The effects of reduced impact logging and logging intensity on stand
damage, biomass loss and tree species richness in tropical forests: a
meta-analysis

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Abstract

Background. At least a fifth of tropical forests have been logged in the recent past. This practice is an important source of timber but there are concerns about its long-sustainability and impacts on biodiversity and carbon storage. However, there is wide variation in the impacts of logging, making generalisation, and thus policy implementation, difficult. Recent syntheses of animal biodiversity have indicated that differences in logging intensity – the volume of wood removed per hectare – may help explain some of these differences. In addition there have been suggestions that reduced impact logging (RIL) may reduce some of the negative effects of logging.

Methods. We aimed to test these hypotheses using meta-analyses to explore differences in the impacts of logging on (1) residual tree damage, (2) aboveground biomass and (3) tree species richness.

Results. Our results indicate that RIL may reduce residual tree damage when compared to conventional methods, but that at higher logging intensities this effect is negated. Changes in aboveground biomass were negatively related to logging intensity, but any effect of RIL was obscured by it being carried out at relatively low intensities. Tree richness appeared to initially increase at low intensities but was reduced at higher intensities.

Discussion. Our results give only weak support to the hypothesis that RIL reduces the negative impacts of logging on tree damage, and do not support suggestions that RIL reduces loss of biomass or species richness. However, we do not think this is because there is no difference between the impacts of RIL and conventional logging but rather that better evidence is needed to assess these differences. We suggest that studies that take account of plot-level differences in logging intensity are likely to provide a solution to this knowledge gap.
Introduction

Over 400 million hectares of tropical forest are designated as logging concessions (Asner et al., 2009), making selective logging – the removal of selected trees from a stand – one of the most widespread human disturbances in tropical forests (Asner et al., 2009). Tropical logging produces approximately one eighth of global timber (Blaser et al., 2011) and is an important contributor to many local and national economies. However, logging can have negative impacts on biodiversity (Berry et al., 2010) and lead to increased carbon emissions (Bryan and Shearman, 2010; Nepstad et al., 1999). Current practices can endanger the long-term sustainability of timber production (Gourlet-fleury et al., 2013) and there have been suggestions that we may be approaching ‘peak timber’ in the tropics (Shearman et al., 2012).

Logging impacts are driven by its effects on mortality and recruitment of trees and thus forest structure. Mortality of large trees in selectively logged forests is high compared to undisturbed forests, since large trees are usually those with highest timber value and are therefore more likely to be harvested (Lindenmayer et al., 2013) However, mortality of smaller non-timber trees is also often increased in logged forests when compared to undisturbed forests, since harvesting and transportation of logs can result in damage to non-target trees (Picard et al., 2012). These increases in mortality result in a reduction in biomass (Putz et al., 2012) and can also result in changes in tree community composition, for example when the species recruited are not the same as those that have died, or when recruitment cannot keep pace with mortality (Baraloto et al., 2012; Gourlet-Fleury et al., 2013a). However, logging in tropical forests does not have a uniform effect on forest structure (Burivalova et al. 2014), and there is substantial variation in logging impacts on tree damage, biomass and biodiversity. For this reason, there is a need for meta-analyses of logging impacts, in order for general responses to be identified.

Previous meta-analyses of the impacts of selective logging of tropical forest have indicated that biomass losses following logging can be as low as 4% or as high as 66%, while changes in tree species richness can vary between -53% to +27% of the values found in unlogged forests (Putz et al., 2012). However, the potential causes of this variation have not been explored in previous reviews (Clark and Covey, 2012; Putz et al., 2012). As logging intensity (the volume of wood extracted per hectare) increases, so does the number of trees harvested and the proportion of residual trees that are damaged (Picard et al., 2012). A higher logging intensity is likely to lead to greater reductions in above-ground biomass because of the greater removal of trees and increased mortality of non-target trees (Mazzei et al., 2010; Sist et al., 1998). The relationship between logging intensity and species richness appears to be more complex, with the potential colonisation of generalist species leading to maintenance or an increase in species richness with low intensity.
logging and a reduction of richness at higher intensities. For example, a humped relationship between logging intensity and species richness has been identified for birds, but changes in richness for other vertebrates tend to be linear reductions (Burivalova et al., 2014).

