Improved timber harvest techniques maintain biodiversity in tropical forests

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Tropical forests are selectively logged at 20 times the rate at which they are cleared, and at least a fifth have already been disturbed in this way [1]. In a recent pan-tropical assessment, Burivalova et al. demonstrate the importance of logging intensity as a driver of biodiversity decline in timber estates [2]. Their analyses reveal that species richness of some taxa could decline by 50% at harvest intensities of 38 m^3 ha^{-1}. However, they did not consider the extraction techniques that lead to these intensities. Here we conduct a complementary meta-analysis of assemblage responses to differing logging practices: conventional logging and Reduced-Impact Logging (RIL). We show that biodiversity impacts are markedly less severe in forests that utilise RIL, compared to those using conventional logging methods. While supporting the initial findings of Burivalova et al., we go on to demonstrate that best practice forestry techniques curtail the effects of timber extraction regardless of intensity and, therefore, that harvest intensities are not always indicative of actual disturbance levels resulting from logging. Accordingly, forest managers and conservationists should advocate practices that offer reduced collateral damage through best practice extraction methods, such as those used in RIL. Large-scale implementation of this approach would lead to improved conservation values in the 4 million km^2 of tropical forests that are earmarked for timber extraction [3].

Selective logging is the removal of specific timber trees from a forest stand, resulting in patchy canopy openings and extensive road networks, with associated negative impacts on biodiversity [4]. Forest damage can be minimised by employing techniques such as pre-harvest inventories, planned logging road networks, directional felling and winching, all of which are key components of RIL (Fig.S1a) – for further details see [5]. Consequently, RIL improves forest sustainability and ecosystem service provision [6, 7]. Indeed, the adoption of RIL across production forests globally would cut carbon emissions by an estimated 160 million tonnes per year, equivalent to ca.10 percent of carbon emissions from deforestation [8]. While RIL has received growing attention (Fig. S1b), few studies have directly compared the biodiversity impacts of this selective logging practice with those of conventional selective logging (CL), making it difficult to build a strong evidence-base to inform conservation management and forestry policy.

Here we address this knowledge gap via a pan-tropical meta-analysis that utilises species abundance information to examine the relative consequences of contrasting logging regimes. All available logging effect studies that compared primary tropical forest with CL and/or RIL forests were included in our analyses, amounting to 3474 comparisons from 41 studies (see Experimental Procedures in Supplemental Information). Tropical ecologists have reported both increases and decreases in diversity in response to selective logging at almost equal frequency [2], so we assess assemblage change to better account for shifts in the balance between generalist and specialist species that are expected following disturbance.

Our analyses revealed the effects of RIL to be consistently lower than those of CL, with smaller shifts in species abundance after logging under RIL (mean Hedge's g±95% CI: CL=0.476±0.03; RIL=0.393±0.05; Fig.1). This finding could be attributed to differences in harvest intensity, logging practices, or both. To control for intensity, we repeated effect size calculations to include only those CL studies with comparable harvest levels to those of RIL ($\leq$30 m^3 ha^{-1}), and the pattern remained the same (Fig.1). Considering different taxonomic groups separately, our dataset revealed smaller detrimental effects under RIL for birds, arthropods and mammals (Fig.1), especially bats (Fig.S2a). There were insufficient data to compare amphibians among logging techniques. Similarly, we could not examine the data grouped by geographic region, as no suitable RIL studies exist outside of the Neotropics. However, within this region, RIL still resulted in smaller effect sizes (Fig.S2b).

Although, like Burivalova et al., our meta-regression showed an association between logging intensity and effect sizes (CL and RIL combined: Q_{model}=4.75, p=0.03), when partitioned by extraction method, a further important result is evident. Restricted to CL, there is no relationship (Q_{model}=0.44, p=0.51), even when considering only extraction intensities comparable with RIL (CL≤30 m^3 ha^{-1}: Q_{model}=0.45, p=0.500; Fig.1 inset). Conversely, effect sizes under RIL are positively related to logging intensities (Q_{model}=27.6, p<0.001; Fig.1 inset). Reported harvest intensities under CL are thus not closely related to levels of collateral damage, whereas they are under RIL. This may be expected because harvest levels are recorded as the amount of commercial timber extracted, but this metric fails to account for the actual levels of stand disturbance associated with factors that are mitigated under RIL (e.g., falling timber crushing non-harvest trees, indiscriminate use of bulldozers etc.). Meta-regressions of time since logging showed no effect under CL (Q_{model}=1.18, p=0.277) or RIL (Q_{model}=1.60, p=0.206), demonstrating that differences in forestry practices rather than time since disturbance are primarily driving biodiversity change. Consequently, solely considering harvest intensities puts the conservation value of production forests at risk of continued poor extraction practices.

