



The impact of logging roads on dung beetle assemblages in a tropical rainforest reserve



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ABSTRACT

The demand for timber products is facilitating the degradation and opening up of large areas of intact habitats rich in biodiversity. Logging creates an extensive network of access roads within the forest, yet these are commonly ignored or excluded when assessing impacts of logging on forest biodiversity. Here we determine the impact of these roads on the overall condition of selectively logged forests in Borneo, Southeast Asia. Focusing on dung beetles along >40 km logging roads we determine: (i) the magnitude and extent of edge effects alongside logging roads; (ii) whether vegetation characteristics can explain patterns in dung beetle communities, and; (iii) how the inclusion of road edge forest impacts dung beetle assemblages within the overall logged landscape. We found that while vegetation structure was significantly affected up to 34 m from the road edge, impacts on dung beetle communities penetrated much further and were discernible up to 170 m into the forest interior. We found larger species and particularly tunnelling species responded more than other functional groups which were also influenced by micro-habitat variation. We provide important new insights into the long-term ecological impacts of tropical logging. We also support calls for improved logging road design both during and after timber extraction to conserve more effectively biodiversity in production forests, for instance, by considering the minimum volume of timber, per unit length of logging road needed to justify road construction. In particular, we suggest that governments and certification bodies need to highlight more clearly the biodiversity and environmental impacts of logging roads.

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1. Introduction

Large areas of intact habitats rich in biodiversity are being opened up through extractive industries, including selective logging. Logging concessions account for ≈50% of the total area of tropical forests (Blaser et al., 2011), yet a largely overlooked impact of timber extraction is the creation of logging roads. Roads are an integral part of extractive industries, which require not only large transportation routes, but also secondary haulage trails and smaller access pathways, creating a sprawling ‘fishbone’ pattern of compressed barren surfaces mostly unpaved. For instance, in Borneo alone it is estimated there are over 270,000 km of such logging roads (Gaveau et al., 2014).

Roads can have negative ecological consequences by removing and degrading adjacent habitat, acting as barriers to dispersal, creating edge effects, and increasing the risk of road kill, fire, hunting and the

colonisation by invasive species (Laurance et al., 2009; Benitez-Lopez et al., 2010; Rytwinski and Fahrig, 2013; Clements et al., 2014; Padmanaba and Sheil, 2014; Dar et al., 2015). The construction of roads across the tropics is therefore an urgent concern for conservation (Laurance and Balmford, 2013; Bicknell et al., 2015; Barber et al., 2014; Laurance et al., 2014), but further attention is needed to evaluate the long-term impacts of logging roads, which remain in the landscape long after logging has been completed (Gullison and Hardner, 1993; Ernst et al., 2016). Few studies, however have focused on the impacts of roads in tropical forests, let alone specific logging roads. Understorey bird communities were observed to decline, while termite community composition differed with proximity to unpaved road clearings in Amazonia (Laurance, 2004; Dambros et al., 2013). Dung beetle communities were negatively affected by logging dumps, skid trails and access roads shortly after logging in Malaysia (Hosaka et al., 2014a), and small mammal community composition differed between logging road types (variations in size, use and time since abandonment) in Central Africa (Malcolm and Ray, 2000). However, most studies of the impacts

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of logging on biodiversity have either explicitly or implicitly avoided roads in their sampling protocols, leading to calls for further studies of their impacts on biodiversity and ecosystem functioning (Hamer et al., 2003; Broadbent et al., 2008; Laufer et al., 2013).

This study is based within a 1 Mil ha logging concession in Sabah, Malaysian Borneo. Selective logging has been widespread in this region with extraction levels some of the highest globally (Cleary et al., 2007). In Sabah alone the total length of logging roads is estimated at >37,000 km, with a density of 0.65 km per km² (Gaveau et al., 2014). Timber extraction in the immediate area of our study site was completed 23 years ago, which provides an ideal opportunity to examine the long-term impacts of logging roads across a large scale and through continuous forest. We use dung beetles (Coleoptera: Scarabaeidae, Scarabaeinae) as our model taxon, as they are a key indicator group that contributes to diverse ecosystem processes (Gardner et al., 2008; Nichols et al., 2008) and is sensitive to environmental changes (Nichols et al., 2007).

The question of how far edge effects alongside roads penetrate into the forest is vital for understanding the overall impacts of logging on biodiversity. We address this key question by investigating the magnitude and extent of edge effects along logging roads (Harper et al., 2005; Harper and Macdonald, 2011), focusing on key vegetation and soil characteristics, and the species richness, community composition and abundance of different dung beetle functional groups. We then assess whether changes in vegetation characteristics can explain the observed changes in dung beetle community structure from the road edge to the logged forest interior. Finally, we compare logged forest with nearby primary forest to assess the additional impact of roads on dung beetle biodiversity, beyond that directly attributable to harvesting of timber.

