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Simulation of succession in a neotropical forest: High selective logging intensities prolong the recovery times of ecosystem functions

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ABSTRACT

There is increasing concern, to what extent production forests in the Neotropics are sustainably managed. The implementation of effective forest management strategies that are ecologically beneficial plays thus a central role to prevent forest degradation. However, to identify effective forest management strategies, there is a need for methods supporting the decision-making process.

The main objective of our study is to analyze the mid- and long-term impacts of different management intensities, such as varying the minimum stem diameter of harvestable commercial trees, on the dynamic and structure of a species-rich tropical lowland forest of French Guiana. Therefore, we have applied the management module of a dynamic forest model and analyzed simulation experiments for undisturbed forest growth and selective logging.

For the first time we were able to quantify the mean recovery times of multiple ecosystem functions and properties (biomass, gross primary production, leaf area index, Shanon diversity, timber volume) after selective logging.

Accordingly, we validated simulation results (biomass, number of trees harvested) of selective logging with forest inventory data from the last 32 years. The forest model reliably reproduces the observed pre-logging biomass, tree-size distribution, and logging intensity (10 trees/ha, 39 m^3/ha). In addition, it became clear how strongly management with higher logging intensities influences the forest in the long term: (1) the mean recovery times of the investigated ecosystem functions were significantly extended. With very intensive logging (116 m^3/ha), the average recovery time of forest biomass was almost twice as long as in a moderate simulation scenario (t_{int} 138 a, t_{mod} 77 a). Similar patterns were observed for other ecosystem functions, e.g. timber volume (t_{int} 158 a, t_{mod} 62 a). (2) Additionally, the functional composition shifted, as up to 30% pioneer tree species in particular invaded the forest.

This innovative use of forest growth models may help in the development of ecologically reasonable forest management strategies.

1. Introduction

Forest ecosystems bind carbon and thus have a stabilizing effect on the global climate (IPCC, 2014; Pan et al., 2011; Watson et al., 2018). In particular, tropical forests play an important role in the global carbon cycle (Houghton et al., 2015; Malhi and Grace, 2000), as they store about 363 ± 28 Pg of the Earth's terrestrial carbon in their living biomass (Bonan, 2008; Pan et al., 2013). Logging is widely practiced in topical regions with about half of all humid tropical forests (> 4.0 10^8 ha) that can be designated as production forests (Blaser et al., 2011). Depending on choices of management strategies (e.g. stem diameter of cutting threshold, cutting cycles) of a silvicultural treatment (e.g. enrichment planting, liana pruning, and thinning around potential crop trees), there is a risk that large areas of these forests will change their

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carbon storage behavior from sinks to sources (Putz et al., 2008b; Bonan, 2008). Tropical forests are a net carbon source as a result of human-induced forest disturbances (Baccini et al., 2017) and most of the world's remaining tropical forests are logged (Pearson et al., 2017). Against this background, it is of global relevance that efforts are made to reduce carbon emissions from forestry (Houghton et al., 2015), and forest management strategies also have a key role within the frameworks of climate and biodiversity protection (IPCC, 2014; Pan et al., 2013). Currently, two challenges are discussed by the public: (i) Often, logging techniques applied are not sustainable on a long-term, which may result in ecosystem degradation due to overexploitation (Huth et al., 2004; Molina, 2009; Reischl, 2012; Roopsind et al., 2018; Steffen et al., 2015) and (ii) management decisions may suffer from an incomplete understanding of the long-term effects of forest management strategies on the growth or carbon balance of tropical forests (Houghton et al., 2015; Werger et al., 2011).

On an international level, action programs have been implemented to reduce detrimental impacts of logging. Prominent examples are the climate protection instrument REDD+ (Danielsen et al., 2011; Mollicone et al., 2007; Tyukavina et al., 2015; World Bank, 2011) and certification systems, such as FSC or PEFC (Clark and Kozar, 2011; Durst et al., 2006; Rotherham, 2011). Such programs create incentives through compensation payments or certification of timber to initiate a transformation of conventional forestry into sustainable forest management (Long, 2013). If timber and carbon stocks do not recover at healthy harvesting intervals, these managed forests become susceptible to conversion to intensified land use with all the associated carbon emissions (Asner et al., 2006; Roopsind et al., 2018), and the objectives of the action programs may not be achieved. Different challenges arise: On the one hand, it is difficult to quantify the regional biomass distribution and logging rates on a high degree of detail (Gibbs et al., 2007; Malhi and Grace, 2000; Van Breugel et al., 2011), which is important to estimate variations in the global carbon balance. Regarding this, the vegetation status is one of the most uncertain variables in quantifying the carbon cycle (Pan et al., 2013). On the other hand, the long-term effects of the applied management strategies on forest growth need to be studied (Houghton et al., 2015; Piponiot et al., 2016a). Consequently, a successful implementation of such international action programs requires methods and knowledge to assess the impact of forest management options, such as selective logging, on forest growth in the tropics (De Sy et al., 2015; Molina, 2009; Reischl, 2012; Steffen et al., 2015). Forest models can be used to assess the long-term effects of current management actions (Huth et al., 2004; Shugart et al., 2018) and thus contribute to the decision-making process (De Sy et al., 2015). Complex interrelationships between ecosystem functions and management strategies can thus be revealed.

