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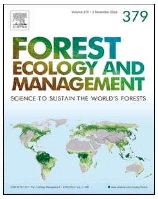

The imprint of logging on tropical forest carbon stocks: A Bornean case-study

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ABSTRACT

In tropical forests, selective logging generates a significant reduction of above-ground carbon stocks, due to direct removal of a few large merchantable individuals, and the death of smaller injured or smashed trees following harvesting. Several studies have shown a strong correlation between logging intensity and a reduction of biodiversity, wood production, and biomass stocks. However, little is known about the long-term effects of logging on the main forest carbon (C) stocks in above and below-ground tree biomass, deadwood, litter, and soil. In this study we quantified C stocks in 28 0.25-ha plots located in a mixed Dipterocarp forest, Borneo, Indonesia, logged 16 years ago at different intensities ranging from 0 to 57% of initial biomass removed. We investigated the effect of logging intensity, topography, and soil variables on each C stock using linear mixed models. Sixteen years after logging, total C stocks ranged from 218 to 554 Mg C ha^{-1} with an average of 314 ± 21 Mg C ha^{-1}, of which more than 75% were found in live trees. Logging intensity was found to be the main factor explaining the variability in carbon stored in above- and below- ground biomass of tree DBH > 20 cm and deadwood. Simultaneously, the proportion of deadwood increased with logging intensity reaching 13.5% of total C stocks in intensively logged plots (> 20% removal of initial biomass). This study confirmed, therefore, the need to limit logging intensity to a threshold of 20% of initial biomass removal in order to limit the long-term accumulation of deadwood after logging, probably due to high post-logging mortality. With more than half of all Bornean forests already logged, accounting for total C post-logging is key to better assess the long-term carbon footprint of commercial logging in the region, and is a necessary step towards the development of C-oriented forest management in the tropics.

1. Introduction

Bornean forests have mainly been exploited since the 1960s and with little concerns on ecological drawbacks and no implementation of appropriate logging and management practices (Nasi and Frost, 2009; Nicholson, 1979; Putz et al., 2008). With increasing awareness on the fast degradation of Bornean forests, guidance to reduce the negative impacts of logging have been proposed since the 1990s, but remains poorly implemented in practice (Nasi and Frost, 2009). In 2010, almost half of the Bornean forests had been affected by commercial timber extraction (Gaveau et al., 2014) and deforestation is still ramping up at high rate due to fast expansion of commercial plantations, such as oil palm (Margono et al., 2014). The remaining tropical forests, not only in Borneo, but all around the tropics, are under increasing anthropogenic pressure (Potapov et al., 2017) and logged forests are likely to play a key role in the future provision of ecosystem services, such as the production of wood, sequestration of carbon and maintenance of biodiversity (Edwards et al., 2014; Sist et al., 2015).

Even though reduced-impact logging techniques have been proposed and applied in the tropics (Miller et al., 2011; Putz et al., 2008), poor implementation of these prescriptions still makes selective logging largely detrimental for tropical forest ecosystems. Widespread damages to residual stands and soils (e.g. Picard et al., 2012; Pinard et al., 2000) induced long-lasting reduction of both biomass (Rutishauser et al., 2015) and timber (Vidal et al., 2016) stocks. Incidental damages are unavoidable, being directly related to logging intensity (Sist et al.,

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2003b) and to the methods of tree felling and skidding (Pinard and Putz, 1996; Sist and Nguyen-Thé, 2002). Carbon (C) emissions induced by incidental damages, log wastes, and infrastructures can be up to 2–3 times higher than the C emissions related directly to extracted logs (Pearson et al., 2014). Recent studies showed that commercial logging was found to be a major source of green-house gas emission, forming up to 50% of annual emissions related to forest degradation (Pearson et al., 2017).

While timber is generally exported, incidentally killed trees, along with logging residues, remain in the forest as deadwood and slash in the forest floor and can form up to 50% of total C stocks in logged forests (Osone et al., 2016; Pfeifer et al., 2015). By creating large canopy gaps, logging also affects the production of litter (Prasetyo et al., 2015). In logging gaps, the increased temperature on the forest floor was shown to enhance the decomposition of deadwood and litter (Zhang et al., 2008; Zhou et al., 2007). Further, increased availability of C in soil may accelerate the decomposition of deeper organic material in the soil where the micro-fauna is nutrient limited (Fontaine et al., 2004). This phenomenon is called priming effect (Fontaine et al., 2003) and may explain the sharp decrease of SOC observed 50 years after logging in a tropical logged African forest (Chiti et al., 2015).

Most C studies investigating the effects of logging in Bornean forests have focused on above-ground biomass (e.g. Ioki et al., 2014; Kenzo et al., 2010; Morel et al., 2011) with a few exceptions also looking at other C pools (e.g. Osone et al., 2016; Pfeifer et al., 2015; Saner et al., 2012). A better understanding of the distribution and variability of C stocks in logged forests is required to accurately estimate the carbon footprint of logging activities. The present study offers to quantify carbon stocks in five major pools, namely above and below-ground tree biomass, deadwood, litter, and organic carbon in soil at Malinau Research Forest, Borneo, Indonesia. Based on the hypothesis that logging has a significant influence on C stocks after 16 years, this study specifically aims to: a) estimate total C stocks and the proportion of each C pool along a gradient of logging intensity (ranging from 0 to 57% of initial biomass removed), and b) identify the factors influencing the variability in these C pools. Getting detailed estimates of C stocks post-logging and knowing the effect of logging intensity on total C stocks will help refine the carbon budget of managed forests and develop C-oriented forest management.

