Research Article

Assessing sampling biases in logging impact studies in tropical forests

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Abstract

The ecological responses of tropical forest wildlife to selective timber extraction have received considerable attention in the last few decades, yet there is little consensus among the large number of studies about the most appropriate sampling design. Here, we reviewed 26 years of tropical forest logging literature to evaluate the relationship between sampling design and the quality of information reported, which varied greatly among 75 studies. Most studies (88%) failed to include a pre-logging baseline condition in the sampling design, and the temporal scale of post-logging studies was generally inadequate. Studies also usually failed to report key information on study areas; only half of the articles reported some information on the spatial scale of the study, and only one-third presented some quantitative metric to describe forest habitat structure. Additionally, most studies (64%) failed to report the type of forest management and almost half (45%) did not describe the intensity of timber harvest in the logged areas. These sampling and reporting biases in logging studies hugely undermine the comparability among studies. We conclude with some general guidelines to maximize comparability among studies, and to enhance the potential usefulness of future logging studies for wildlife conservation strategies in tropical forest regions.

Key words: Selective logging, forest management, sampling design, fauna, wildlife

Resumo

As respostas ecológicas da fauna de florestas tropicais para extração seletiva de madeira tem recebido atenção considerável nas últimas décadas, no entanto há pouco consenso entre os estudos quanto ao desenho amostral mais apropriado. Neste estudo, analisamos 26 anos de literatura sobre extração de madeira em florestas tropicais para avaliar a relação entre o desenho amostral e a qualidade das informações fornecidas, o que variou bastante entre os 75 estudos. A maioria dos estudos (88%) não incluiu condições pré-extração, e a escala temporal pós-extração dos estudos foi geralmente inadequada. Os estudos também falharam em relatar as principais informações sobre as áreas de estudo; apenas metade dos artigos relatou algumas informações sobre a escala espacial do estudo, e apenas um terço apresentou alguma métrica quantitativa para descrever a estrutura florestal. Além disso, a maioria dos estudos (64%) não informou o tipo de manejo florestal e quase metade (45%) não descreveu a intensidade de extração de madeira nas áreas exploradas. Esse viés de amostragem e falhas nas informações fornecidas nos estudos reduzem a comparabilidade entre os mesmos. Concluímos com algumas diretrizes gerais para maximizar a comparabilidade entre os estudos, e melhorar a utilidade potencial de futuros estudos de extração de madeira para as estratégias de conservação de fauna em regiões de florestas tropicais.

Palavras-chave: Corte seletivo, manejo florestal, desenho amostral, fauna, vida silvestre

Received: 26 October 2012; Accepted: 12 December 2012; Published: 18 March 2013.

Cite this paper as: Laufer, J., Michalski, F., and Peres, C. A. 2013. Assessing sampling biases in logging impact studies in tropical forests. *Tropical Conservation Science* Vol. 6(1):16-34. Available online: www.tropicalconservationscience.org

Introduction

The growing global demand for forest products has markedly fueled the expansion and intensity of the logging industry in tropical forest regions [1-4]. The last remaining tracts of pristine tropical forests safeguard the highest tree species diversity and the most valuable timber species [5], raising questions about the long-term viability of timber extraction [6]. This is especially true in Amazonia, which holds over half of the world's remaining tropical forest [7].

Selective logging has been proposed as a type of land use that is the least detrimental to animal and plant communities in tropical forests [8-11]. Hence, a growing number of studies have sought to determine the effects of selective logging on tropical forests [12]. However, most of these studies incorporate potential biases and use different sampling techniques, taxonomic groups, temporal and spatial scales, forest management treatments, and other covariates that could affect the strength and direction of their results [10, 13-16].

The application of different sampling designs in studies evaluating the ecological effects of selective logging on fauna render their comparability difficult, reducing the effectiveness of conservation initiatives in tropical forests [17]. These differences can be found in spatial scales and duration of studies, biodiversity metrics used, number of spatial and temporal replicates, and information on habitat structure and composition within the study areas.

One of the key points in study design is the choice of spatial scale used, which is intimately related to the effect size of disturbance [18] and the biological traits of species [17]. Based on the intermediate disturbance hypothesis [19], a number of authors have suggested that small-scale selective logging may increase species richness and diversity by boosting habitat heterogeneity and paving the way for habitat specialists and generalists to coexist side by side [20-21]. However, the same taxa observed at a landscape scale may indicate a reduction in species turnover and higher levels of habitat homogeneity, leading to lower regional biodiversity metrics [18]. Thus, there is need to understand how the variation in the intensity of disturbance acts on the entire landscape, since logging areas are rarely selected randomly, and usually allocated to gentle topographic slopes with higher concentrations of commercially valuable timber species [22-23].

The correct understanding of historical data of any given study area, including the forest management type applied, is critical background information for logging studies, because landscape history and context (e.g. hunting, clear-cutting, and fire - [24-25]) can affect results and their interpretation. The history of logging disturbance (e.g. volume harvested, density of logging roads and skid trails built to extract roundlogs, collateral damage, and use of mechanized extraction) should also be evaluated to better understand the results obtained [21, 26-28]. The intensity of timber harvesting is also directly and positively related to ecological impacts on wildlife and forest structure [8, 23, 29-30].

The time lag between the end of any logging disturbance and the start of data acquisition may also strongly influence the results of selective logging studies [22, 31-32]. When field studies are carried out within five years after selective logging is discontinued, this can affect results due to the possibility of response delay or ecological relaxation of many organisms (e.g. many species affected are associated with low reproductive rates and long life cycles [31, 33-35]). On the other hand, studies conducted a long time (>15 years) after the latest logging disturbance have other confounding variables that must be taken into account in interpreting results. For example, over long time scales natural disturbance events could affect the study area (e.g. natural forest succession, hurricanes or drought [28, 33, 36]), all of which can mask ecological responses to anthropogenic disturbance.

