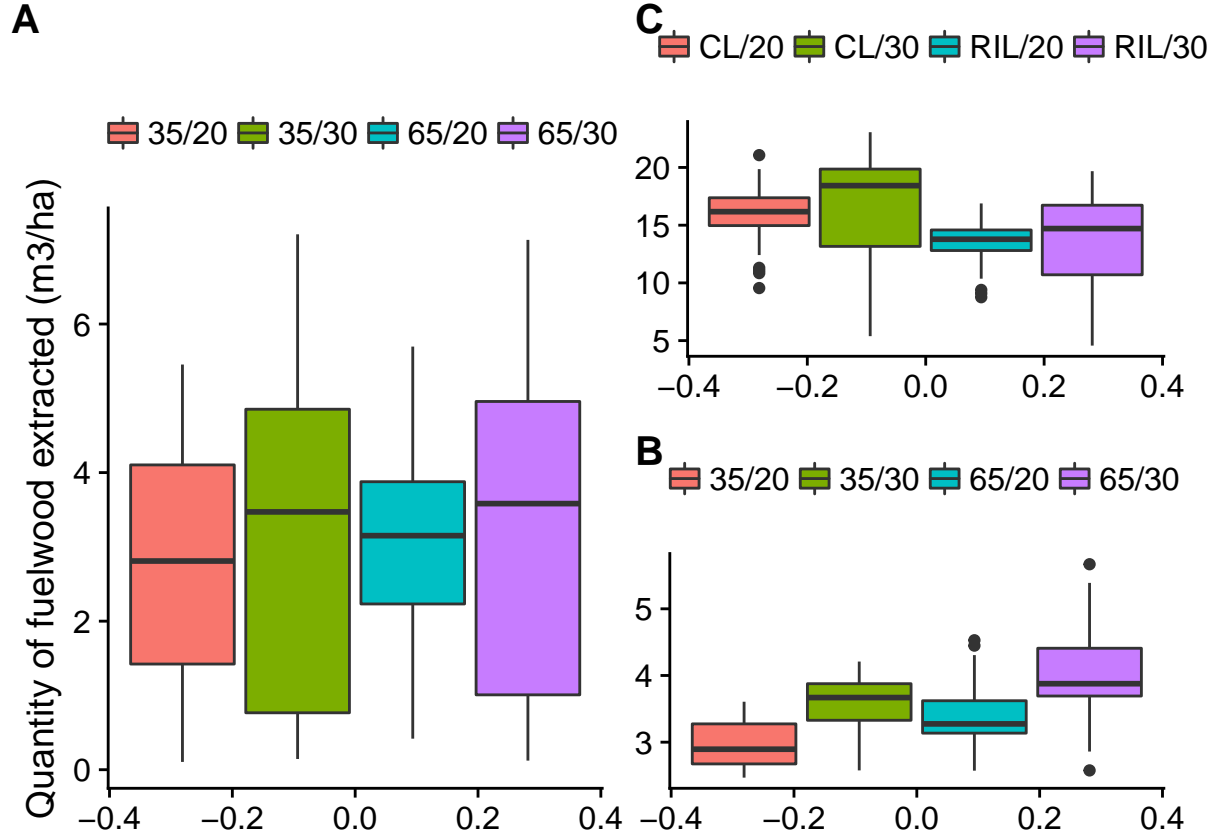


Figure 13: Estimated usable fuelwood volumes during the 2 firsts cutting cycles, originating from : A - Rotten trees, with a comparison between cutting cycle durations (35 or 65), and target volumes (20 or 30); B - Main tracks, with the same label correspondence as A; and C - Secondary track, with separation 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.

The average usable fuelwood quantities (Figure 13) 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 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 regener-

ation exposed above. In fact, for the first rotation only it depends directly on the target volume.

