

Identifying thresholds of logging intensity on dung beetle communities to improve the sustainable management of Amazonian tropical forests



Filipe M. França^{a,b,*}, Fábio S. Frazão^c, Vanesca Korasaki^d, Júlio Louzada^{a,b}, Jos Barlow^{a,b,e}

^a Lancaster Environment Centre, Lancaster University, Bailrigg, Lancaster LA1 4YQ, United Kingdom

^b Departamento de Biologia, Universidade Federal de Lavras, Lavras, MG 37200-000, Brazil

^c Memorial University of Newfoundland, 230 Elizabeth Ave, St. John's, NL A1B 3X9, Canada

^d Universidade do Estado de Minas Gerais, Av. Prof. Mario Palmério, 1001, Frutal, MG 38200-000, Brazil

^e Museu Paraense Emílio Goeldi, Av. Magalhães Barata, 376, Belém, PA 66040-170, Brazil

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ABSTRACT

Selective logging is the most widespread driver of tropical forest disturbance. As such, it is critically important to identify at which spatial scale logging intensity should be measured and whether there are clear thresholds in the relationship between logging intensity and its impacts on biodiversity or ecological processes. We address this using a robust before-and-after logging experimental design in the Brazilian Amazon, using a gradient of logging intensity measured at two different spatial scales. We assessed the impacts of selective logging using dung beetle communities and their ecological functions of dung removal and soil bioturbation. Our findings provide novel empirical evidence that biological consequences from Reduced Impact Logging (RIL) depend strongly on the scale at which logging intensity is measured: dung beetle local species richness and composition were strongly associated with logging intensity measured at a 10 ha scale, while dung beetle-mediated soil bioturbation was more strongly associated with logging intensity measured across 90 ha. Contrary to expectations, we found concave-shaped relationships between logging intensity and biodiversity and ecosystem functioning, demonstrating that sensitive dung beetle species and important processes may be lost following even low intensity anthropogenic forest disturbances. Taken together, these results suggest that production forests in the tropics need to reconsider the scale at which logging intensity is regulated, and put in place measures that further incentivise land sparing to enhance biodiversity conservation.

1. Introduction

> 403 million hectares of tropical forests have been officially designated for timber concessions (Blaser et al., 2011), where selective logging is one of the most widespread economic activities (Guariguata et al., 2010). Although it is undoubtedly less environmentally severe than many other human disturbances (Barlow et al., 2006; Gibson et al., 2011), selective logging remains an important driver of tropical forest degradation (Gatti et al., 2015), reducing carbon stocks (Berenguer et al., 2014) and negatively affecting both forest biodiversity (Barlow et al., 2016; Martin et al., 2015) and ecosystem functioning (Griscom et al., 2017; Slade et al., 2011). Given its spatial extent and economic importance, improvements in the sustainability of forest management are fundamental for conservation in the tropics (Bicknell et al., 2014b); sustainable forest management is the most adopted REDD + intervention in tropical regions (Salvini et al., 2014) and is enshrined as a key aim of international biodiversity targets for 2020 (Convention on

Biological Diversity, 2014).

Although the ecological consequences of Reduced Impact Logging (RIL) operations are well studied, there are three key knowledge gaps which limit the ability of ecological science to inform policy and management decisions. First, there is no evidence to determine the most appropriate spatial scale for prescribed limits on logging intensity. For example, Brazilian Forestry legislation (CONAMA, Resolution no. 1 of 2015) requires Annual Planning Units in Amazonia to maintain at least 15% of all large trees, or three large trees per 100 ha from each exploited species, as seed bearers. However, these requirements, including the use of the 100-ha scale, are not supported by scientific evidence. This lack of information is important as a growing number of studies on different taxa demonstrate spatial scale-dependent responses of species richness to logging impacts (Cleary et al., 2009; Imai et al., 2012), and there is also growing evidence that other biological metrics could respond to forest degradation at different spatial scales (Martel et al., 2007; Solar et al., 2015).

* Corresponding author at: Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, United Kingdom.
E-mail address: f.machadofranca@lancaster.ac.uk (F.M. França).