In addition, understanding the structure and composition of the forest and the organisms investigated before and after logging disturbance can provide essential information for more accurate assessments about the effects of selective logging and its effects on faunal structure and composition [37-40]. The lack of baseline information on the pre-cutting period can result in incorrect assessments of species distributions due to the spatial heterogeneity of forest species within the study area [41]. Furthermore, complementarity afforded by pre- and post-logging data and a long-term study in the aftermath of logging is often the best approach to understand the effects of disturbance [22].

Additionally, the synergistic interactions between logging and other co-occurring land-uses and natural climatic variability comprise one of the main threats to tropical forest biodiversity [3, 42]. Therefore, organismal response to changes in forest structure/composition induced by concomitant activities must also be evaluated. Synergistic effects may affect the results and/or obscure the potential effects of selective logging [43]. For example, hunting and wildfires have been identified as activities that aggravate the effects of selective logging when occurring in the same area [3, 7, 23-24, 44-46]. Selective logging opens up access to isolated forests, facilitating hunter access [47], which in turn can create markets for bushmeat and increase hunting in new logging areas [3]. The bushmeat supply to local villages increased by 64% near a logging concession in the Democratic Republic of Congo following the creation of logging roads [46]. Intensive hunting pressure can alter the species diversity, standing biomass and structure of animal communities [48-49], all of which can mask the effects of logging disturbance alone.

Despite the role of spatial and historical context in local ecological responses to selective logging, there is no consensus among researchers over the most appropriate sampling design to evaluate the effects of selective logging on tropical forest species [18]. This consensus is absent even at the continental scale, and there is also little agreement on how to report key forest habitat and management information. Furthermore, few studies describing the influence of time scale and harvesting intensity are available [13-14, 50-52], so that differences in cause-effect relationships associated with the responses detected remain obscure.

Here, we assess the wide variation in sampling design of studies addressing the basic question of how selective logging affects forest wildlife in tropical forest regions. We compiled a comprehensive checklist of neotropical and paleotropical studies on the effects of logging-induced forest disturbance on both vertebrates and invertebrates, in order to: (1) evaluate the relationship between sampling design and the quality of the information reported, to ensure comparability among studies, and (2) provide guidelines on which relevant information should be reported in any literature resulting from those studies. We aim to provide clear directions to maximize comparability among studies, and to enhance the potential usefulness of future studies for wildlife conservation strategies in tropical forest regions.

Methods

Compilation of studies

We reviewed the available formal logging literature focusing on tropical forest fauna. We first conducted a search of ISI Web of Knowledge on the 3rd August 2012, using the terms "selective logging," "logging," or " timber" together with "tropical forest" and "fauna," "vertebrates," "invertebrates" or "wildlife." These searches returned a total of 249 publications, which were then examined and filtered to ensure we considered all studies reporting on the impact of tropical timber extraction on any faunal taxa. We explored studies that reported on the effects of logging *per se* as well as those considering other anthropogenic perturbations in tropical forests (e.g., clear-cutting, monocultures, and wildfires) coupled with logging. From the initial total of 249 potential articles we obtained, only 36 met these criteria. We conducted another search using the same keywords within Google Scholar and identified an additional 14 relevant articles within the first 50 records. Additionally, we included 25 articles based on our background reading but not found in the searches that also addressed our research questions. This resulted in a total of 75 articles.

Articles were reviewed to extract the following data: 1) geographic location and coordinates; 2) taxa studied (small mammals, bats, birds, reptiles, amphibians, medium and large-bodied mammals, and invertebrates); 3) spatial scale of the study, including the total area sampled (i.e. measured on the basis of the most extreme vertices describing the study area polygon, excluding for Ernst et al. [27], Barlow et al. [53], Cleary [54], Johns [55], and Jones et al. [56], which considered much longer distances between study plots [> 800 km] and we used the largest studied area of each one as spatial scale), and the distances between study sites, measured from any logged sampling area to the nearest unlogged primary forest or between sampling sites, such as transects, traps or point counts, between forest management treatments; 4) recovery time scale (years between the cessation of any logging activity and the time of data acquisition); 5) management type of each study site (i.e., reduced-impact selective logging – hereafter Reduced Impact Logging or RIL, conventional selective logging – hereafter Conventional Logging or CL, non-mechanized selective logging – hereafter Non-mechanized logging or NML, or unreported by the study), including number of cutting cycles, and selective logging intensity (e.g., stump density - stems/ha, basal-area removal - m^2/ha, or volumetric removal - m^3/ha). This was often reported as stems per hectare or cubic meters per hectare, so we used different metrics to evaluate the intensity of selective logging; 6) habitat quality of residual logged and unlogged areas (i.e., based on maps, tree density, or forest basal area); 7) presence of (pseudo) control areas and availability of pre-logging data on flora or fauna from logged areas; 8) sampling technique (e.g., line-transect census, point counts, traps); 9) use of environmental covariates to interpret the results; 10) co-occurrence of other anthropogenic disturbances that could affect the results (e.g., wildfire, hunting, and fragmentation) in the study area.