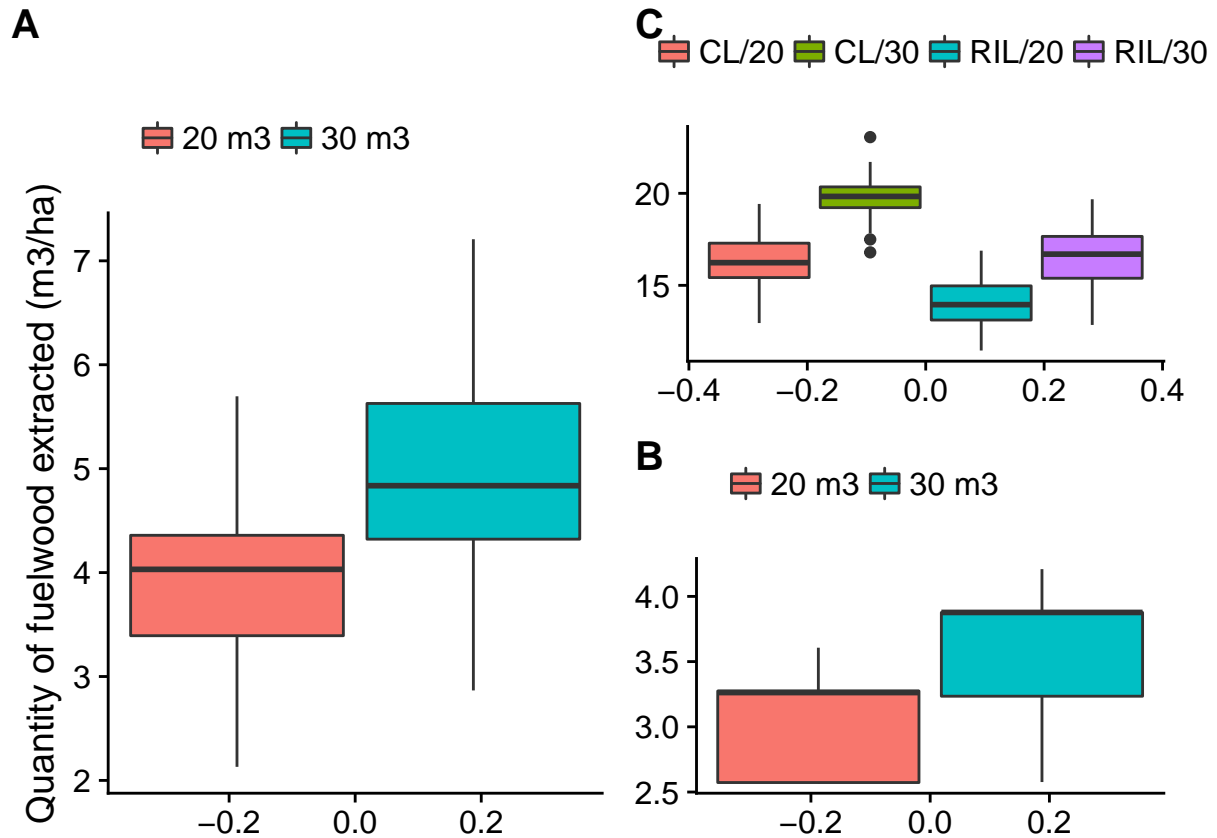


Figure 14: Same fuelwood estimates only for the first culling cycle. A - Rotten trees, with a comparison between target volumes (20 or 30); B - Main tracks, with the same label correspondence as A; and C - Secondary track, with separation on logging techniques (CL or RIL); Black horizontal lines point the median of the distributions. Color boxes encompass values between the 1st and 3rd quartile. Black points are extreme values.