Selective logging is the least detrimental disturbance faced by tropical forests [9], and logging estates are increasingly considered important to global conservation [4]. Although our study shows that best practice forestry estates should not be considered equal in conservation value to primary forests, our analyses suggest that implementing RIL more widely would result in substantial gains for biodiversity compared to the status quo. Focusing on reduced logging intensity alone could result in larger expanses of primary forest being logged to meet timber demand. This may be incompatible with forestry economics as it would likely reduce profits. Furthermore, expanding the logged area would be unfavourable for conservation, as more biodiversity is retained where high harvest intensities are combined with the sparing of primary forest reserves, rather than universally harvesting at lower intensities [10]. By contrast, our study suggests that even at high harvest intensities, RIL will result in lower impacts than CL, providing strong justification to improve logging practices. Unfortunately, uptake of RIL has remained slow with conventional practices continuing to dominate the industry [3], so action is required among governments of tropical timber producer and consumer states to insist on best practice forestry.

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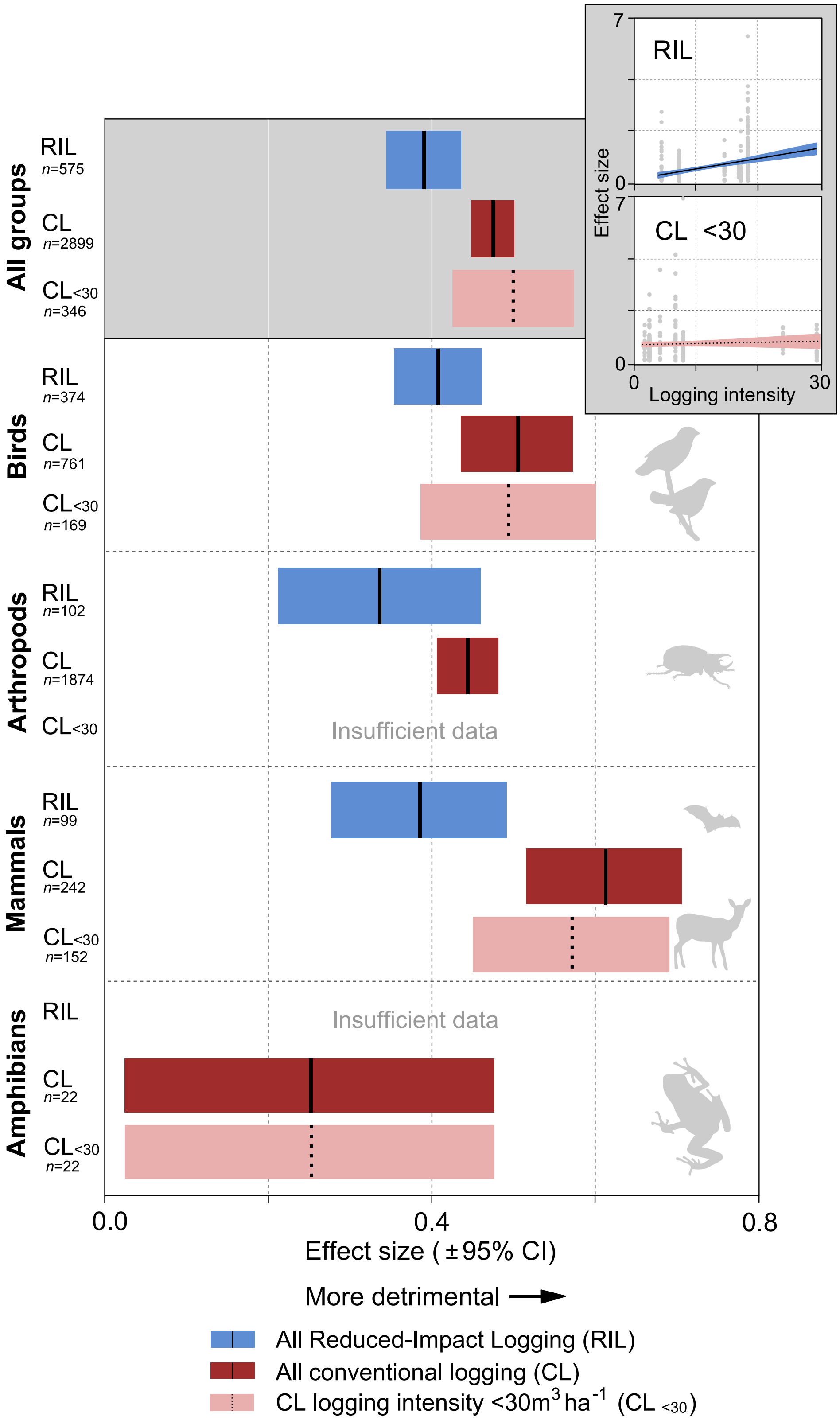
REFERENCES