When the report failed to provide geographic coordinates, we used Google Earth (GE) to obtain the most approximate coordinates supported by maps of the study area and key landmarks such as rivers, roads, villages, towns and other visual features that could be clearly distinguished by GE images. When studies reported more than one study site coordinate, we calculated the mean positional fixes between these points, with equal distances between all points reported. The mean distances reported within any given study ranged from 0.5 to 12.9 km (mean = 1.38 km). However, for two intercontinental comparative studies, coordinate points from each study area were plotted in the map [27, 55]. We used the ArcGis 9.2 [57] in order to produce the final distribution map (Fig. 1).

When we were unable to find reliable information on forest management patch size, distance between sampling sites or distance to the nearest unlogged primary forest, we simply estimated these values based on maps and spatial scale provided by the reports, and/or based on GE images. We selected the longest time interval when examining studies that compared different periods between the onset of forest disturbance and data collection. In order to standardize the time scale variable, whereby we recorded the time between logging activity and data collection, we calculated the time (years) from the last year of any reported disturbance until the onset of field sampling within each study.

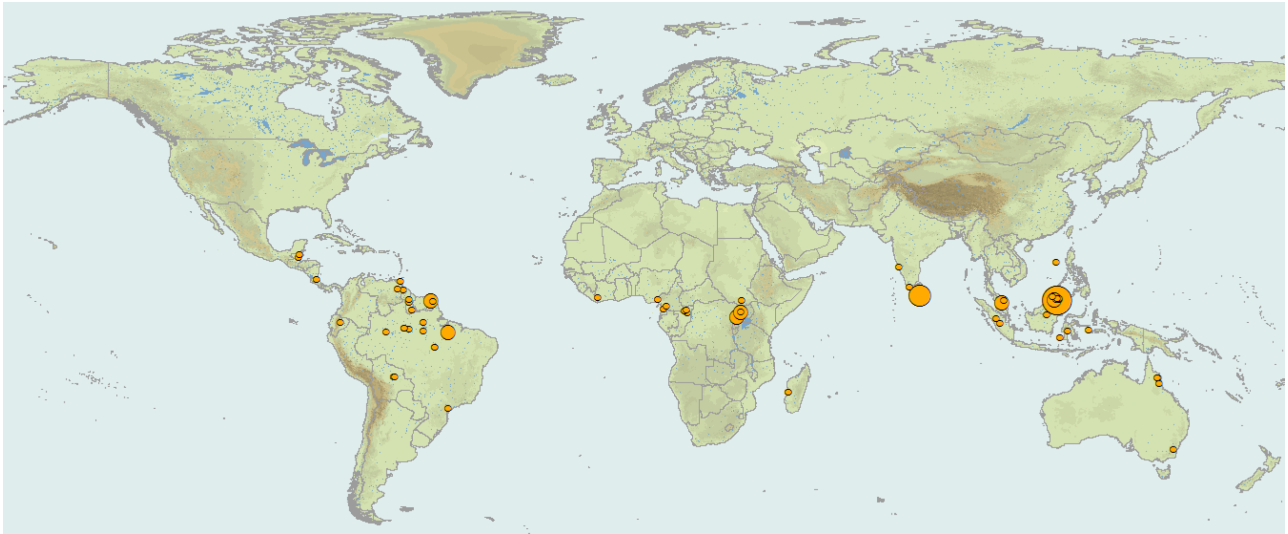

Fig. 1. Geographic distribution of single taxon or multi-taxa studies on faunal responses to selective logging in Tropical Forests (see Appendix 1 for references). Orange circles are sized proportionally to the total number of studies at each site (range = 1 - 4 studies per site).

Results

Geographic and taxonomic spread of studies

The 75 papers we selected (Fig. 2, Appendix 1) were published from 1986 to 2012, most of them since 2000 (72%). Most studies were carried out in South/Southeast Asia (39%), followed by South America (31%), Africa (20%), Oceania (5%), and Mesoamerica (5%) (Fig. 1, Appendix 1). Most logging impact studies took place in Malaysia (27%), especially the state of Sabah in Borneo (21%), followed by Brazil (17%) and Uganda (9%). However, most Asian studies are concentrated in few geographic areas, whereas those in the Neotropics are more widely distributed, with only a few countries having more than three studies (Fig. 1).

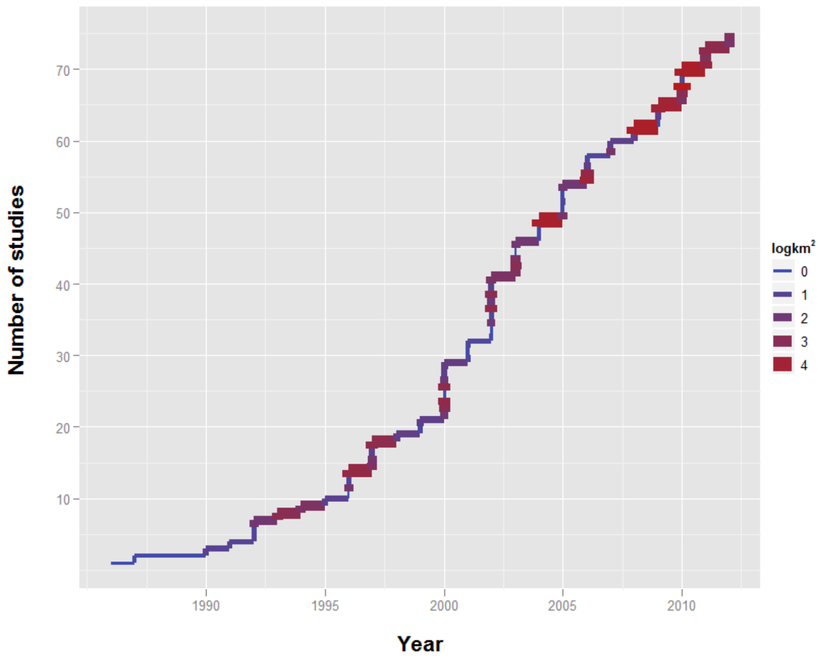

Fig. 2. Annual number of logging studies from 1986 to 2012. Line thickness is proportional to the total area sampled ($\log_{10}$ km^2) in each study.