APPENDIX 5: MORTALITY CURVE FOR PARACOU

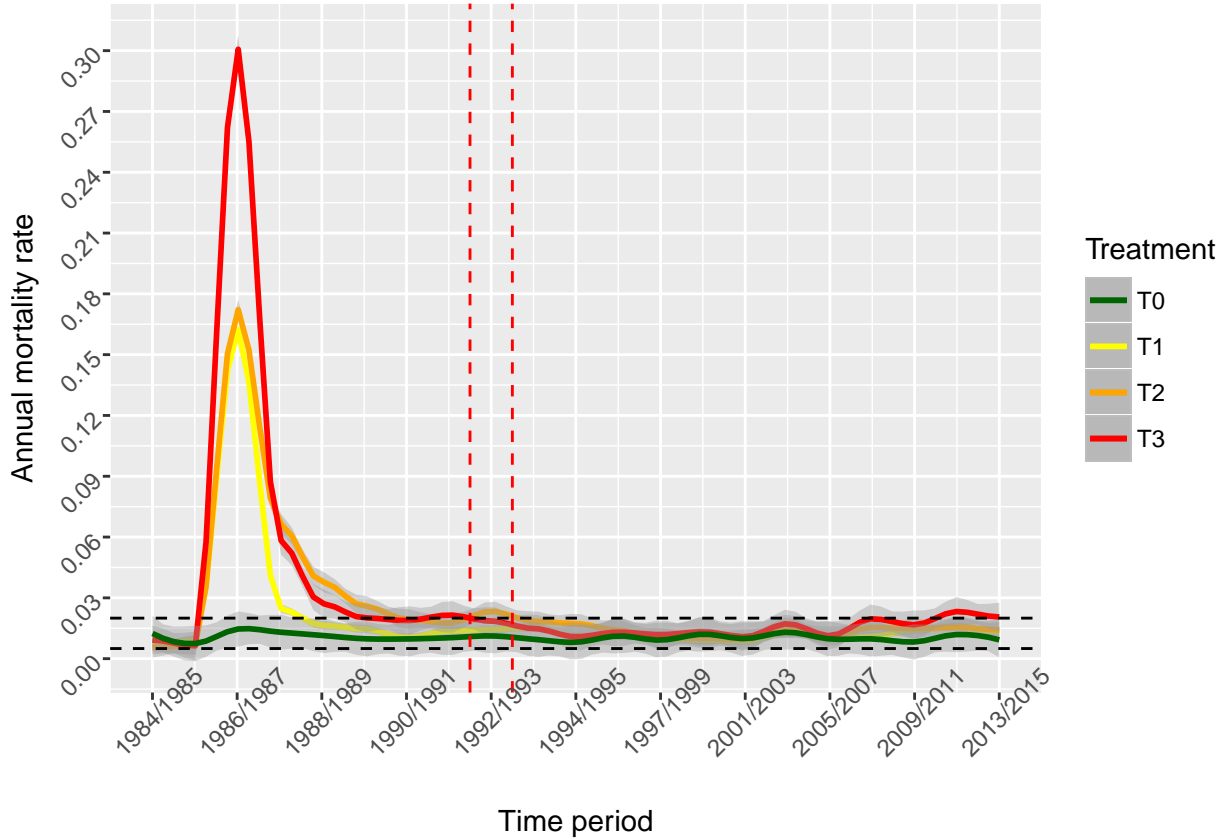


Figure 15: Annual mortality rates at Paracou plots, pooled by treatment. T0 are control plots, T1 are conventionally logged plots, T2 are logged plots with additional Stand Improvement treatment (thinning by poison girdling), T3 are plots logged for timber and additional fuelwood, having also undergone Stand Improvement treatments. Grey bands around the curves are pseudo-confidence intervals generated with `geom_smooth` (package `ggplot2`). The plots were logged in 1986/1987.