1. Asner, G.P., Rudel, T.K., Aide, T.M., Defries, R., and Emerson, R. (2009). A Contemporary assessment of change in humid tropical forests. Conservation Biology *23*, 1386-1395.
2. Burivalova, Z., Şekercioğlu, Çağan H., and Koh, Lian P. (2014). Thresholds of logging intensity to maintain tropical forest biodiversity. Current Biology *24*, 1893-1898.
3. Blaser, J., Sarre, A., Poore, D., and Johnson, S. (2011). Status of Tropical Forest Management 2011. ITTO Technical Series No 38, (International Tropical Timber Organization, Yokohama, Japan).
4. Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E., and Laurance, W.G. (2014). Maintaining ecosystem function and services in logged tropical forests. Trends in Ecology & Evolution *29*, 511-520.
5. Putz, F.E., Sist, P., Fredericksen, T., Dykstra, D. (2008). Reduced-impact logging: Challenges and opportunities. Forest Ecology and Management *256*, 1427-1433.
6. Miller, S.D., Goulden, M.L., Hutyra, L.R., Keller, M., Saleska, S.R., Wofsy, S.C., Silva Figueira, A.M., da Rocha, H.R., and de Camargo, P.B. (2011). Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. Proceedings of the National Academy of Sciences of the United States of America *108*, 19431-19435.
7. West, T.A.P., Vidal, E., and Putz, F.E. (2014). Forest biomass recovery after conventional and reduced-impact logging in Amazonian Brazil. Forest Ecology and Management *314*, 59-63.

8. Putz, F.E., Zuidema, P.A., Pinard, M.A., Boot, R.G.A., Sayer, J.A., Sheil, D., Sist, P., Elias, and Vanclay, J.K. (2008). Improved tropical forest management for carbon retention. PLoS Biology. *6*, 1368-1369.
9. Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., et al. (2011). Primary forests are irreplaceable for sustaining tropical biodiversity. Nature *478*, 378-381.
10. Edwards, D.P., Gilroy, J.J., Woodcock, P., Edwards, F.A., Larsen, T.H., Andrews, D.J.R., Derhe, M.A., Docherty, T.D.S., Hsu, W.W., Mitchell, S.L., et al. (2014). Land-sharing versus land-sparing logging: reconciling timber extraction with biodiversity conservation. Global Change Biology *20*, 183-191.

FIGURE



All groups
RIL n=575
CL n=2899
CL<30 n=346
Birds
RIL n=374
CL n=761
CL<30 n=169
Arthropods
RIL n=102
CL n=1874
CL<30
Insufficient data
Mammals
RIL n=99
CL n=242
CL<30 n=152
Amphibians
RIL
Insufficient data
CL n=22
CL<30 n=22
0.0
0.4
0.8
Effect size (±95% CI)
More detrimental
RIL
CL <30
Effect size
Logging intensity
7
0
30
All Reduced-Impact Logging (RIL)
All conventional logging (CL)
CL logging intensity <30m3 ha-1 (CL <30)

Figure 1. Effect sizes and meta-regressions of Reduced-Impact Logging and conventional logging.

Main: Mean effect size (Hedge's g ± 95% CI) of Reduced-Impact Logging (RIL: blue) and conventional logging (CL: reds) impacts on tropical forest biodiversity. Black vertical lines indicate means, and box width shows the confidence intervals. Lighter reds with dashed mean include only CL studies with timber harvest intensities comparable to RIL ($\leq 30 m^3 ha^{-1}$). Top (dark grey section) comprises comparison across all taxonomic groups combined. Bottom (white) is partitioned by taxonomic group: birds, arthropods, mammals and amphibians. *n* gives the number of species-level comparisons used in the calculation of effect sizes. Inset: meta-regression (shaded area ± 95%CI) of RIL and CL effect sizes against logging intensity ($m^3 ha^{-1}$) at levels lower than 30 $m^3 ha^{-1}$.