In addition to logging intensity, a recent meta-analysis highlighted the potential of differences in the methods used for logging in determining impacts. Bicknell et al. (2014) showed that for similar logging intensities reduced impact logging (RIL) had less negative effects on animal populations than conventional logging methods. RIL involves cutting lianas prior to logging, felling trees in directions selected to cause least impact to surrounding forest, and limiting road construction (Pinard and Putz 1996). Employment of these methods may reduce residual tree damage compared to conventional logging, while reducing impacts on tree biomass and biodiversity (Gullison and Hardner, 1993; Pinard and Putz, 1996). Some studies have suggested that RIL can be carried out at similar intensities to those of conventional logging while causing less damage to residual stands (Pinard and Putz, 1996; Putz et al., 2001; but see Sist et al., 2003). If this is true, RIL may be able to achieve similar timber yields to conventional methods whilst reducing losses of tree biodiversity and the amount of stored carbon.

While recent meta-analyses of the impacts of logging in tropical forests have suggested that differences in methods and logging intensity are important for explaining observed differences in responses of animal populations (Bicknell et al., 2014) and species richness (Burivalova et al., 2014), there has been no such meta-analysis on the impacts of logging on trees this. This, despite such evidence being important for informing management of logged tropical forests, especially for programmes such as REDD+ that focus on carbon storage and sequestration. In this study, we aim to address this knowledge gap by conducting a meta-analysis to determine what factors relating to logging method and intensity might explain differences in (1) residual stand damage, (2) aboveground biomass loss, and (3) tree species richness.

**Methods**

**Systematic review**

We defined selectively logged tropical forests as native forests between the latitudes of 40°N and 40°S (Newbold et al., 2013) that have been subjected to the selective removal of trees for timber. We undertook a systematic review using standard methods (Pullin and Stewart, 2006) as outlined in the supplementary materials. Once the search was completed, irrelevant papers were discarded. Our inclusion criteria were that: (i) studies must present data on residual stand damage following logging or above-ground tree biomass and/or species richness of trees from at least one
undisturbed forest and one logged forest site; (ii) sites should have spatially replicated measures of
the metrics of interest in both logged and unlogged sites with at least three plots present in each.

This rule was relaxed for the studies of residual stand damage since very few were replicated or had
comparisons with unlogged sites; (iii) logged sites could not be affected by multiple disturbance
types, such as fire; and (iv) studies were carried out in terrestrial forests, excluding mangroves.

For articles that measured changes in biomass or species richness we extracted the mean,
standard deviation and sample size of metrics in both logged and unlogged forests. For studies of
forest damage we extracted the mean of each metric used to assess damage. We also recorded the
geographic location (latitude and longitude), region (Americas, Africa, or Asia), method of logging
used (RIL or conventional selective), the number of years since logging, and volume of wood
extracted (m$^3$ha$^{-1}$) and/or number of trees felled per hectare. For sites that had been logged twice,
we calculated logging intensity as the sum of the volume extracted over both cycles, following
Edwards et al (2013). For details of studies used see the supplementary materials.

**Statistical Analysis**

**Calculation of metrics of damage and intensity**

Prior to analysis we standardised metrics of stand damage and logging intensity. Metrics
used to measure residual stand damage fall into two groups: tree-based measurements and area-
based measurements (Picard et al., 2012). While tree-based measures attempt to identify the number
or proportion of trees damaged per hectare or per tree felled, area based measurements aim to
identify the area or proportion of total area of plots in which trees have been damaged. Conversion
between the two types of metric is difficult since they show non-linear relationships (Picard et al.,
2012), so for this study we concentrated on studies that directly measured damage of trees.