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Résumé : Les forêts tropicales abritent la moitié de la biodiversité terrestre mondiale, fournissent d'importants services écosystémiques à l'humanité, et sont un important réservoir de carbone. Ces forêts font face à de nombreuses menaces, dont la déforestation à des fins agricoles, et l'exploitation forestière sélective. Cette dernière a affecté ou affectera la majorité des forêts tropicales, et a longtemps été une pratique incontrôlée. La Gestion Forestière Durable a été mise en avant pour tenter de résoudre ce problème, s'appuyant notamment sur les principes de l'Exploitation à Faible Impact et des incitations financières, comme le programme REDD+. Cependant, certains auteurs ont remis en question la durabilité réelle d'une telle exploitation. Evaluer l'impact des pratiques forestières est une tâche difficile, au vu des échelles de temps impliquées. En complément des efforts de suivi, la modélisation peut s'avérer utile pour fournir un aperçu des effets de l'exploitation forestière à plus long terme. TROLL est un modèle spatialement explicite, individu-centré, qui simule un grand nombre d'espèces d'arbres. TROLL offre d'intéressantes perspectives en écologie théorique et appliquée. Nous avons exploré le potentiel de ce modèle pour simuler l'exploitation sélective, et explorer la durabilité de plusieurs scénarios. Nous avons commencé par paramétrer 547 espèces à partir de la base de données BRIDGE, pour simuler d'importantes étendues de forêt, et avons ensuite essayé de réaliser une évaluation et calibration des trajectoires post-coupe simulées, en partant de données réelles. La calibration fut impossible à cause d'une mortalité exagérée dans les forêts d'entrées, pendant les premières années de simulation. Nos analyses suggèrent que TROLL a une structure spatiale différente de celle de vraies forêts, peut être à cause d'une sur-estimation de la compétition pour la lumière, le rendant inadapté à simuler à partir de vraies données pour le moment. Nous avons adapté la version existante du module simulant l'exploitation dans TROLL, pour implémenter plusieurs pratiques et paramètres sylvicoles. Nous avons réalisé un premier jeu de simulations sur deux forêts ayant des volumes de départ contrastés, durant 5 rotations. Nos résultats indiquent que l'exploitation sélective, telle qu'elle est pratiquée en Guyane Française, pourrait mener à un épuisement des volumes totaux d'espèces commerciales, ainsi qu'à une baisse du stock de carbone au fil des récoltes, et cela même pour des rotations de 65 ans, avec des intensités de $20m^3$ et les techniques de l'EFI. Ces résultats sont cependant préliminaires et manquent de réplication, ils doivent donc être interprétés avec précaution. Des analyses plus poussées sur des scénarios plus nombreux sont requises afin de confirmer et affiner nos résultats. TROLL, combiné avec le modèle d'exploitation que nous avons mis à jour, présente un potentiel prometteur pour explorer différents scénarios sylvicoles, et répondre à des problématiques appliquées.

Mots clés : Gestion Forestière Durable, Simulation, Exploitation forestière, Modélisation, Modèle individu-centré.

Abstract: Tropical forests shelter half the terrestrial biodiversity worldwide, provide important services to humanity and are a major reservoir of carbon. These forests face numerous threats, among others deforestation for agriculture and selective logging. Selective logging affected or will affect the majority of tropical forest outside protected areas, and has long been an uncontrolled predatory practice. Sustainable Forest Management (SFM) has been promoted to answer this issue, relying on Reduced Impact Logging, and financial incentives such as REDD+. However, some authors asked whether these techniques are sustainable. Assessing the sustainability of Forest Management is a difficult task, because of the efforts needed by field studies, and time scales involved. To complement monitoring efforts, the use of models can provide valuable insights of longer-term effects of selective logging. TROLL is an individual-tree-based, spatially explicit forest model that uses functional traits to simulate the life cycle of a wide range of tree species. TROLL offers promising perspectives in studying ecological theories and applied problems. We explored the potential of this model to simulate selective logging and assess the sustainability of different scenarios. We preliminarily parametrized 547 species from the BRIDGE dataset to simulate large forest plots, and we attempted to evaluate and calibrate the simulated post-logging trajectories inputting real forest censuses in the model. The calibration was impossible because of exaggerated mortality in the inputted forests during the first years of simulation. Spatial structure analysis suggests that TROLL has a different spatial structure than real forests, maybe due to overestimation of competition for light, thus making unadapted the use of real data inputs for now. We adapted the existing version of the module that simulates selective logging in TROLL, to implement cutting cycles, conventional logging, and designation based on timber interest ranks. We did a preliminary set of simulations on two forests that had contrasted timber volumes, to assess the importance of silviculture parameters over five cutting cycles. Our results indicate that selective logging, as applied in French Guiana and neighboring countries, may lead to a depletion of total timber stocks and high-grade species, along with a decrease of carbon stocks over harvests, even for 65 years cutting cycles with $20m^3$ harvested and RIL techniques. However, our results are preliminary, lack replication, and thus have to be interpreted carefully. Further, extensive analyses are needed to confirm and refine our findings. TROLL, combined with the logging model we updated, has a promising potential to explore a wide range of silviculture scenarios, and address applied problematics.

Keywords: Sustainable Forest Management, Simulation, Selective logging, Modeling, Individual-based model.