To investigate the effects of selective logging on the regeneration ability of five forest attributes in French Guiana (Paracou), we applied the individual-based forest growth model FORMIND with a newly implemented management module (Fischer et al., 2016; Kammesheidt et al., 2002). One original aspect of the study are the complex analyses in which the recovery times of several forest attributes were taken into account simultaneously. In addition to biomass, model outputs such as gross primary production, the leaf area index, the functional diversity of the species groups, and timber volume could be projected with a high degree of detail. In our study, we defined the recovery of a specific forest attribute as followed: Once an attribute value has reached its mean value of the pre-logging phase after the simulated logging intervention, we considered the remaining forest stands at the Paracou site as recovered.

The Paracou research station is located in the permanent forest estate (PFE) of French Guiana (Piponiot et al., 2016a). When the Paracou experiment was established in 1982, the main research focus was on timber and its sustainable renewal in order to strengthen the development of management rules in the PFE area. Forestry forms the primary economic sector's main part of the country and about 45% of the PFE areas have been certified according to PEFC (PEFC International, 2017) since 2013. This high proportion demonstrates the importance of forestry for the country and at the same time indicates the interest of the French National Forest Service (ONF) in resource-efficient, modern forestry techniques. The available forest inventory data from Paracou provide an excellent basis for the parameterization of forest models. Cooperation with the ONF helped to further develop model studies, from which other tropical regions can also benefit. The linkage of these precise field data with the individual-based forest growth model FORMIND enabled us for the first time to evaluate the effects of logging on tree growth in a high degree of detail – such as five forest attributes simultaneously, in an annual resolution, for three successional stages – and a qualitatively good reproduction of the observed pre- and post-logging biomass values and tree size distribution. This kind of innovative use of forest growth models can assist in the development of ecologically reasonable forest management strategies.

In this study, we address the following research questions:

1. Is it possible to reproduce the medium-term dynamics of a selectively logged forest with individual-based forest modeling?
2. How do different management intensities (stem diameter of lower cutting threshold) affect the ecosystem functions of the forest (biomass, gross primary production, leaf area index, diversity, timber volume)?
3. How are the recovery rates of the forest's ecosystem functions influenced by logging intensities?

To examine these questions, the FORMIND forest model was parameterized for the Paracou site. Secondly, we compared the simulation results with field data. Then, we analyzed different logging scenarios in simulation experiments. Finally, we analyzed the mean recovery times of diverse forest attributes across logging intensities very detailed from an ecological point of view. For investigating different intensities of selective logging, the model parameter of the minimum stem diameter at breast height of harvestable commercial trees was varied (hereinafter referred to as dbh of lower cutting threshold).

2. Material and methods

2.1. The Paracou test site and forest inventory data

The Paracou test site is located in French Guiana (Location: 5°16′28″N, 52°55′25″W), which belongs to the Guiana Shield, north-eastern of the Amazon Basin. More than 94% of French Guiana's land area is covered with moist lowland *terra firme* rain forest that has a high number of tree species (150–220 species per hectare) and standing biomass (Fauset et al., 2015). The floristic composition is typical of Guianan rainforests with dominant families including Leguminoseae, Chrysobalanaceae, Lecythidaceae, Sapotaceae and Burseraceae (Guitet et al., 2014).

In 1984, twelve 6.25 ha plots, each one divided into 4 subplots of 1.56 ha, were established. All trees with a stem greater than 0.1 m diameter breast height (dbh) have been identified, tagged, mapped, and measured in these plots. From 1986 to 1988 different logging treatments were applied to 9 plots (details in Blanc et al., 2009; Hérault and Piponiot, 2018), with 4 plots established as controls (T0). Furthermore, there was one undisturbed 25-hectare-plot that was set up in 1992. In 3 logged plots (T1), selected timbers were extracted, with an average of 10.4 tress (from 5.8 to 15.4 trees) greater than 0.5 m dbh removed per hectare, corresponding to a timber volume average of 32.5 m^3/ha (from 15.4 to 51.8 m^3/ha). In 8 plots, in which intensive timber stand improvement (TSI) was applied, logging intensity averaged 20.6 trees (from 5.1 to 41.7 trees) greater than 0.5 m dbh removed per hectare, corresponding to a timber volume average of 53.4 m^3/ha (from 12.4 to 109.8 m^3/ha). Subsequent poison girdling of selected non-commercial species killed an average of 16.6 trees greater than 0.4 m dbh/ha. Skid