We used the proportion of residual trees damaged after logging as our metric of stand
damage. Following Picard et al. (2012) we used linear mixed models to determine the relationship
between the number of trees damaged per hectare and the proportion of residual trees damaged
where both had been measured. The continent on which studies were undertaken was included as an
interaction in these models since forest stem density and tree size varies considerably across the
tropics (Slik et al., 2013), and therefore the slopes of these relationships could be expected to vary
by continent. This model was then used to predict the proportion of residual trees damaged in
studies where such data were not directly available. A similar process was undertaken to convert
metrics of logging intensity to the metric used in this study, m$^3$ wood removed ha$^{-1}$. The number of
trees harvested per hectare was the only other metric commonly used and therefore a linear mixed
model of the relationship between this variable and the volume of wood removed was produced,
accounting for continent level differences in this relationship. Where data on volume of wood removed were not available from a study values were imputed using coefficients from this model. All of these models used a Gaussian error distribution.

Impacts of logging on damage, biomass loss and species richness

To determine the effect of logging intensity and different logging methods on the proportion of residual trees damaged, an unweighted linear mixed model was used. Prior to model fitting the response variable was logit transformed so that values were strictly constrained between 0 and 1 (Warton and Hui, 2011). Random effects were used to identify data from the same study since their responses are likely to be more similar to each other than those of forests from different studies. We tested how logging volume affected the proportion of residual trees damaged, and whether logging method changed the slope of this relationship. Previous work by Picard et al. (2012) suggested that the relationship between logging damage and intensity is non-linear and so models with quadric and log terms were also tested. R² statistics were obtained using the method of Nakagawa and Schielzeth (2013).

For the analysis of the impact of logging intensity and logging method on changes in above-ground biomass and species richness, a weighted approach was used. Where standard errors of the mean were missing from studies, they were estimated using imputation methods (Koricheva et al., 2013) which are likely to bias results less than excluding studies with incomplete information (Nakagawa and Freckleton, 2008). To achieve this, the relationship between the coefficient of variation for logged and unlogged sites for tree richness or biomass and plot size at which data were collected was estimated using linear models. The literature on human-disturbed forests suggests that smaller sampling plots result in greater between-sample variation and therefore higher coefficients of variation, indicating that this approach is empirically supported (Wagner et al., 2010). Unweighted linear models were then used to predict the coefficient of variation for studies missing these data, and missing standard deviations were calculated by multiplying this prediction by the value of richness or biomass measured at the site.

To analyse the effects of logging on carbon pools and tree species richness, the log response ratio of differences between sites was calculated and models were weighted so that more precise studies had more weight (Borenstein et al., 2009; Hedges et al., 1999). We fitted a random effects meta-regression to account for pseudo-replication at the level of individual studies when the same unlogged site was used as a comparator for multiple logged sites. In the analyses of richness, estimation method (rarefied or not rarefied) was included as a random effect since this has been shown to cause between-study differences in the past (Cannon et al., 1998; Gotelli and Colwell, 2001), but the nature of any difference was not a focus for this study.
We tested the effects of logging method and logging intensity in determining post-logging biomass and changes in tree species richness. It is also possible that the time since a site was last logged and the location of study may play a role in determining logging impacts (Burivalova et al., 2014) and so these variables were also included in models. All plausible models that had >3 data points per parameter were assessed and R² values were calculated (see supplementary materials for details of all models tested).

In model selection AICc was used to determine the relative likelihood of a model being the ‘best model’. All models of tree damage with a ΔAICc<7 were averaged to produce coefficient estimates (Burnham et al., 2011). Since this is not possible for the weighted analyses of impact on biomass and species richness, the model with the lowest AICc was chosen as the most parsimonious model. All statistical analyses were performed in R 3.0.2 (R Development Core Team, 2011), with unweighted analyses carried out using the lme4 package (Bates et al., 2014), weighted analysis carried out using the package metafor (Viechtbauer, 2010) and figures drawn using ggplot2 (Wickham, 2009).

Results

The systematic review yielded 62 studies, from which we extracted data on residual tree damage from 38 sites, and 43 and 9 paired, replicated sites that measured biomass and tree species richness respectively. Median logged-site age for those sites where biomass was measured was 4.5 years (min=0, max=30) and for sites where richness was measured it was 5 years (min=0, max=50). Sites were mostly located in Asia and South America, with relatively few in Africa (Figure 1).