2. Materials and methods

2.1. Study site

Malinau Research Forest (MRF) was established in 1998/1999 with the aim to develop a sustainable forest management program that reduces logging-impacts and preserves the biodiversity along with the wellbeing of local communities (Cifor and ITTO, 2002; Gunarso et al., 2007; Sist et al., 2003b). MRF is located in a logging concession owned by PT Inhutani II in Malinau, North Kalimantan (2°45′N, 116°30′E). The area is 100–300 m above sea level with 10–70% slope and an annual rainfall of around 3790 mm. The forest is mainly composed of Dipterocarps, of which most species are prized commercial species, and stands among the most diverse Indonesian forests with 205 tree species inventoried (Sheil et al., 2010). MRF was selectively logged in 1999/2000 with different intensities, ranging from 3 to 13 trees harvested per hectare (Sist et al., 2003b). The Indonesian selective logging and planting system (TPTI) allows all commercial trees with diameter at breast height (DBH) over 50 or 60 cm (depending on the forest type) to be harvested within a felling cycle of 35 years. In MRF, the targeted commercial tree species were *Agathis borneensis*, *Dipterocarpus* spp., and *Shorea* spp. (Sist et al., 2003b).

2.2. Experimental design

Twenty-four 1-ha plots (100 m × 100 m) were randomly established in 1998/1999 before logging occurred (Sist et al., 2003b). In each plot, all trees with a DBH > 20 cm ($DBH_{>20}$) were mapped, tagged, and identified to the lowest taxonomic level. Trees were identified by a professional botanist in 1999/2000 and herbarium vouchers were deposited in Herbarium Bogoriense. A total of 6696 trees were identified at species (85.1%), genus (10.7%), and family (4.2%) levels. Logging took place in 1999/2000. An overview of logging intensity and techniques used in MRF is given elsewhere (Sist et al., 2003b). Before logging (1999), all trees $DBH_{>20}$ were systematically recorded, girth at breast height measured and crown forms and positions recorded. Tree status (live or dead), stem damages, and cause of death of all trees were recorded in all plots 8 months after logging (Sist et al., 2003b). In 2015, 7 out of 24 1-ha plots were surveyed and diameter of all trees $DBH_{>20}$ was measured at 130 cm or 50 cm above any buttress or deformity. Additionally, in 2016, ten quadrats of 10 m × 10 m were randomly placed in each of those 7 plots to measure trees with DBH between 5 and 20 cm ($DBH_{5\text{-}20}$), deadwood, and litter. For 2015 and 2016 measurements, trees were identified by an experienced parabotanist at species (74.9%), genus (25%), and family (0.1%) levels. Tree girths were measured at 130 cm using a tape meter and converted into diameter, while total and trunk heights were measured using a laser rangefinder (Bushnell G-Force 1300 ARC). After data collection, a soil pit was dug in 2 quadrats chosen randomly in each plot (except in plot C09 where 3 pits were dug) leading to a total of 15 soil pits.

2.3. Logging intensity and C stocks

Logging intensity is defined as the ratio between the biomass lost at first post-logging measurement and pre-logging biomass stock (expressed as a percentage of pre-logging biomass). Biomass lost corresponds to the summed biomass of timber harvested and injured trees that died before the first post-logging census. Usually injured trees will die during the first 2 years after logging (Shenkin et al., 2015; Sist et al., 2014) and damages will be concentrated around gaps created by harvested trees (Pearson et al., 2014). Logging intensity was estimated at 0.25-ha scale (each plot was divided into 4 subplots (50 m × 50 m) giving 28 subplots in total) to account for the large heterogeneity in logging treatment and damages within 1-ha plots. Logging intensity ranged from 0 to 57% of initial biomass lost (Table A1). Neither tree biomass, nor logging intensity was not found spatially correlated above 30 m (Figs. A1 and A2), avoiding pseudo-replication among subplots.

Five main C stocks were assessed as recommended by IPCC (2006), and quantified within each subplot: C stored in (i) live trees with a DBH between 5 and 20 cm, hereinafter $AGC_{5\text{-}20}$, and larger than 20 cm DBH ($AGC_{>20}$), (ii) coarse roots of trees DBH 5–20 and > 20 cm (referred to as $BGC_{5\text{-}20}$ and $BGC_{>20}$, respectively), (iii) deadwood composed of coarse woody debris (CWD) having a diameter > 10 cm and standing dead trees DBH > 10 cm, (iv) litter, and (v) soil organic carbon in the top 1 m (SOC). Carbon stocks were calculated using a nested design: $AGC_{>20}$ and $BGC_{>20}$ were estimated across the whole 0.25-ha subplot, whereas $AGC_{5\text{-}20}$, $BGC_{5\text{-}20}$, CWD, litter, and SOC were estimated in the 10 × 10 m quadrats and then averaged by subplot. For the sake of simplicity, a default ratio of 47% was used to estimate the carbon content of both live and dead biomass (IPCC, 2006). Total C stocks correspond to the sum of all five C stocks at subplot level expressed in Mg C ha^{-1}.

2.3.1. Above- and below ground biomass (AGB and BGB)

AGB was estimated using a generic allometric model including DBH, wood density (ρ) and a climate index (E) (Chave et al., 2014). Such generic allometric models were shown to be more accurate and less biased than local models, notably in Dipterocarp forests (Rutishauser et al., 2013). Wood densities arise from the Global Wood Density Database (Chave et al., 2009; Zanne et al., 2009) using the lowest taxonomic level available. For species not present in the database, a wood density of $\rho = 0.58\ g\ cm^{-3}$ were used. Root biomass ($BGB_{>20}$ and