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Sustaining conservation values in selectively logged tropical forests: the attained and the attainable

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Abstract

Most tropical forests outside protected areas have been or will be selectively logged so it is essential to maximize the conservation values of partially harvested areas. Here we examine the extent to which these forests sustain timber production, retain species, and conserve carbon stocks. We then describe some improvements in tropical forestry and how their implementation can be promoted.

A simple meta-analysis based on >100 publications revealed substantial variability but that: timber yields decline by about 46% after the first harvest but are subsequently sustained at that level; 76% of carbon is retained in once-logged forests; and, 85-100% of species of mammals, birds, invertebrates, and plants remain after logging. Timber stocks will not regain primary-forest levels within current harvest cycles, but yields increase if collateral damage is reduced and silvicultural treatments are applied.

Given that selectively logged forests retain substantial biodiversity, carbon, and timber stocks, this "middle way" between deforestation and total protection deserves more attention from researchers, conservation organizations, and policy-makers. Improvements in forest management are now likely if synergies are enhanced among initiatives to retain forest carbon stocks (REDD+), assure the legality of forest products, certify responsible management, and devolve control over forests to empowered local communities.

Introduction

Strict protection of purportedly pristine forests will likely remain a conservation priority in the tropics (e.g., Sodhi *et al.* 2009; Gibson *et al*. 2011), but the values of other sorts of forests are increasingly being recognized (e.g., Ghazoul & Sheil 2010). Increased recognition that the posited dichotomy between primary and modified habitats is artificial and often obstructive (Miller *et al.* 2010; Sheil and Meijaard 2010) has led to increased attention to the environmental values of secondary and selectively logged forest (e.g., Chazdon *et al.* 2009; Berry *et al*. 2010; Edwards *et al.* 2011, Gibson *et al*. 2011). Here we evaluate timber production and the conservation values of selectively logged tropical forests and discuss how these values can be enhanced. This focus seems justified given that tropical forests are logged at about twenty times the rate at which they are cleared (Asner *et al*. 2009) and that 403 million hectares of tropical forest are officially designated for timber production (Blaser *et al.* 2011). Furthermore, because selectively logged forests are classified as "degraded," they are very susceptible to conversion to non-forest land uses (e.g., Xingli *et al*. 2011).

We performed a simple meta-analysis to assess the extent to which selectively logged tropical forests retain their productive potential for timber, carbon stocks, and species richness. Based on this meta-analysis we argue for the distinction between exploitative timber extraction and responsible forest management. With this distinction recognized, attention can focus on improving forest management practices through enhancing synergies between initiatives to improve national and international forest governance (e.g., demand-side legality assurance legislation), market-based initiatives (e.g., forest product certification and crediting for reduced greenhouse gas emissions), and devolution of control over forests to empowered local communities.

The attained: conservation values and timber productive potentials of selectively logged tropical forests

In our unweighted meta-analysis we used 59 studies from lowland tropical forests in 10 countries on three continents that reported on timber production from selectively harvested forests (Tables S1 and S2). These studies used a variety of simulation models calibrated with measured rates of tree growth, mortality, and recruitment to predict commercial timber volume increments over government-mandated minimum harvest cycles of 20-40 y starting with old-growth(=primary) forest. Logging intensities in the studied forests varied by more than two orders-of-magnitude (1-220 m^3/ha) and the periods of post-logging monitoring of stand dynamics were always less than a single harvest cycle. Landscape-level and long-term impacts of repeated logging were not addressed in the studies reviewed, and few provide the information needed to compare harvesting practices. Nevertheless, given the allowed presence of researchers, we suspect that there was a bias towards better run logging operations.