Supplemental Information

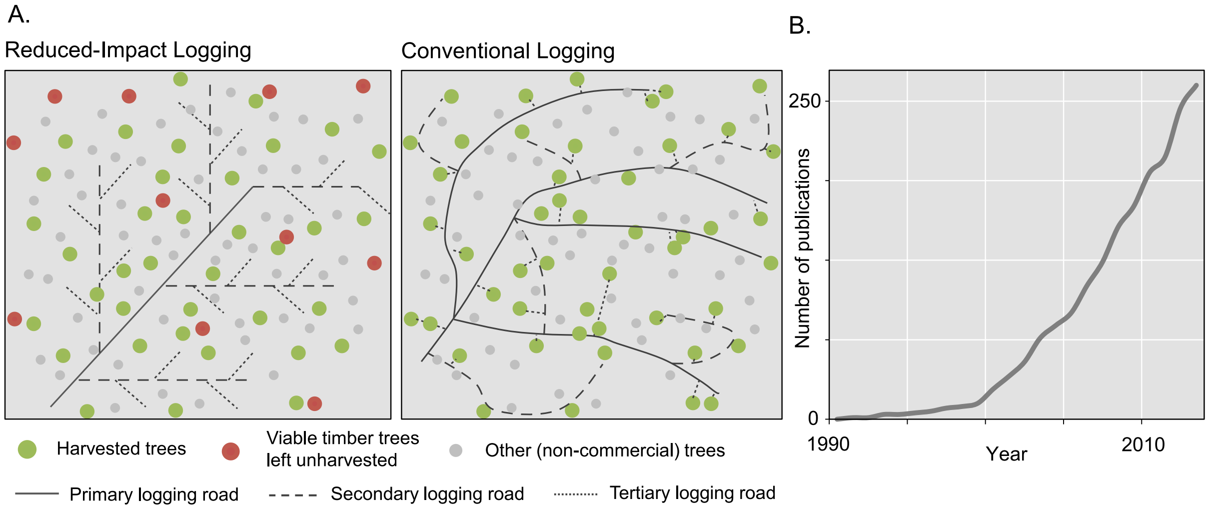


Figure S1. A. Example aerial view of logging road layout for Reduced-Impact Logging **(**RIL) and conventional logging (CL) in tropical forests. Logging roads under RIL are planned after a forestry inventory, and typically result in 20% less total logging road area. Minimum felling diameters and distances between extracted trees are used. Trees felled under RIL are winched to logging roads (reducing the overall road lengths), and directional felling and vine cutting are used to minimise damage to adjacent trees (vine cutting prevents connected trees from being dragged down during felling). RIL guidelines vary by context and country, and include many other treatments and technologies (e.g. reducing soil compaction, mitigating impacts to watercourses, setting of maximum operational slopes, use of specialised tree hauling equipment). RIL is economically viable and can result in greater profits than CL over the long-term [1]. There is freely available financial modelling software to enable a rapid assessment of the economic viability of RIL under specific contexts (RILSIM: http://blueoxforestry.com). B. RIL has received increasing interest in recent years, as evidenced by the cumulative number of studies published with “Reduced-Impact Logging” in the title, keywords, or abstract from 1990 – 2013 (ISI Web of Science).