Figure 1 - Geographic location of studies used in our analyses on change in aboveground biomass and species richness in response to logging.
The most parsimonious model for predicting the volume of wood logged per hectare compromised as predictors the number of trees extracted per hectare and the continent where studies were undertaken, with an interaction between the two and had a high explanatory power ($R^2=0.93$). This model indicated that for each tree removed a greater volume of wood was removed, the slope of the relationship being highest in Asia followed by Africa and the Americas (Figure S1). The most parsimonious model for converting from the number of trees damaged per hectare to the proportion of trees damaged per hectare did not require inclusion of study location as a variable and also had high explanatory power ($R^2=0.95$, Figure S2).

Figure 2 - Impact of selective logging intensity and logging technique on the proportion of residual tree stems damaged in tropical forests (n=38). Points represent single sites, solid lines are the predictions the most parsimonious linear mixed effects model ($R^2=0.45$) and dashed lines represent the 95% confidence intervals of these estimates. Red points and lines refer to sites where conventional harvest methods were used and blue points and lines where RIL techniques were used. For details of alternative models considered see Table S1.

Residual stand damage

The model that best explained the proportion of residual tree stems that were damaged included an interaction between the logarithm of logging intensity and the logging method ($R^2=0.45$). No other models had a ΔAICc <7 (Table S1). Predictions suggested that damage to the...
residual logging stand increased as a function of the logarithm of the logging intensity (Figure 2). This model also suggested that at low logging intensities, RIL tended to cause less residual damage than conventional logging, but at high intensities the two methods became more similar in the residual damage that they caused (Figure 2). However, the 95% confidence intervals for predictions were very wide indicating large variation in damage on residual tree stems for both methods.

![Image of Figure 3](image_url)

**Figure 3** – Impacts of selective logging intensity on changes in aboveground biomass (n=32). Blue symbols are those sites where reduced impact logging (RIL) was carried out, red symbols correspond to conventionally logged sites with size indicative of study weight. The solid lines represent the predictions from the weighted meta-regression model with lowest AICc ($R^2=0.96$), and the dotted lines the corresponding 95% confidence intervals. The horizontal dashed line indicates when there is no difference between logged and unlogged sites. Note that RIL sites tend to be logged at a lower intensity than conventionally logged sites. For details of alternative models considered see Table S2.

**Impacts of logging intensity and method on biomass and species richness**

Increased logging intensity led to reduced post-logging biomass and the slope of this relationship differed between RIL and conventional methods (Figure 3, Table S2). The model explaining variation in biomass effect size with greatest support ($R^2=0.96$, Table S2) suggested a
linear relationship between logging intensity and changes in biomass and an interaction between
this and logging method. The model indicated that RIL techniques may result in lower biomass
losses per m$^3$ of wood removed per hectare at intensities >50m$^3$ ha$^{-1}$, but higher biomass losses
below this (Figure 3). However the relatively low intensities at which RIL sites tended to be logged
compared to conventional sites reduced statistical power, and confidence intervals for the
predictions for RIL and conventional logging overlapped.

![Graph showing impacts of logging intensity on tree species richness](image)

**Figure 4** - Impacts of logging intensity on tree species richness (n=9) following logging. Blue
symbols are those sites where RIL was carried out, red symbols correspond to conventionally
logged sites with point size indicative of study weight. The solid line represents the predictions
from the weighted meta-regression model with lowest AICc ($R^2=0.36$), and the dotted lines the
corresponding 95% confidence intervals. The horizontal dashed line indicates when there is no
difference between logged and unlogged sites. For details of alternative models considered see
Table S3.

The model that explained variation in tree species richness effect size most effectively
suggested a negative relationship with intensity of logging, with a positive intercept (Figure 4, Table
S3). Only one other model had a ΔAICc<7 that included intensity and intensity squared, and the
most parsimonious model had an $R^2$ of 0.36. Too few studies assessed the impact of RIL on species
richness to conduct an analysis of its effect relative to conventional logging.
Discussion

Our results indicate that the impacts of selective logging in tropical forests on residual stand damage, biomass loss and species richness change are largely explained by differences in logging intensity. Residual tree damage also appears to be reduced at lower intensities under RIL when compared to conventional logging. However the effect of RIL on biomass loss was difficult to assess owing to the confounding effects of differences in logging intensity.

