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Assessing timber volume recovery after disturbance in tropical forests – A new modelling framework

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ABSTRACT

One third of contemporary tropical forests is designated by national forest services for timber production. Tropical forests are also increasingly affected by anthropogenic disturbances. However, there is still much uncertainty around the capacity of tropical forests to recover their timber volume after logging as well as other disturbances such as fires, large blow-downs and extreme droughts, and thus on the long-term sustainability of logging.

We developed an original Bayesian hierarchical model of Volume Dynamics with Differential Equations (VDDE) to infer the dynamic of timber volumes as the result of two ecosystem processes: volume gains from tree growth and volume losses from tree mortality. Both processes are expressed as explicit functions of the forest maturity, *i.e.* the overall successional stage of the forest that primarily depends on the frequency and severity of the disturbances that the forest has undergone. As a case study, the VDDE model was calibrated with data from Paracou, a long-term disturbance experiment in a neotropical forest where over 56 ha of permanent forest plots were logged with different intensities and censused for 31 years. With this model, we could predict timber recovery at Paracou at the end of a cutting cycle depending on the logging intensity, the rotation cycle length, and the proportion of commercial volume.

The VDDE modelling framework developed presents three main advantages: (i) it can be calibrated with large tree inventories which are widely available from national forest inventories or logging concession management plans and are easy to measure, both on the field and with remote sensing; (ii) it depends on only a few input parameters, which can be an advantage in tropical regions where data availability is scarce; (iii) the modelling framework is flexible enough to explicitly include the effect of other types of disturbances (both natural and anthropogenic: e.g. blow-downs, fires and climate change) on the forest maturity, and thus to predict future timber provision in the tropics in a context of global changes.

1. Introduction

Tropical forests are increasingly prone to anthropogenic disturbances: in 2017, only 20% of the remaining tropical forests were considered as undisturbed and structurally intact (Potapov et al., 2017), and this proportion is likely to decrease under future human pressure (Lewis et al., 2015). Disturbances, here defined as occasional events provoking sharp biomass losses (Rykiel, 1985), alter forest structure, notably average tree height (Tyukavina et al., 2016; Rutishauser et al., 2016), thus decreasing in turn carbon and timber stocks (Espírito-Santo et al., 2014). Human activities are increasing the frequency and severity of disturbances in tropical forests, both directly (e.g. through logging

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and fires (Potapov et al., 2017)) and indirectly (e.g. through climate change and forest fragmentation (Laurance and Williamson, 2001)). In this context, assessing the effect of disturbances on the recovery of tropical forests is of paramount importance to better estimate future timber provision. The latter is predominantly done through selective logging that consists in harvesting a few high-value tree species and leaving the rest of the forest to natural recovery. Such forest management is widespread: it has been estimated that between 2005 and 2010, more than 50% of carbon emissions from tropical forest degradation were caused by selective logging (Pearson et al., 2017) and 425 Mha (c. 30% of the world wet tropical forests) are currently intended for timber production by National Forest Services (Blaser et al., 2011; Pan et al., 2013).

Though most of the forest cover is maintained after selective logging, typically 50–90% (Asner et al., 2002; Cannon et al., 1994; Laporte et al., 2007), opening the forest and felling trees has deep environmental consequences, such as an obvious reduction of timber stocks (Keller et al., 2004), but also large carbon emissions due to wood harvest and incidental mortality (Pearson et al., 2014), modification of tree species composition (de Avila et al., 2015) or fauna diversity (Burivalova et al., 2014). In the absence of subsequent disturbances (*e.g.* clear-cutting, fire, new logging events), the forest naturally regenerates and recovers at least part of its ecosystem values (e.g. carbon and timber stocks Piponiot et al., 2016a,b; Rutishauser et al., 2015; Blanc et al., 2009), before being selectively logged again. With logging rotation generally ranging between 20 and 30 years (Blaser et al., 2011), such cutting cycle duration may be sufficient to recover C stocks but not the volume of commercial species (Rutishauser et al., 2015; Roopsind et al., 2017) leading to unsustainable wood production on the long run.

There has been a strong debate over the past two decades on the role of selective logging in production forests as a tool for tropical forest conservation (Rice et al., 1997; Bawa and Seidler, 1998; Putz et al., 2001; Edwards et al., 2014). If logged forests are to be considered as a piece of an integrative conservation scheme, they should at least retain most of their environmental and economical values in time: this is the main challenge for modern tropical forest management. Sustainable forest management is indeed defined by the International Tropical Timber Organisation as "*the process of managing forest to achieve one or more clearly specified objectives of management […] without undue reduction of its inherent values and future productivity and without undue undesirable effects on the physical and social environment*" (ITTO, 1992). Due to the social and economical benefits it brings, sustainable timber harvest is even considered to be an efficient tool that gives additional value to forests that would else be cleared for agriculture (Edwards et al., 2014). One of the cornerstone of sustainability in forest management is the maintenance of high productivity (ITTO, 1992) to allow the recovery of timber stocks at the end of a cutting cycle. This is a critical point as in most selectively logged forests, this criterion is not achieved and many studies report a drop in total volume at the end of the first cutting cycle (Putz et al., 2012).