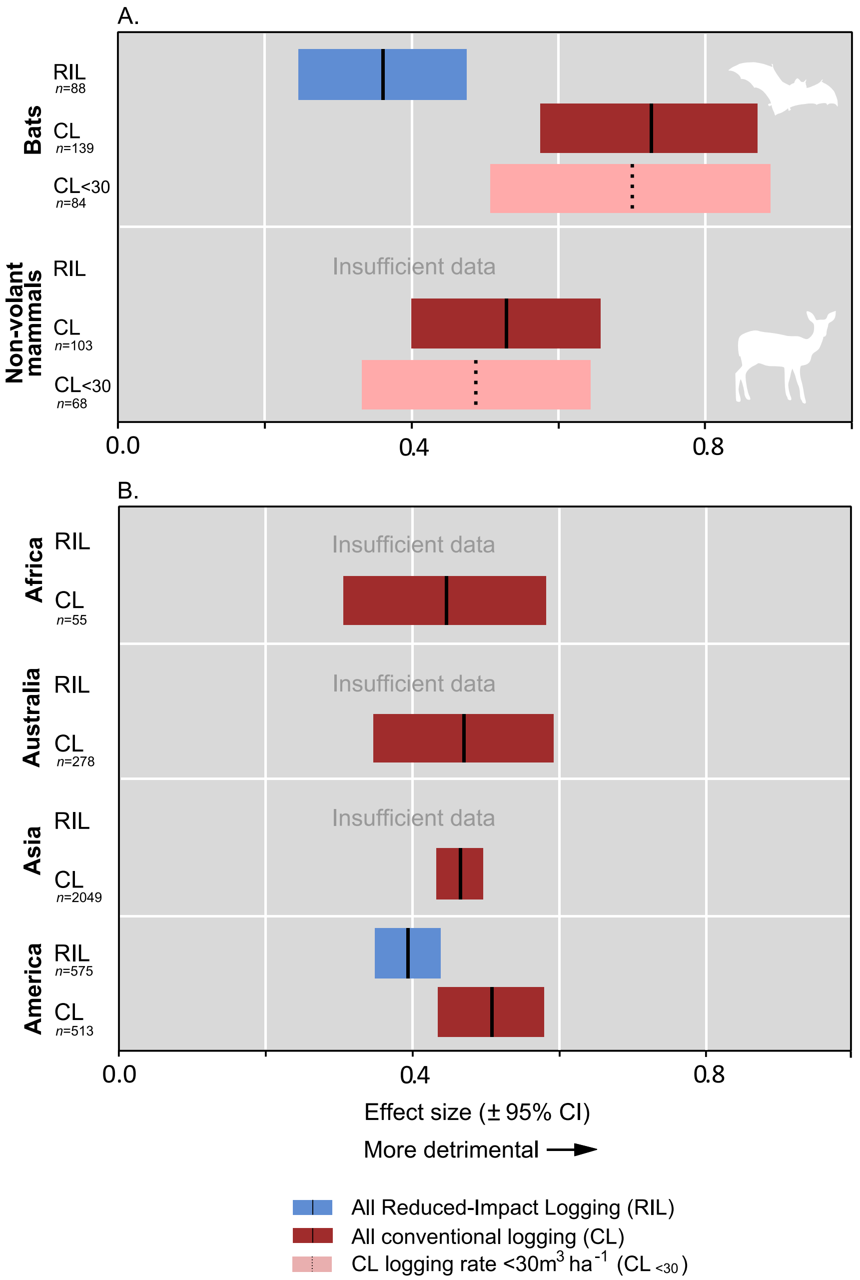


Figure S2. Mean effect size (Hedge's g ± 95%CI) of Reduced-Impact Logging (RIL: blue) and Conventional Logging (CL: reds) impacts on tropical forest biodiversity. Black vertical line shows the mean, and the box width indicates the confidence intervals. Lighter reds with dashed mean include CL studies where the logged sites were harvested at levels comparable to RIL (≤30 m^3 ha^{-1}). *n* gives the number of comparisons used in the calculation of effect sizes. A. Partitioned by bats and non-volant mammals. B. Partitioned by continent; America includes tropical South and Central America.

Experimental procedures

Inclusion criteria for studies used in the meta-analysis

Using ISI Web of Science and Scopus, we searched for all logging effect studies published between 1975 and May 2014. We used the terms “logging” OR “forestry” OR “timber” combined with “tropic*” AND “fauna” OR “wildlife” OR “biodiversity” OR “bird*” OR “bat*” OR “mammal*” OR “frog*” OR “amphibian*” OR “invertebrate*”. We also checked for further studies in the reference lists of papers identified by the search. In total, 1053 studies were located, which we filtered and retained if they met the following inclusion criteria: (i) reported the effects of industrial logging uncoupled from other anthropogenic disturbance in tropical forests (e.g. fragmentation, hunting, etc.); (ii) included measures of biodiversity abundance at sites in both primary and logged forests to allow calculation of effect sizes; and, (iii) indicated that the primary forests had not been subject to human disturbance. We also added data from our own study in Guyana (Bicknell et al. in review) which met these criteria. Where studies did not report the raw data or the variability of abundance estimates, we contacted the authors for this information. In some cases the authors had misplaced the data, and in others we received no response, so these studies were excluded. Where the same data were published in more than one study, we used them only once, utilizing the data from the most recent publication. To account for the spatial heterogeneity of logging impacts across production landscapes, all studies included in the analysis had a minimum of two independent samples across the study area. In most cases, these were randomly distributed. A small set of studies targeted specific interventions (e.g., gaps, logging roads/skid trails, etc.), and were only included if they also sampled the wider logged landscape.