In relation to the taxonomic group covered, most studies evaluated the effects of logging on vertebrates (70%) followed by invertebrates (30%) (Fig. 3, Appendix 1). Butterflies, ants, and beetles comprise the most studied invertebrates, with all remaining taxa representing 28% of all studies. However, all lepidopterans combined (butterflies and moths) represent the most popular invertebrate taxon in the logging impact literature (31%). Medium and large-bodied mammals, and primates in particular, represent the most heavily studied verterbrate taxa (44%), followed by birds (28%), small nonvolant mammals (12%), herpetofauna (11%) and bats (5%).

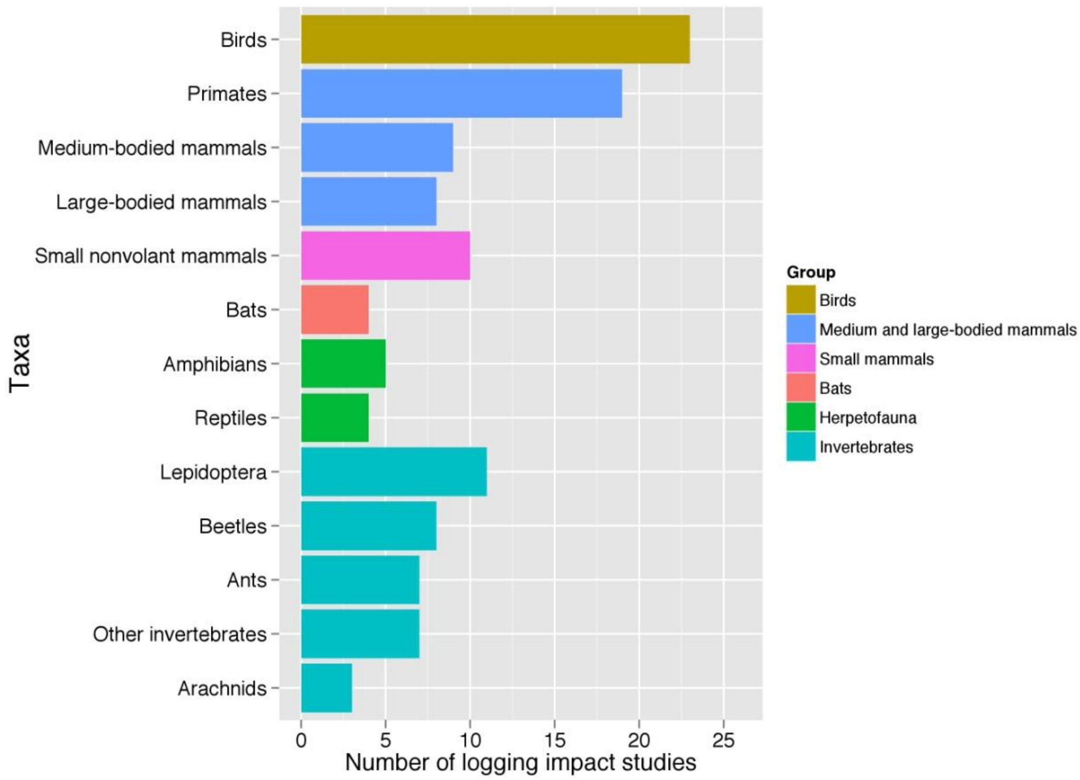

Fig. 3. Number of logging studies per faunal group studied. Frequency distribution of 13 faunal groups from single taxon and multi-taxa logging impact studies published from 1986 to 2012 (n = 75 articles) in tropical forests.

Potential sampling biases

Spatial and time scale

The spatial scale of the studies we reviewed ranged from less than one square kilometre to tens of thousands of square kilometres (<1 – ~53,000 km^2) (Fig. 4). Although many studies assessed logging effects at a scale of dozens to thousands of square kilometres, 38 studies were carried out at scales below 100 km^2 (Appendix 1) and 14 addressed even smaller spatial scales (<10 km^2) (Fig. 4).

Invertebrate studies were conducted at highly variable spatial scales (range = 2 - 16900 km^2) with the smallest and largest scales in two studies on butterflies and termites in Belize and Sumatra [22, 28], and ants and spiders in Amazon [58], respectively. Compared with invertebrates, vertebrate studies were conducted at larger spatial scales (range = <1 - 53,000 km^2). Overall, the spatial scale used in multi-taxa studies was larger than those considering a single taxon (Fig. 4).

An overview of recovery time scales showed that most studies (45%) were carried out long after the cessation of logging disturbance (> 15 years). The remaining studies evaluated logging effects at medium

(6-15 years, 35%) or short time scales (≤ 5 years, 20%) following logging. However, 32% of all studies were conducted >20 years after logging disturbance. The only study representing a much longer time period (> 50 years) used a theoretical rather than empirical modelling approach [38].