Critical assessments of the sustainability of timber production require clarity about what is to be sustained. Here we accept that the number of harvested species increases over time with enhanced marketability but do not accept reductions in minimum harvest diameters. With these assumptions, our meta-analysis revealed that, on average, just over 54% of the timber volume extracted during the first harvest from primary forest will be available for the second and third cuts (Table S2; Figure 1). In contrast, if only the same species continue to be harvested, only 35% of the original timber stock will be available for the second cut and yields will likely decline thereafter (Table S1). It is important to emphasize that the among-study variation in volume recovery rates is huge (range = 0-220%; Tables S1 and S2), presumably due to differences in logging intensities and techniques, as well as ecological differences among the commercial species. In spite of this variation, average volume recovery was significantly below 100% (one-sample t-tests, Table S5). To our surprise, we did not find any published studies on timber recovery from the same tree species from tropical Asia, the region harboring the most important timber-yielding tree species. Studies on African timber species were also scarce. In view of the importance of international sales of tropical timber (Kastner *et al*. 2011) and the attention given to sustainable forest management over the past 20 years, it is remarkable that information on timber recovery has been published for only27 tree species.

Considering the impacts of selective timber extraction on carbon stocks, the 22 studies we found suggested that, soon after logging, once-harvested stands retain about 76% of their above-ground live carbon (Figure 1). The high variation in carbon retention (47-97%) reflects the range in harvest intensities and undoubtedly also the care with which harvests were performed (Table S3). In the five cases in which logging was carried out by trained and supervised crews working with the aid of detailed harvest plans, substantially more biomass was retained through the first harvest than in matched areas that wer conventionally logged (Pinard & Putz 1996; Bryan *et al*. 2010; Medjibe 2012; Medjibe *et al*. 2011; Miller *et al*. 2011). After logging in at least some forests, carbon recovery rates can be extremely rapid if harvests are performed with care (Pinard 2009).

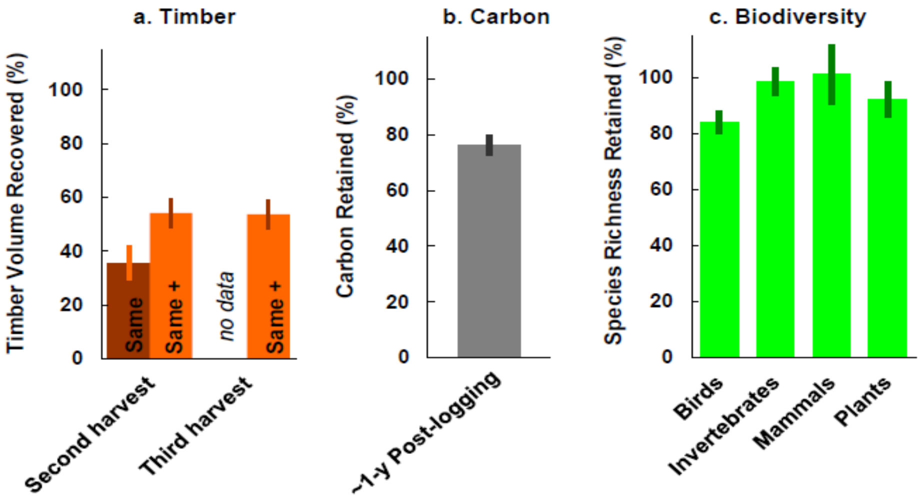

Figure 1. What is sustained in logged tropical forests? Three elements of sustainability based on simple meta-analyses of studies that reported: (a) merchantable timber volumes after one or two government-specified cutting cycles of 20-40 years each if the same tree species is harvested ('Same') or additional species are harvested ('Same+'); (b) carbon in living tree biomass approximately one year after selective logging; (c) species richness of birds, invertebrates, mammals, and plants in selectively logged forests compared to undisturbed old-growth forests. Means and standard errors in a, b and c are based on 59, 22, and 109 studies, respectively (see Supplemental Tables in Supporting Information for data and sources).