2. Material and methods

2.1. Study location

The study site was the Yayasan Sabah (YS) logging concession in eastern Sabah (4° 58' N, 117° 48' E). Most of this concession (95%) has been selectively logged, including the 238,000 ha Ulu Segama-Malua Forest Reserve (US-MFR) of which 97,000 ha (41%) has undergone a single rotation of timber extraction (once-logged forest). Harvesting took place between 1987 and 1991, with a yield $\approx 115 \text{ m}^3$ of timber per ha (Fisher et al., 2011), and 17% of the land area was marked by roads and skid trails (Pinard and Cropper, 2000). All roads used in this study are un-paved and are still in use and maintained, though not for logging activities. Vegetation along the road edge varies in height and complexity due to initial logging activities and more recent maintenance (e.g. repairing of collapsed bridges).

2.2. Dung beetle and vegetation sampling

Fieldwork was conducted between August and October 2009, March and September 2011, and June and August 2014. To quantify changes in dung beetle assemblages in proximity to roads, we created 24 sampling plots which were widely spaced across the landscape with a minimum distance of 650 m (mean \pm SD: 5.9 km \pm 3.7) between plots. Each plot contained six traps at distances of 0 m, 6 m, 12 m, 25 m, 50 m and 100 m from the road edge (144 traps in total). To ensure independence of samples, traps were a minimum of 50 m apart (Larsen and Forsyth, 2005) in a staggered design following Barnes et al. (2014) (see Fig. A1). We considered that edge effects were unlikely to extend beyond 100 m (Benedick et al., 2006; Broadbent et al., 2008; Lucey and Hill, 2011; Gray et al., 2016) but to check whether or not this was the case and to determine how dung beetle assemblages differed between road edges and the interior of logged forest, we also placed traps ($n = 58$) 100 m apart along 14 transects at distances of 170 m to 550 m from the nearest road edge, with 4–5 traps per transect and a minimum distance of 500 m (mean = 11.9 km \pm 8.5) between transects. We also sampled

in primary forest, using 60 traps placed a minimum of 100 m apart along 12 transects of five traps each (mean distance between transects = 4.5 km \pm 3.0) (see Fig. 1). We used standardised baited pitfall traps for all sampling. In each case a single trap, baited with human dung, was placed for four days and re-baited after 48 h, with beetles collected every 24 h (Edwards et al., 2011). We used reference collections (T. Larsen) housed at the Forest Research Centre, Sandakan, Malaysia and Smithsonian Museum, Washington DC, USA to assist identification.

Species vary greatly in their contributions to community biomass, which in turn can affect ecosystem functioning (Slade et al., 2007). To determine biomass per trap, we calculated the average mass (g) of each dung beetle species, multiplied this by the number of individuals in a trap, and summed across species. To determine body masses, individuals (up to a maximum of 15 per species) were dried for four days at 60 °C and weighed to the nearest 0.001 g using a precision balance (SBC 31; Scaltec Instruments GmbH, Germany). We also measured body length (base of head to tip of elytra) and width (distance between outer margins of elytra), to the nearest 0.1 mm using dial callipers and calculated body size (length * width) to allow extrapolation of body mass for species that could not be weighed (Text B1, Fig. B1).

Additionally, 15 micro-habitat variables were measured at each sampling location within 100 m of the road edge ($n = 144$) and a subset of interior forest locations ($n = 24$) to determine how soil characteristics, leaf litter depth and vegetation structure, including tree characteristics, varied with distance from the road edge (Text C1).

2.3. Data analysis

2.3.1. Edge effects

To examine how species richness, abundance and biomass of dung beetles, the abundance of different functional groups, vegetation structure and soil characteristics varied with distance from the road edge, we firstly used a piecewise regression to determine if a breakpoint (an abrupt change in a relationship) in our data was present. We ran a GLM with negative binomial error distribution (or in the case of certain vegetation variables a LM) with *distance* as a continuous variable, and then using this model we ran a piecewise regression (using the *segmented* package in R). To determine if the piecewise regression was the best model we compared AIC values (following Ochoa-Quintero et al., 2015; Magnago et al., 2015). The piecewise regression allowed us to determine whether there was a significant influence of distance and to identify any discrete breakpoint in a particular variable ($P < 0.05$).

Secondly, we assessed the magnitude of edge influence (MEI: Harper and Macdonald, 2011; Dodonov et al., 2013), described as the amount a particular variable differs at the 'edge' compared to the 'interior', using the calculation of $MEI = \frac{(e-i)}{(e+i)}$ where e represents the average of a given variable at a *particular distance* from the edge, and i represents the average of a given variable within the *interior* habitat away from the edge. If a given distance from the edge (e) is equal to the interior (i) then $MEI = 0$, MEI is bounded by 1 and -1 allowing for ease of comparison between variables. To examine the distance over which edge effects penetrated into the forest adjacent to roads (referred to as the distance of edge influence - DEI) we used a randomised method of edge influence (RTEI: Harper and Macdonald, 2011), described as the range of distances away from the edge (towards the interior) where there is a significant edge influence (Harper et al., 2005). This method follows three steps; i) observed MEI is calculated, ii) then randomised values of MEI are calculated from a complete variable pool (edge plus interior values) where the number of edge and interior sites are kept constant, and iii) then randomised values of MEI are compared to observed values to determine the significance of observed MEI (see Harper and Macdonald, 2011 for further details). The analyses were run separately for each distance (e) away from the road edge. This randomisation technique reduces type 1 errors by accounting for variation between sampling sites at a specific distance from the edge. We used 10,000

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