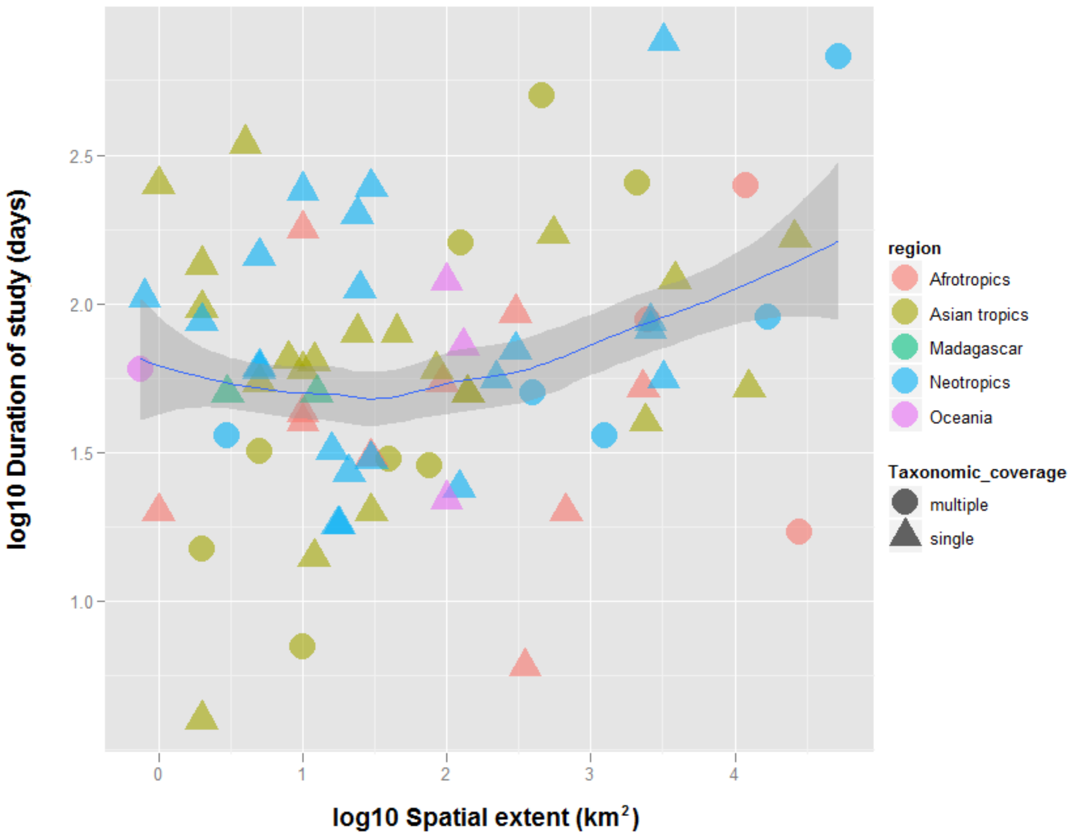

Fig. 4. Relationship between study duration and spatial extent of tropical forest logging studies. Symbols show values from different regions and the taxonomic coverage of 75 logging impact studies published from 1986 to 2012. The line shows predictions from loess regression and the grey shaded area is the 95% confidence interval.

Forest quality report

The information on forest habitat structure reported by authors varied greatly, as well as the quality of figures and/or maps presented in these studies. Half of the articles showed a figure or map with some information about scale, ranging from regional to local scales of the study sites, sampling design (sampling points or transects), logged patches, type of habitat and surrounding landscape. However, only 16 of these studies clearly presented a map of the study area, and 15 studies reported the habitat and/or landscape surrounding the study sites.

From all studies compiled, 24 presented some quantitative metric to describe forest structure, with 11 articles providing information on forest basal area (m^2/ha). The remaining studies reported other quantitative variables to describe habitat structure such as the number, density (trees/ha), and volume (m^3/ha) of trees in the original stand or removed by logging. From all 24 studies with some information on forest structure, only eight presented quantitative metrics of both logged and unlogged forest separately, while other studies only presented a brief description of logged or unlogged forest.

Forest management report

Despite its critical relevance, 64% of the studies we reviewed did not even report the type of forest management used in the logged forests studied. From those papers reporting forest management type, the most common was conventional logging, followed by reduced-impact logging, and non-mechanized logging, occurring in 17%, 12%, and 4% of the studies, respectively.

The intensity of timber harvest in the study areas was reported under four different metrics, of which stems and cubic meters per hectare were most frequent. The intensity of harvest was also measured by the percentage of trees basal area removal (m^2/ha), or ranked (e.g. low intensity - [59]). Those studies reporting the logging intensity in terms of volumetric removal (m^3/ha) reported ranges from 0.22 in the Democratic Republic of Congo [20] to 145.3 m^3/ha in Sabah, Borneo [32]. The logging intensity of the studies that reported stems/ha, ranged from 0.23 stem/ha in a mahogany logging operation in southeastern Amazonia [60] to 19.5 stem/ha in Guyana [27].

Other relevant sampling information

Most studies reviewed here (93%) used faunal empirical data, and almost all studies (96%) used both a primary or unlogged forest as a control site, while only three studies failed to use a control site. Although the acquisition of fauna and pre-logging habitat data was highlighted as very important in order to understand disturbance effects [61], these data were missing from the majority of the studies (88%).

The use of environmental covariates to interpret the effect of logging on forest fauna was common in most studies (71%), although the number of covariates and the sampling technique used ranged widely. Most of these covariates were linked with forest structure (e.g., canopy openness, topography, forest type, logging damage). Information on presence or absence of other disturbances that could influence the organism's responses (e.g., hurricanes, hunting, agriculture or fire) was reported in approximately half of the studies (55%).