Impacts of logging on stand damage and biomass

Our meta-analysis indicates that logging intensity is the primary driver of differences in non-target tree damage in selectively logged tropical forests, as previously noted in other studies (Picard et al., 2012; Sist et al., 1998). However, our results from a wide range of sites also support the hypothesis that RIL is causes lower damage to residual trees than conventional logging, especially at lower intensities. Similar observations have been made in the field by Sist et al. (1998) who indicated that RIL reduced residual damage by around 50% when logging was carried out at intensities <65 m³ ha⁻¹ in Indonesian Borneo, but that values were similar to conventional logging at higher intensities.

Given that residual damage to trees is likely to account for the majority of carbon losses as a result of selective logging, this indicates that RIL may be useful in reducing carbon losses at the stand scale (Gourlet-Fleury et al., 2013b; Mazzei et al., 2010). However, there is a large amount of between-study variation in the impacts of logging intensity and methods on stem damage, which suggests either that other variables that are important, such as the density of log extraction routes or the steepness of slopes where logging was undertaken (Putz et al., 2000), have not been considered in our models. Equally, this variation may be a result of the large variation in between-study methods used to assess stem damage.

Impacts of logging on aboveground biomass

Our analyses emphasize that accounting for harvesting intensity is vital for understanding effects of logging on above-ground biomass. The volume of wood removed per hectare was by far the best predictor of changes in biomass in response to timber harvest. Logging intensity varies by region (Figure S3 & Putz et al., 2001), and is relatively high in Asia (mean 99.3 m³ ha⁻¹ in this study) compared to South America and Africa (mean 31.3 and 17.9 m³ ha⁻¹ respectively). This variation in intensity may reflect the fact that SE Asian forests are largely dominated by dipterocarp trees, which have high timber value (Corlett and Primack, 2005), and thus contain a larger number
of harvestable timber trees per hectare compared to other regions. The combination of higher logging intensities and higher above-ground biomass in SE Asian forests than in other areas of the tropics (Slik et al., 2013) is likely to result in greater per ha carbon emissions from forests logged in SE Asia than Africa or Latin America.

We find weak support for the hypothesis for a difference between the impacts of RIL and conventional selective logging on post-logging biomass. Although models suggested a difference in the relationship between logging intensity and biomass loss for RIL and conventional logging this is driven by relatively few data points (Figure 3, n=7 for RIL). This lack of data from studies of RIL and the relatively low logging intensities at which RIL is carried out when compared to conventional selective logging make firm conclusions about this relationship difficult (Figure S3). Unless studies of RIL are carried out at a similar range of intensities to conventional selective logging its potential carbon benefits, aside from those resulting from lower logging intensities, are almost impossible to assess.

**Impacts of logging on species richness**

As for above-ground biomass, logging intensity best explained differences in tree species richness caused by logging. However, compared to above-ground biomass, the slope of this relationship was much less steep, with an apparent initial increase in species richness at low intensities. The most plausible explanation for this increase is an influx of generalist species from surrounding non-forest areas (Carreño-Rocabado et al., 2012) leading to an initial post-harvest increase in richness. Similar relationships have recently been observed between logging intensity and bird species richness, while other vertebrates showed a decline even at low intensities (Burivalova et al., 2014).

Our results suggest that tree species richness may be relatively insensitive to subtle changes in forest cover (Cannon et al., 1998). However, changes in species richness provide no information about the identity and function of individual species. Community composition is likely to be impacted by selective logging, with forest-dependent species sensitive to disturbance becoming less abundant or locally extinct (Sheil et al., 1999) and generalist species increasing in abundance (Baraloto et al., 2012; Gourlet-Fleury et al., 2013a). However, analysis of logging impacts on community composition is hindered because most studies of logging are spatially pseudoreplicated, leading to biased estimates of change (Ramage et al., 2013).