Previous studies simulating post-logging timber recovery have made large uses of individual-based models (Huth and Ditzer, 2001; Kammesheidt et al., 2001; Valle et al., 2007; Sebbenn et al., 2008) or transition matrix models (Macpherson et al., 2010; Gourlet-Fleury et al., 2005a,b). Such models perform well at locally predicting forest dynamics (Liang and Picard, 2013), but their high level of complexity and data requirements make the understanding of emergent patterns uneasy (Grimm, 2005). Furthermore, recruitment of small trees is a key process for long-term prediction in transition matrix models as well as in individual-based models (Liang and Picard, 2013; Berger et al., 2008; Fischer et al., 2016) and requires data from permanent sample plots with measurements of trees from relatively low size classes, typically above 10 cm of Diameter at Breast Height (DBH) or less (Gourlet-Fleury et al., 2005a,b; Phillips et al., 2004). Because small trees are particularly numerous in tropical forests, measuring them is costly (Picard et al., 2010; Kiyono et al., 2011): for example it takes approximately 10–15 times longer to measure all trees above 10 cm DBH than only trees above 50 cm DBH (Alder and Synnott, 1992). In this context, high-quality data coming from long-running permanent sample plots remain scarce in the tropics, hampering large-scale modelling of forest dynamics that would feed forest management plans with robust productivity predictions (Picard et al., 2010).

On the other side of the spectrum, coarse scale models such as Dynamic Global Vegetation Models (DGVM; e.g. LPJ-DGVM Sitch et al., 2003) allow efficient large-scale forest dynamics prediction with little input data, relying on a wide set of mechanistic assumptions. These models were initially developed to simulate ecosystem carbon fluxes, but can be used to predict volume dynamics when coupled with individual-based models (e.g. SEIB-DGVM Sato et al., 2007). Nevertheless DGVMs generally adopt a top-down approach, and are thus not fit to integrate field data such as inventory data, that are merely used for validation. As a consequence DGVMs can sometimes have conflicting results and poorly predict observed regional patterns of carbon dynamics (Johnson et al., 2016).

In this study, we propose an original model of Volume Dynamics with Differential Equations (VDDE) to assess total volume stocks and recovery based on forest inventory data. Instead of using detailed information (*i.e.* all trees) to model all demographic process (*i.e.* recruitment, growth and mortality) with great precision, we deliberately chose to favour model simplicity and rely upon broadly available data, *i.e.* the volume of all trees above 50 cm DBH (the official minimum cutting DBH in most tropical countries Blaser et al., 2011) hereinafter referred to as total volume. The VDDE model was developed and calibrated with data from the Paracou research station, a long-term large-scale disturbance experiment in Amazonia, where 56 ha of tropical forest have been monitored for 30 years after being disturbed (selective logging, poison girdling, fuelwood harvesting).

Anthropogenic or natural disturbances, such as logging or droughts, affect forests as a whole and induce a shift in forest functioning (Hérault and Piponiot, 2018). Even though the return frequency of these episodic succession-inducing events is not well known, this abrupt disturbance – slow recovery has long been described in tropical forests, as well as in temperate and boreal forests (Frolking et al., 2009; Liu et al., 2011; Chambers et al., 2013). Our assumption is that both the volume gain and the volume loss from mortality (hereinafter referred to as volume mortality) inherently depend on the overall successional stage of a forest (Rödig et al., 2018; Volkova et al., 2018), hereinafter referred to as forest maturity. While at our study site, a limited number of disturbances (selective logging, poison girdling and fuelwood harvesting) were experienced, tropical forests may undergo many other forms of anthropogenic and natural disturbances, such as droughts or fires that, similarly to logging, are associated with over-mortality that can drastically decrease trees > 50 cm DBH volume. Their effect on the forest volume dynamics can thus be modelled within the VDDE framework as a decrease in the forest maturity.

2. Methods

2.1. Study site

The study is based on data from Paracou research station (5°18′ N, 52°55′ W), a long-term large-scale disturbance experiment located in a lowland tropical forest in French Guiana (Gourlet-Fleury et al., 2004). The climate is affected by the north/south movements of the Inter-Tropical Convergence Zone and the site receives nearly two-thirds of its annual 3041 mm of precipitation between mid-March and mid-June, and less than 50 mm per month in September and October (Wagner et al., 2011). The forest composition is typical of the Guyana Shield rainforests (ter Steege et al., 2013), dominated by Chrysobalanaceae, Fabaceae and Lecythidaceae, and with approximately 180 species of trees ≥ 10 cm DBH per ha. 12 permanent forest plots (75 ha total) were