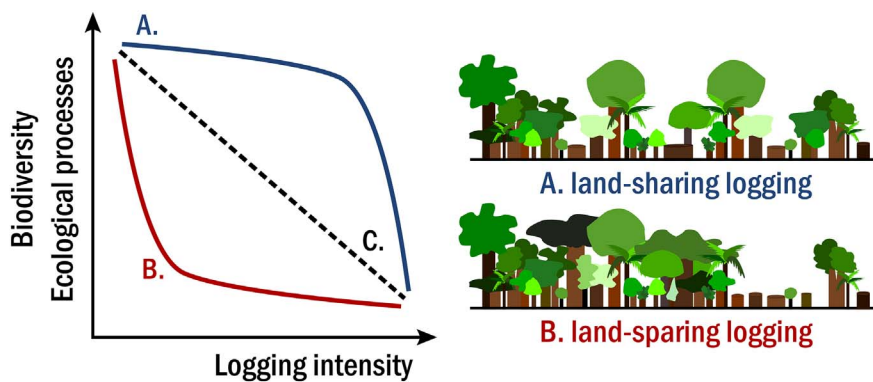


Fig. 1. Theoretical non-linear relationships between logging intensity and metrics of ecological integrity. Concave (or concave-down) responses to increasing logging intensity (A, in blue) would support land-sharing strategies, with logging intensities set below the changepoint. Convex (or concave-up) responses (B, in red) suggest land-sparing would be a more effective way of preserving biodiversity and ecological functions. Existing evidence (Burivalova et al., 2014) suggests there is a linear decrease in species richness across multiple taxa (C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The second key limitation relates to the shape of the biological responses to logging intensity. Recent meta-analysis studies have demonstrated that logging impacts on forest structure and biodiversity are proportional to logging intensity (Burivalova et al., 2014; Martin et al., 2015). They also highlight the possibility of non-linear biological responses, suggesting there may be thresholds in logging intensity above which animal species richness decreases (Burivalova et al., 2014). Defined as change points or zones at which sudden regime shifts occur from one ecological condition to another, ecological thresholds are likely if disturbance intensity induces non-linear effects on community structure, composition and ecological functioning (Huggett, 2005). Identifying these thresholds is therefore a major challenge for improving the sustainability of forest management (DeFries et al., 2004), and depending on the shape of the biodiversity response (Fig. 1), could even help inform decisions about the land-sparing vs. land-sharing logging management debate (Edwards et al., 2014a; Law and Wilson, 2015; Phalan et al., 2011). Yet, no study has identified any such threshold with selective logging (Burivalova et al., 2014).

Finally, despite progress made in our understanding of the logging impacts on species composition and ecosystem functions (Ewers et al., 2015; Imai et al., 2012), the majority of these investigations treat selective logging as a uniform disturbance with mean effect size. As a result, we still lack empirical evidence outlining how multiple metrics of ecological integrity, including species composition and ecological functioning, respond along gradients of selective logging intensity.

We address the above knowledge gaps using a robust Before-After-Control-Impact (BACI) experimental design in the eastern Brazilian Amazon to assess how logging intensity, and the spatial scale at it is measured, affects dung beetle species richness, biomass, species composition, and their associated ecological functions of dung removal and soil bioturbation. We focus on dung beetles (Coleoptera: Scarabaeinae) as they are good predictors of responses of many other taxa (Edwards et al., 2014b; Gardner et al., 2008a) and have been recommended as cost-effective and highly responsive indicators of changes caused by human disturbances in tropical forests (Bicknell et al., 2014a; França et al., 2016a). We focus on richness and composition as these metrics have been frequently used to assess changes in α (local diversity) and β -diversity (compositional turnover), respectively (Gardner et al., 2008b; Socolar et al., 2016). We include biomass because it has been frequently used to evaluate the consequences of tropical forest degradation on dung beetles (França et al., 2016b; Griffiths et al., 2016b) and is a key trait influencing dung beetle-mediated ecological functions (Gregory et al., 2015; Griffiths et al., 2016a). Finally, we measure the dung burial and soil bioturbation functions (Nichols et al., 2008), which provide insights into how dung beetles may modify the soil microflora (Slade et al., 2016b), enhance the plant growth (Griffiths et al., 2016a; Yamada et al., 2007), and even reduce greenhouse gas emissions (Slade et al., 2016a).

We explore two hypotheses. First, while management decisions limiting timber extraction are made on a 100-ha scale, we predict that

smaller scale (10 ha) measurements of logging intensity will better predict responses of dung beetle community metrics and ecological functions. This is because logging intensity varies more when measured at smaller scales (large scales tend to converge to landscape averages) and because dung beetles are known to be sensitive to local changes in forest structure and microclimate following disturbance (Mehrabi et al., 2014; Silva and Hernández, 2016). Second, we use the spatial scale identified as the strongest predictor in the first hypothesis to examine the shape of the responses of dung beetle metrics to gradients of selective logging intensity. We predict that these relationships will be better explained by threshold-like models that are concave in shape rather than linear ones. We make this prediction because (a) concave-shaped threshold relationships have been found in land-use change studies assessing the relationships between forest cover and estimates of species richness based on multiple taxa (Muyllaert et al., 2016; Ochoa-Quintero et al., 2015), and because (b) dung beetle diversity and ecological functions are known to decrease in highly disturbed forests (Braga et al., 2013), but can be maintained in low-intensity logged forests (Slade et al., 2011) or even after repeated logging rotations (Edwards et al., 2014).

2. Methods

2.1. Study area

The study was based within the 1.7-Mha *Jari Florestal* logging concession located at the State of Pará in the north-eastern Brazilian Amazon (0°27'S 51°40'W; Appendix A, Fig. A.1). The region comprises a mosaic of regenerating native vegetation and *Eucalyptus* plantations embedded within a large matrix of virtually undisturbed primary forests (Barlow et al., 2010; Gardner et al., 2008b).

This RIL concession covers about 544,000 ha of native forest, and the logging plan follows the FAO model code over a 30-year cutting cycle (Dykstra and Heinrich, 1996). During the pre-harvest inventory the logging concession is subdivided into 10 ha (250 × 400 m) planning units where commercially viable trees with d.b.h ≥ 45 cm are mapped, identified and measured to provide the basis for planning the logging. The harvesting and extraction of timber along skid trails take place during the dry season (August to November), one year after the planning inventory. RIL is supported by using directional felling to minimize incidental damage to other trees, and cutting lianas on large trees during the inventory stage (Putz et al., 2008).

2.2. Experimental design

We used the company's pre-harvest operational plan to select 34 sites (hereafter sample units) in the timber concession. These included five control sites that would not be logged during the course of the study, and 29 logging units which were destined to be logged between July and September 2012. As we aimed to assess the logging impacts as

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