Discussion

There is an increase in the number and extent of sustainable-use reserves worldwide, as 86% of all global protected areas now permit some form of human use [62]. Consequently, there is a huge opportunity to integrate multiple resource use, including selective logging, in the largest remaining expanses of tropical forest [63]. Additionally, there is a global increase in certification applications [61]. Among the minimum requirements for certification, logging companies must gather information that is also useful to assess the effects of selective logging (e.g., 100% inventory, spatial data on canopy trees, harvested species, forest stand, and timber offtake). This creates a unique opportunity for new logging studies to use these data. However, such studies and their results must be standardized to enhance comparability [64]. The availability of comparable data for logging studies would contribute to the long-term conservation and sustainability of large mosaics of logged and unlogged tropical forests.

Published logging studies differ in several aspects that limit any comparative analysis on logging impacts [64]. Differences include focal taxa, forest management system, spatial and temporal scales of the studies, and a general failure to address potentially confounding covariates (Appendix 1). Due to the complexities of the forest management study system few studies provide appropriate summaries on the effects of selective logging on wildlife [11, 14, 51, 65-67].

Choice of Spatial and Time scale

Logging impacts increase the challenges of analyzing the effect of spatial scale on naturally heterogeneous tropical forest landscapes [26, 39, 68]. Indeed, several authors have suggested that the impact of logging depends on the spatial scale of the study [18, 69]. The spatial heterogeneity of the study area must therefore be explicitly considered in the sampling design [70-72]. Additionally, selective logging disturbance is not homogeneous throughout the landscape, with areas containing higher basal areas of commercially valuable timber species typically being the most intensively impacted [21, 56].

In general, studies showed an increase of biodiversity metrics between logged and unlogged forests at small spatial scales. This occurs due to an increase of non-forest dependent organisms associated with greater habitat disturbance after logging [10]. Logging could therefore be erroneously interpreted as a low impact disturbance. However, if we consider larger spatial scales, the same biodiversity metrics may decrease [20]. Different effects have been variously reported for butterflies [14, 18, 50], small mammals [73], beetles [20] and medium and large vertebrates [40]. This variation in biodiversity metrics is in broad agreement with the intermediate disturbance theory [19].

In fact, logging operations may be far more degrading than our perception prior to this review, as there is no consensus to date on the ecological impacts on forest wildlife, with many studies reporting highly idiosyncratic and/or species-specific responses to logging disturbance [15, 31, 33, 58]. For instance, while population density of some primates decreases in logged forests in central Guyana, it increases for some terrestrial gamebirds (Tinamous) at the same site [31]. Thus, until more studies describe the effects of logging on different faunal groups, we cannot determine whether or not the overall effects of selective logging on forest wildlife are benign or detrimental.

Recovery time scale is a critical criterion to interpret the effects of selective logging, because the length of time after disturbance can affect the magnitude and nature of responses of forest organisms [74]. In addition, it is hardly possible to compare studies with different time scales [75]. Studies carried out within a single period after logging provide only a snapshot of the structure of animal populations and fail to consider the natural population dynamics in different forest successional stages [32]. This snapshot of faunal community structure could generate misleading interpretations as a consequence [74]. Although some authors were unable to detect a clear pattern between biodiversity metrics and time-lag after logging [76], other researchers found differences between species. This may be a function of post-harvest recovery time and disturbance intensity [27, 30]. The heavier the disturbance, the more time is required for forest recovery. An anuran community showed strong signs of recovery during four years after logging disturbance, but the time-lag selected by the study is often insufficient to observe complete recovery [27]. In peninsular Malaysia, primates exhibited a very slow recovery response to disturbance, so that longer-term data were required before robust conclusions could be reached [37]. In Uganda, two primate species (*Cercopithecus mitis* and *C. ascanius*) continued to decline even three decades after logging, while *Colobus guereza* were found at higher density in logged than unlogged forest [33]. This variation could be explained by species-specific traits [31], such as trophic guild [58], population abundance, and home range mobility. In an avifaunal study in a logged forest in French Guiana, bird species richness did not recover to levels observed in primary forest even 10 years after moderate logging disturbance [21]. In Uganda, long-term research conducted after logging showed that even after three decades the bird community had lost a large number of forest-dependent species [30].

Researchers must consider that the results from different time scales during long-term studies could also be affected by synergistic interactions between logging and other forms of anthropogenic disturbance and natural climatic variation [23]. These confounding variables must be controlled to avoid misleading interpretations [43]. Therefore, we recommend the use of long time scales relative to the generation time of target taxa to evaluate the degree to which selective logging affects wildlife. In addition, any type of disturbance must be reported in studies investigating effects of selective logging.

Baseline data and control sites

Spatially correlated studies including both pre and post-logging forest sites provide a much better approach to study the effects of logging than simply using a space-for-time substitutional approach. Longitudinal studies can compare the same forest before and after logging harvests and can explicitly control for several environmental gradients within sites [56], which are typically subject to inherent systematic biases in the choice of logging areas by operators (e.g., logged-over forest tends to be associated with higher pre-logging basal areas). Most studies reviewed here lacked before-and-after data, so researchers should meet the assumption of forest homogeneity in order to compare data within and between studies [69]. Additionally, this presupposes that any structural or compositional differences found in patterns of species abundance and diversity between logged and unlogged forests are induced by logging [17, 77], when this is often not the case. It is essential to know the degree of within-forest heterogeneity in the absence of logging [39] and collect preliminary data on existing populations prior to logging [78], in order to have a better understanding of long-term variation in biodiversity metrics.