Data extraction

To ensure that each effect size calculation was produced from a properly replicated sample, where a study sampled multiple sites from one forest patch, we took the mean of these, rather than drawing comparisons from potentially non-independent samples [2]. We excluded measures of richness, as under low impact disturbance such as selective logging, the number of species does not sufficiently represent changes in species composition, as logged forests regularly hold similar richness to neighbouring undisturbed forests for most taxonomic groups [3]. Additionally, richness metrics do not take account for the community becoming dominated by generalist species, alongside the loss of some specialists. Indeed, similar numbers of selective logging studies have reported decreases in biodiversity as have reported increases [4], thus obscuring the signal. We therefore included all pairwise effect size comparisons of abundance for every species in each study to represent changes in community composition. Each comparison was classified by logging type, logging intensity, time since logging, taxonomic group, and geographic region. For studies that had been logged over more than one cutting cycle, we used the cumulative logging intensity from all cutting cycles. To directly compare CL with RIL at equal logging intensities we took the subset of CL studies that were logged at intensities ≤30 m^3 ha^{-1} as this was the maximum logging intensity under the RIL studies included. We also categorised region into continents (tropical Asia, Africa, South and Central America, Australia); and taxonomic group into birds, mammals, arthropods and amphibians. We further separated bats from non-volant mammals as these taxa use forest resources in different ways (Fig. S2). Our final dataset included studies from across the tropics, among multiple logging intensities and timeframes. Likewise, it comprised of data on bats, birds, terrestrial large and small mammals, primates, frogs and several groups of arthropods (e.g. butterflies, ants, bees, beetles, termites, spiders and flies).

Meta-analysis

For each pairwise measure of species abundance, we calculated the bias-corrected Hedges' g of the difference between primary and logged means, standardised by the pooled standard deviation following [5]. We used the random-effects model to calculate the mean effect size, where each study was weighted by the inverse of its variance, plus the inter-study variance. We calculated the effect size for RIL and CL separately, and for each categorical subgroup (logging intensity, taxonomic group and region). We tested the dataset for possible publication bias by visually examining a funnel plot of the effect size plotted against the standard error of the effect size. The symmetry of the points either side of zero, and the fact that small effect sizes were not published at a lower frequency, indicated that publication bias did not affect the dataset.

Data extracted from studies which did not report logging intensity were only used in the overall calculation of effect size for the entire dataset. Furthermore, because logging intensities in all of the RIL studies that met the inclusion criteria were ≤ 30 m^3 ha^{-1}, we repeated effect size calculations under comparable intensities of CL. All of the RIL suitable studies were from South and Central America and, therefore, we conducted a separate analysis partitioned by region. Where studies reported logging intensities as trees ha^{-1}, we converted this to m^3 ha^{-1} based on the mean conversion from other studies in the same geographic region that reported both tree and volume extraction intensities, as done by [4] and only affected <3% of the sample. Finally, we conducted meta-regressions of the effect sizes against logging intensities and time since logging for the entire dataset and separately for RIL and CL. Effect sizes and meta-regression were calculated in the programme Comprehensive Meta-analysis [6].

Studies included in the meta-analysis

Azlan, J.M. and Sharma, D.S.K. (2003). Camera trapping the Indochinese tiger, *Panthera tigris corbetti*, in a secondary forest in Peninsular Malaysia. Raffles Bulletin of Zoology 51, 421-427.

Bernard, H., Fjeldsa, J. and Mohamed, M. (2009). A case study on the effects of disturbance and conversion of tropical lowland rain forest on the non-volant small mammals in north Borneo: Management implications. Mammal Study 34, 85-96.

Bicknell, J. and Peres, C.A. (2010). Vertebrate population responses to reduced-impact logging in a neotropical forest. Forest Ecology and Management 259, 2267-2275.

Bicknell, J.E., Struebig, M.J. and Davies, Z.G. Reconciling timber extraction with biodiversity conservation in tropical forests using Reduced-Impact Logging. In review at Journal of Applied Ecology.

Bicknell, J.E., Struebig, M.J., Phelps, S., Mann, D.J., Davies, R. and Davies, Z.G. (2014). Dung beetles as indicators for rapid impact assessments: Evaluating best practice forestry in the neotropics. Ecological Indicators 43, 155-161.

Castro-Arellano, I., Presley, S.J., Saldanha, L.N., Willig, M.R. and Wunderle, J.M. (2007). Effects of reduced impact logging on bat biodiversity in terra firme forest of lowland Amazonia. Biological Conservation 138, 269-285.