Assessments of the impacts of logging on biodiversity are more complicated than those on timber yields or carbon stocks. Published studies vary in whether they focus on changes in species richness, species composition, or of particular taxa. Variation in temporal and spatial scales further complicates comparisons. For example, biodiversity impacts on obligate forest understory species soon after intensive logging are likely to be more severe than the longer-term impacts of low intensity logging on a wide variety of taxa averaged over large spatial scales that include enclaves of un-harvested forest. Also, disturbance often allows generalist species to enter closed forests where they were previously absent, thus increasing local diversity (Bongers *et al*. 2009). These limitations notwithstanding, a meta-analysis based on 109 studies of selective logging of primary tropical forest carried out 1-100 years after a single harvest (Table S4) revealed modest impacts on species richness of birds, mammals, invertebrates, and plants (Figure 1). Birds represented the most severely affected of the groups studied; selectively logged forests supported, on average, only 84% of the species richness of unlogged forest ($P<0.001$; Table S5). For plants, mammals, and invertebrates, average species richness of harvested and not-yet harvested forests did not differ significantly. These results are in agreement with those of Gibson et al(2011), who reported only slightly reduced biodiversity in selectively logged forests. Remarkably, reports from Borneo suggest substantial biodiversity retention after extremely intensive exploitative logging (Cannon *et al.* 1998, Edwards *et al*. 2011) as well as after heavy logging followed by strip planting with native timber species (Ansell *et al*. 2011). These overall favorable results are especially impressive given that few studies were conducted in forests with third-party certification for good management (van Kuijk *et al.* 2009), which suggests that further improvements are possible (Meijaard *et al.* 2005).

In addition to noting the substantial variability in the results of the studies we reviewed, we recognize that species richness data cannot reveal changes in species composition. Furthermore, the mostly near-term effect studies we reviewed cannot account for the possibility of longer-term species losses (i.e., extinction debts). In regards to changes in species composition in response to logging, we note that due to differences in harvest intensities and techniques as well as changes in the harvested tree species, the reported impacts on disturbance-sensitive, rare, or otherwise noteworthy species are mixed (Putz *et al*. 2001; Meijaard *et al*. 2005; Fisher *et al*. 2011; Nasi *et al.* 2012). We also note that populations of old-growth species are more likely to rebound than to decline with time after a selective harvest as long as hunting and fire are excluded (Poulsen & Clark 2010) and premature re-entry logging is prohibited . We base this hopeful prediction on the observation that biodiversity research is typically carried out soon after logging in the areas most heavily affected and not in the substantial areas that are regenerating after previous harvests. Also disregarded are forest patches within designated cutting blocks that remain unscathed due to lack of harvestable timber or restrictions on harvesting near rivers, on steep slopes, or in designated high conservation value areas.

The attainable: improving conservation values and timber yields in managed tropical forests

Decreases in timber yields after the first harvest from old-growth forests seem inevitable. For selectively logged forests to regain during 20-40 year harvest cycles the volumes of timber accumulated over the preceding centuries, forest management practices would need substantial modification. In particular, harvest intensities would need to be reduced, which would reduce profits, and post-logging silvicultural treatments would need to be applied, which carries some financial as well as environmental costs. In the interest of retaining the many other values of managed forests, we recommend acceptance of a "primary forest premium," with subsequent yields sustained at an agreed upon lower level.

Although seldom recognized outside of forestry circles, the notion of a primary forest premium is not new; 100 years ago Gifford Pinchot (1910) accepted a downward adjustment of yield expectations after enjoyment of what he termed "nature's bounty." The allowable magnitude of the primary forest premium should reflect both biophysical capacities of forests and land-use objectives, but could be substantially higher than the 46% observed with current management practices. Alternatively, sustained yields in the sense of fixed annual or periodic yields of the same quantities, qualities, sizes, or species might not be required. Instead, the focus could be on the use of production systems and harvesting practices that are compatible with the stated, long-term, multiple objectives of management and do not adversely affect the productive capacity of the site or impair species survival.

Including more species in estimates of future timber stocking may seem like unwarranted lowering of expectations, but over time and with dwindling supplies, mills typically accept smaller and lower quality logs of a wider variety of species (Aplet *et al.* 1993). Nevertheless, sequential depletion of species remains a concern that can be mitigated through application of silvicultural treatments designed to augment the regeneration and growth of the most valuable species. On the other hand, some changes in species composition are an inevitable consequence of even gentle management of tropical production forests.