Improved use of control sites is also required to effectively compare faunal abundances between treatments (i.e., different logging intensities or management systems). Control sites can also differ in terms of floristic composition, patch scale, forest habitat heterogeneity [69], topography, levels of harvest intensity [56], and previous history of anthropogenic disturbance other than logging. In some studies the "undisturbed" control forest site used was far from undisturbed [78-82], yet these areas are frequently considered to be a satisfactory baseline to compare logging effects on faunal abundances. Including these differences in the results is essential for interpreting site comparisons and for understanding effects that can actually be assigned to logging [31, 76]. In addition, the use of truly undisturbed primary forest as control site is desirable whenever possible to avoid misleading interpretations.

Quality of report information

Our review shows that variation in the collection of essential information limits our ability to compare tropical forest logging studies. For example, basic but critically important information such as geographic coordinates of study areas are rarely reported [22, 32, 58, 69]. Many of the studies we reviewed failed to present a map showing the geographic location of the logged and unlogged forest areas, the availability of unlogged primary forest or other relevant information on surrounding habitat types (e.g., secondary forest, plantation, pasture). Such data (geographic location/surrounding habitat) are essential to understand the spatial structure of faunal responses to local- and landscape-scale phenomena, and ultimately evaluate the impact of selective logging on the wildlife. At a minimum, this information should be reported in a map or table in addition to a distance scale.

Most studies did not even report the forest management system applied in the study areas. The type of forest management has a differential influence on wildlife responses [60]. In general, conventional logging has much greater impacts on faunal species than reduced impact logging [36, 40, 58]. In addition, logging damage information is essential and complementary to forest management type in assessing logging impacts on forest structure and faunal communities [73, 83-84]. Measures such as canopy fracture, standing tree density, tree mortality, density of skid trails, density of logging roads and patios, and basal-area offtake (m^2/ha) or harvested timber volume (m^3/ha) should be reported in all logging studies. Other information particularly relevant to African and Neotropical frugivores, is the identification of the harvested timber species, since some harvested species provide key food resources to forest wildlife [21, 33, 55, 74, 85-86].

Implications for conservation

Logged areas will become of increasingly greater importance for tropical forest wildlife conservation [6], considering the growing global demand for timber products and the resulting increase in the intensity and extent of selective logging in vast areas of tropical forests [2, 64]. Here, we showed that most of the studies we reviewed have marked differences in sampling designs and the quality of the supporting information they provide, which hugely undermines the comparability among studies. In order to enhance any quantitative synthesis of logging studies and contribute to quantitative assessments of the ecological sustainability of this pattern of land-use, we list some information that we consider critical for future selective logging studies.

- Whenever possible, large spatial areas must be used, in order to evaluate both landscape or regional scale changes in ecological responses of forest organisms to logging;

- Preference should be given to long-term monitoring programmes, in order to identify changes in long-lived species and/or slow recovery trajectories across generations in short-lived species;

- Studies should report both pre- and post-disturbance data to determine species response while avoiding pseudoreplication in sampling designs;

- It is essential to use appropriate control forest sites in the same landscape incorporating the logged forest sites, or to use forest areas with comparable structure and species composition in both logged and unlogged sites;

- Studies should report detailed information on forest management systems, forest habitat quality (e.g. basal area, m^2/ha), sampling design (e.g. field techniques, replication, distance between primary forest and sample sites), and other potential natural (e.g., wind throws) and anthropogenic disturbances (e.g. hunting and wildfire) that can also affect the study areas and confound the effects of logging on study organisms.

Acknowledgements

JL was funded by a Brazilian Ministry of Education (CAPES) PhD studentship. We are grateful to Alejandro Estrada and two anonymous referees for comments on the manuscript.

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Appendix 1. List of reviewed selective logging studies in Tropical Forest. In Forest management column the "np" means that the information was not reported. Continents are: LA – Latin America, AS – Asia, AF – Africa, OC – Oceania.

Source	Source data	Continent	Forest management	Taxonomic coverage	Spatial scale (km^2)	Time scale (years)	Control site	Pre data	Co-variates	Empirical data	Habitat quality	Landscape	Map
[87]	ISI	LA	np	single	5	12	yes	no	yes	yes	yes	yes	no
[26]	other	AS	np	single	4	6	no	no	yes	yes	yes	yes	yes
[58]	ISI	LA	RIL	multiple	16900	0.5	yes	yes	no	yes	yes	yes	yes
[88] *	ISI	AS	np	single	550	20	yes	no	no	yes	yes	yes	yes
[89]	ISI	OC	CL	single	100	35	yes	no	yes	yes	yes	yes	no
[53] *	ISI	LA	RIL	single	3200	-	yes	no	no	no	no	no	no
[90] *	ISI	AS	np	single		30	yes	no	yes	yes	yes	yes	no
[73] *	ISI	AS	np	single	85	25	yes	no	no	yes	yes	yes	yes
[71]	ISI	AS	CL	multiple	40	18	yes	no	no	yes	yes	yes	yes
[31]	other	LA	RIL	multiple	1250	33	yes	no	yes	yes	yes	yes	yes
[91] *	other	AF	NML	single	350	30	yes	no	no	yes	yes	yes	no
[92]	ISI	LA	RIL	single	18	1.7	yes	no	no	yes	yes	yes	no
[33]	other	AF	np	single	10	28	yes	no	yes	yes	yes	yes	no
[68]	ISI	AF	np	single	3	19	yes	no	yes	yes	yes	yes	yes
[93] *	other	AS	CL	single	2400	16	yes	no	yes	yes	yes	yes	yes
[32]	other	AF	CL	multiple	12000	33	yes	no	yes	yes	yes	yes	no
[79]	other	LA	CL	single	300	33	yes	no	yes	yes	yes	yes	no
[54]	other	AS	np	single	12	-	yes	no	no	yes	yes	yes	yes
[94]	other	OC	RIL	multiple	0.75	1.6	yes	yes	yes	yes	yes	no	yes
[95] *	ISI	AF	np	single	1	45	no	no	yes	yes	yes	yes	yes
[20] *	ISI	AS	np	single	-	9	yes	no	no	yes	no	yes	no
[25] *	ISI	LA	np	multiple	53000	10	yes	no	yes	yes	no	yes	yes
[18]	ISI	AS	CL	single	-	15	yes	no	yes	yes	no	yes	no
[27]	Google	LA	np	single	30	25	yes	no	yes	yes	yes	no	no
[44] *	ISI	LA	RIL	multiple	-	1	yes	no	yes	yes	yes	yes	no
[96]	other	AF	NML	single	12.5	8	yes	no	yes	yes	yes	yes	yes
[97] *	Google	LA	np	single	220	-	yes	no	yes	yes	yes	yes	no
[8] *	ISI	OC	np	single	100	18	yes	no	yes	yes	yes	yes	yes
[98]	ISI	AS	np	single	10	30	yes	no	yes	yes	yes	yes	yes
[77]	other	LA	RIL	single	25	4	yes	yes	no	yes	yes	no	yes
[99]	other	AS	CL	single	140	12	yes	no	no	yes	yes	yes	yes
[100]	Google	AS	np	single	140	12	yes	no	yes	yes	yes	yes	yes
[80]	ISI	AS	np	single	30	5	yes	no	yes	yes	yes	yes	no
[101] *	Google	AS	np	multiple	10	6	yes	no	no	yes	yes	no	no
[102] *	ISI	AS	np	single	3841	20	yes	no	yes	no	no	yes	yes
[37]	Google	AS	np	single	1	1	yes	yes	yes	yes	yes	yes	yes
[9]	other	LA	np	single	2	11	yes	no	no	yes	yes	yes	yes
[55]	Google	AS	np	multiple	5	12	yes	yes	yes	no	yes	no	no