Clark, C.J., Poulsen, J.R., Malonga, R. and Elkan, P.W. Jr. (2009). Logging concessions can extend the conservation estate for central African tropical forests. Conservation Biology 23, 1281-1293.

Clarke, F.M., Rostant, L.V. and Racey, P.A. (2005). Life after logging: post-logging recovery of a neotropical bat community. Journal of Applied Ecology, 42, 409-420.

Cleary, D.F.R. and Mooers, A.O. (2006). Burning and logging differentially affect endemic vs. widely distributed butterfly species in Borneo. Diversity and Distributions 12, 409-416.

Cleary, D.F.R., Genner, M.J., Koh, L.P., Boyle, T.J.B., Setyawati, T., de Jong, R. and Menken, S.B.J. (2009). Butterfly species and traits associated with selectively logged forest in Borneo. Basic and Applied Ecology 10, 237-245.

Davis, A.J., Holloway, J.D., Huijbregts, H., Krikken, J., Kirk-Spriggs, A.H. and Sutton, S.L. (2001). Dung beetles as indicators of change in the forests of northern Borneo. Journal of Applied Ecology 38, 593-616.

Dumbrell, A.J. and Hill, J.K. (2005). Impacts of selective logging on canopy and ground assemblages of tropical forest butterflies: Implications for sampling. Biological Conservation 125, 123-131.

Edwards, D.P., Larsen, T.H., Docherty, T.D.S., Ansell, F.A., Hsu, W.W., Derhe, M.A., Hamer, K.C. and Wilcove, D.S. (2011). Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. Proceedings of the Royal Society B-Biological Sciences 278, 82-90.

[1]Edwards, D.P., Woodcock, P., Edwards, F.A., Larsen, T.H., Hsu, W.W., Benedick, S. and Wilcove, D.S. (2012). Reduced-impact logging and biodiversity conservation: a case study from Borneo. Ecological Applications 22, 561-571.

Eggleton, P., Homathevi, R., Jones, D.T., MacDonald, J.A., Jeeva, D., Bignell, D.E., Davies, R.G. and Maryati, M. (1999). Termite assemblages, forest disturbance and greenhouse gas fluxes in Sabah, East Malaysia. Philosophical Transactions of the Royal Society of London B Biological Sciences 354, 1791-1802.

[1] This study included CL and RIL but only CL used in the analysis as the RIL sites were logged using CL in their first cutting cycle.

Eltz, T. (2004) Spatio-temporal variation of apine bee attraction to honeybaits in Bornean forests. Journal of Tropical Ecology 20, 317-324.

Gerber, B.D., Karpanty, S.M. and Randrianantenaina, J. (2012). The impact of forest logging and fragmentation on carnivore species composition, density and occupancy in Madagascar's rainforests. Oryx 46, 414-422.

Gormley, L.H.L., Furley, P.A. and Watt, A.D. (2007). Distribution of ground-dwelling beetles in fragmented tropical habitats. Journal of Insect Conservation 11, 131-139

Grove, S.J. (2002). The influence of forest management history on the integrity of the saproxylic beetle fauna in an Australian lowland tropical rainforest. Biological Conservation 104, 149-171.

Heydon, M.J. and Bulloh, P. (1996). The impact of selective logging upon sympatric civet species (Viverridae) in Borneo. Oryx, 30, 31-36.

Heydon, M.J. and Bulloh, P. (1997). Mousedeer densities in a tropical rainforest: The impact of selective logging. Journal of Applied Ecology 34, 484-496.

Knop, E., Ward, P.I. and Wich, S.A. (2004). A comparison of Orang-utan density in a logged and unlogged forest on Sumatra. Biological Conservation 120, 183-188.

Lambert, T.D., Malcolm, J.R. and Zimmerman, B.L. (2005). Effects of mahogany (*Swietenia macrophylla*) logging on small mammal communities, habitat structure, and seed predation in the southeastern Amazon Basin. Forest Ecology and Management 206, 381-398.

Lammertink, M. (2004). A multiple-site comparison of woodpecker communities in Bornean lowland and hill forests. Conservation Biology 18, 746-757.

Marsden, S.J. (1998). Changes in bird abundance following selective logging on Seram, Indonesia. Conservation Biology 12, 605-611.

Ofori-Boateng, C., Oduro, W., Hillers, A., Norris, K., Oppong, S.K., Adum, G.B. and Rodel, M.O. (2013). Differences in the effects of selective logging on amphibian assemblages in three west African forest types. Biotropica 45, 94-101.