**Improving assessments of logging intensity and damage**

Our analyses support conclusions by others (Bicknell et al., 2014; Burivalova et al., 2014) that consideration of logging intensity is vital to understand the impact of logging on biodiversity.
and above-ground biomass. However, it can be difficult to obtain statistics on the volume of wood removed from an area, and when such data are available they are often only available as a mean volume removed per hectare for the entire study area. For individual studies, identification of the importance of logging intensity is extremely difficult. To solve this, the use of metrics of logging intensity such as basal area logged ha\(^{-1}\) may prove fruitful. Previous studies have used such metrics to examine the importance of logging intensity in biomass recovery rates (Mazzei et al., 2010). This has the advantage of allowing an estimate of logging intensity at the plot scale, allowing for more nuanced analyses of logging impacts than is currently possible.

A wide variety of different measures is used to assess residual logging damage in selectively logged forest stands (Picard et al. 2012), fostered by different objectives and hypotheses. We used coefficients to convert between different measures to maximise the value of available data, but this method inevitably introduced additional uncertainties into our analyses. Synthesis would be aided by standardisation of metrics. We suggest the use of standardised metrics when assessing tree damage and recommend that assessments of damage should be carried out at the level of individual trees rather than assessing the proportion of area affected by logging activities. We also suggest that future studies should report the proportion of basal area that is damaged to provide additional information of logging impacts on forest biomass. Furthermore, stratification of logging damage by tree size class would allow an assessment of its potential demographic effects and would therefore aid our understanding of the recovery of logged forests.

**Reducing the negative effects of logging**

Our meta-analysis suggests that the most obvious way of reducing the negative impacts of tropical logging is to reduce local logging intensity. These findings are in contrast to a recent extensive meta-analysis, which suggested that RIL at <30 m³ ha\(^{-1}\) resulted in larger animal populations than conventional logging at similar intensities (Bicknell et al., 2014). The possible reasons for this apparent difference in drivers of logging impact are twofold. Firstly, the work of Bicknell et al. (2014) addressed animal population sizes which are potentially affected to a greater degree by logging at the landscape scale than the metrics we examined for trees. For example forest specialist birds in the Amazon are sensitive roads <10m in width, resulting in reduced patch occupancy for selected species, while tree biomass and species richness have been seen to recover for relatively isolated secondary forests (Martin et al., 2013), though species composition may differ because of dispersal limitation (Chazdon, 2003). RIL results in much lower road densities than conventional logging, thus reducing gaps that animals need to cross as well as edge effects and forest loss at the landscape scale. Secondly Bicknell et al. (2014) used a higher sample size than was available for our meta-analysis. Inclusion of new studies in a meta-analysis such as ours would...
help to clarify this observed disparity.

The results of our study and those of Burivalova et al. (2014) suggest that logging intensity drives carbon and species loss while Becknell et al. (2014) suggest that RIL is less damaging for animal populations. As such, current evidence suggests that RIL at relatively low intensities is likely to be the best way to reduce carbon and biodiversity loss in tropical logged forests. However, given the massive area of tropical forest already designated for logging (Asner et al., 2009), reductions in local intensity, and thus yield, may encourage expansion into previously unlogged areas. This mirrors the situation in agricultural landscapes where the biodiversity benefits of high-yield farming over small areas as opposed low-yield, extensive farming is debated (Benayas et al., 2012; Phalan et al., 2011). Recent work indicates that high intensity logging over a smaller area (‘land sparing’) has better outcomes for tropical forest species than low-intensity extensive timber extraction (‘land sharing’) in Borneo (Edwards et al., 2014). This sparing/sharing framework may prove useful to assess the potential value of differing land-use strategies in landscapes used to provide ecosystem services such as food and timber.

Although reductions in logging intensity may reduce impact, the high demand for timber requires novel solutions that do not drastically reduce current yields but reduce impacts on forest ecosystems. Methods such as silvicultural thinning techniques to remove pioneer species may aid recovery of floral community composition, carbon and timber stocks but further work is needed to assess their effectiveness (Gourlet-Fleury et al., 2013b; Ouédraogo et al., 2011). Although RIL may also provide a solution, further evidence is required to verify this for carbon storage in the form of above-ground biomass. Analyses that take into account plot level variation in logging intensities using collaborative networks such as The Tropical managed Forests Observatory (Sist et al., 2015) offer a potential solution to this.

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References