[74]	other	LA	np	single	-	-	yes	no	yes	no	no	no	no
[22] *	ISI	AS	NML	single	12474	15	yes	no	yes	yes	yes	no	yes
[56] *	ISI	AS	np	single	2	13	yes	no	yes	yes	yes	yes	no
[38]	ISI	AS	np	single	8	100	yes	no	yes	no	yes	no	no
[10] *	ISI	AS	np	multiple	76	40	yes	no	yes	yes	yes	yes	yes
[103] *	Google	AS	np	multiple	2100	27	yes	no	yes	yes	yes	yes	no
[60]	Google	LA	np	single	24	10	yes	no	yes	yes	yes	yes	no
[81]	Google	OC	np	single	130	15	yes	yes	yes	yes	yes	yes	yes
[28]	Google	LA	np	single	2	3	yes	no	yes	yes	yes	yes	no
[104] *	other	LA	np	single	5	10	yes	no	no	yes	yes	yes	no
[105] *	other	LA	np	single	3200	6	yes	yes	yes	yes	yes	yes	no
[78] *	other	AF	np	single	2300	30	yes	no	no	yes	yes	yes	yes
[106]	ISI	LA	np	multiple	400	7	yes	no	no	yes	yes	yes	yes
[107] *	other	LA	CL	single	16	20	yes	no	yes	yes	yes	yes	no
[108]	ISI	LA	np	single	21	0.2	yes	yes	no	yes	no	yes	no
[83]	ISI	LA	np	single	5	10	yes	no	yes	yes	yes	yes	no
[29]	other	LA	RIL	single	0.8	3	yes	no	yes	yes	no	yes	no
[76]	Google	AF	CL	single	672	50	yes	no	yes	yes	yes	yes	yes
[39]	ISI	AF	np	single	93	30	yes	yes	yes	yes	yes	yes	yes
[109] *	ISI	AF	np	multiple	2500	17	no	no	yes	yes	yes	yes	yes
[110] *	ISI	AS	np	multiple	-	-	yes	no	yes	yes	yes	yes	no
[40]	ISI	AS	CL/RIL	multiple	460	13	yes	no	no	yes	yes	yes	yes
[111] *	ISI	AF	np	single	30	48	yes	no	no	yes	yes	yes	yes
[30] *	other	AF	np	single	10	28	yes	no	yes	yes	yes	yes	no
[59] *	other	AS	np	single	12	20	yes	no	yes	yes	yes	yes	no
[17]	ISI	AF	CL/RIL	multiple	27970	48	yes	no	yes	yes	yes	yes	yes
[21]	Google	LA	np	single	2600	10	yes	no	yes	yes	yes	yes	yes
[15]	Google	LA	np	single	2600	10	yes	no	yes	yes	yes	yes	yes
[112]	Google	LA	np	single	17.5	10	yes	no	yes	yes	yes	no	no
[113]	other	AF	np	single	300	3	yes	no	no	yes	yes	yes	yes
[114]	other	AF	CL	single	10	23	yes	no	yes	yes	yes	yes	no
[69]	ISI	AS	CL	single	26000	30	yes	no	yes	yes	yes	yes	no
[36]	other	LA	RIL	single	30	1	yes	no	yes	yes	yes	yes	no
[82] *	ISI	AS	np	multiple	200	28	yes	no	no	yes	yes	yes	no
[72]	ISI	AS	CL	single	30	5	yes	no	no	yes	yes	yes	yes
[52] *	ISI	AS	CL	single	45	6	yes	no	yes	yes	yes	yes	yes
[16]	other	LA	np	single	144	1	yes	no	yes	yes	yes	yes	No

*studies that reported other anthropogenic perturbations (e.g., clear-cut, monocultures, and wildfires) coupled with logging