Peters, S.L., Malcolm, J.R. and Zimmerman, B.L. (2006). Effects of selective logging on bat communities in the southeastern Amazon. Conservation Biology 20, 1410-1421.

Poulsen, J.R., Clark, C.J. and Bolker, B.M. (2011). Decoupling the effects of logging and hunting on an Afrotropical animal community. Ecological Applications 21, 1819-1836.

Presley, S. J., Willig, M.R., Wunderle, J.M. and Saldanha, L.N. (2008). Effects of reduced-impact logging and forest physiognomy on bat populations of lowland Amazonian forest. Journal of Applied Ecology 45, 14-25.

Ribeiro, D.B. and Freitas, A.V.L. (2012). The effect of reduced-impact logging on fruit-feeding butterflies in Central Amazon, Brazil. Journal of Insect Conservation 16, 733-744.

Rossi, J.P. and Blanchart, E. (2005). Seasonal and land-use induced variations of soil macrofauna composition in the Western Ghats, southern India. Soil Biology and Biochemistry 37, 1093-1104.

Scheffler, P.Y. (2005). Dung beetle (Coleoptera : Scarabaeidae) diversity and community structure across three disturbance regimes in eastern Amazonia. Journal of Tropical Ecology 21, 9-19.

Slade, E.M., Mann, D.J. and Lewis, O.T. (2011). Biodiversity and ecosystem function of tropical forest dung beetles under contrasting logging regimes. Biological Conservation 144, 166-174.

Struebig, M.J., Turner, A., Giles, E., Lasmana, F., Tollington, S., Bernard, H. and Bell, D. (2013). Quantifying the biodiversity value of repeatedly logged rainforests: Gradient and comparative approaches from Borneo. Advances in Ecological Research 48, 183-224.

Vasconcelos, H.L., Vilhena, J.M.S. and Caliri, G.J.A. (2000). Responses of ants to selective logging of a central Amazonian forest. Journal of Applied Ecology 37, 508-514.

Wells, K., Kalko, E.K.V., Lakim, M.B. and Pfeiffer, M. (2007). Effects of rain forest logging on species richness and assemblage composition of small mammals in Southeast Asia. Journal of Biogeography 34, 1087-1099.

Whitman, A.A., Hagan, J.M. and Brokaw, N.V.L. (1998). Effects of selection logging on birds in northern Belize. Biotropica 30, 449-457.

Woodcock, P., Edwards, D.P., Fayle, T.M., Newton, R.J., Khen, C.V., Bottrell, S.H. and Hamer, K.C. (2011). The conservation value of South East Asia's highly degraded forests: evidence from leaf-litter ants. Philosophical Transactions of the Royal Society B-Biological Sciences 366, 3256-3264.

Woltmann, S. (2003). Bird community responses to disturbance in a forestry concession in lowland Bolivia. Biodiversity and Conservation 12, 1921-1936.

Wunderle, J.M., Henriques, L.M.P. and Willig, M.R. (2006). Short-term responses of birds to forest gaps and understory: An assessment of reduced-impact logging in a lowland Amazon forest. Biotropica 38, 235-255.

Yap, C.A.M., Sodhi, N.S. and Peh, K.S.H. (2007). Phenology of tropical birds in Peninsular Malaysia: Effects of selective logging and food resources. Auk 124, 945-961.

Supplemental references

1. Medjibe, V.P. and Putz, F.E. (2012). Cost comparisons of reduced-impact and conventional logging in the tropics. Journal of Forest Economics *18*, 242-256.
2. Halme, P., Toivanen, T., Honkanen, M., Kotiaho, J.S., Monkkonen, M., and Timonen, J. (2010). Flawed meta-analysis of biodiversity effects of forest management. Conservation Biology *24*, 1154-1156.
3. Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J. and Zagt, R. (2012). Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. Conservation letters *5*, 296-303.
4. Burivalova, Z., Şekercioğlu, Çağan H. and Koh, L. P. (2014). Thresholds of Logging Intensity to maintain tropical forest biodiversity. Current Biology *24*, 1893-1898.
5. Borenstein, M., Hedges, L.V., Higgins, J.P.T. and Rothstein, H.R. (2009). Introduction to Meta-Analysis. Wiley.
6. Borenstein, M., Hedges, L.V., Higgins, J.P.T. and Rothstein, H.R. (2010). Comprehensive meta analysis. Version 2. Englewood, NJ: Biostat.