One straightforward way to sustain timber yields is to lower the frequency of timber harvests (Sist *et al*. 2003). At least if no silvicultural treatments are applied to increase tree growth rates, cutting cycles would generally need to be lengthened to 50-100 years for full recovery of timber stocks (Kammesheidt *et al*. 2001, Brienen & Zuidema 2007). Both the carbon and biodiversity benefits of reduced frequencies of disturbance would likely be substantial, but with any positive discount rate, the financial costs of such delays can be large. Unfortunately, while often not noticed or reported, the trend is more often in the opposite direction towards premature re-entry logging, which makes financial sense but is detrimental to future timber yields, carbon stocks, and biodiversity.

Reduced harvest intensities would help sustain timber harvests, retain carbon, and maintain pre-intervention forest structure and composition, but not without financial and other costs. Intensities can be lowered by capping harvest volumes, increasing the minimum allowable diameters, or increasing the minimum distances between harvested trees. Of course reducing harvest intensities will impede regeneration of the light-demanding trees species that dominate the tropical timber trade (Fredericksen & Putz 2003). Alternatively, low landscape-level logging intensities can be secured by allowing high logging intensities in some stands to promote regeneration of light-demanding species, but with corresponding increases in areas set aside from logging. In any case, we support the protection of very large trees due to their disproportionately large contributions of food, seeds, and habitat (Sist *et al*. 2003). Though at first sight this appears to sacrifice major timber revenues, many huge trees are hollow or harbor heartrots, and can be difficult to fell and process.

Future timber yields, carbon stocks and recovery rates, and biodiversity retention all increase if collateral damage during harvesting is reduced. Guidelines for reduced-impact logging (RIL) have been available for several decades and such measures are included in the criteria used by most forest certification schemes (Putz *et al.* 2008a). When these practices are properly implemented, damage to remaining trees and soils are substantially reduced (Putz *et al.* 2008b). Use of RIL practices also reduces carbon emissions, but supporting data are scarce and difficult to interpret due to differences in logging intensities (Table S3). In regards to the likely biodiversity benefits of RIL, the sole publication we found (Davis 2000) supports this expectation.

After timber extraction, future timber yields and carbon stock recovery can be enhanced by silvicultural treatments. As has been long-known (e.g., Wyatt-Smith *et al.* 1964) and confirmed recently (Villegas *et al.* 2009), freeing future crop trees from vines and other competitors can increase their growth rates substantially. Given that most of the carbon in tropical forests is in the boles of large trees, these timber volume benefits translate directly into carbon benefits. In regards to biodiversity, even intensive restoration interventions applied in forests severely degraded by very intensive uncontrolled logging reportedly result in few deleterious impacts (Ansell *et al.*2011; Edwards *et al*. 2009). Overall, we need to be aware of the tradeoffs involved in trying to maximize timber yields, carbon storage, and biodiversity retention.

Improved prospects for sustainable forest management

Although tropical forest management practices have improved (Blaser *et al*. 2011), past efforts at reforming tropical forestry fell short of their objectives basically because management for long-term timber production is seldom the most lucrative land-use option (Rice *et al.* 1997). Instead, the most financially profitable option is to extract all the profit-generating timber as rapidly as possible and then either abandon the area or convert it to soybean fields, oil palm or pulpwood plantations, or cattle ranches (Pearce *et al.* 2002; Fisher *et al.* 2011). Even in production forests, requirements to leave marketable trees standing or to delay their harvest incur major opportunity costs and are unlikely to be accepted without sufficient incentives coupled with adequate enforcement (Palmer & Bulkan 2010).

With their high biodiversity, carbon, and other environmental values, well managed tropical forests represent a “middle way” between deforestation and total forest protection. Once environmentalists, civil society, governments, and markets recognize the many benefits of responsible tropical forest management and it is more widely incorporated into diverse portfolios of conservation strategies, the four complementary political, economic, environmental, and social initiatives s mentioned below should be marshaled to promote improvements. These initiatives have natural synergies that need to be explored to enhance biodiversity protection, climate mitigation, timber supplies, and rural livelihoods.

1. Assurance of the legality of forests products through initiatives such as the European Union’s due Diligence Regulation and its linked FLEGT (Forest Law Enforcement, Governance and Trade) Voluntary Partnership Agreements (www.euflegt.efu.int), as well as the 2008 Amendment of the Lacey Act in the USA (www.forestlegality.org), will serve to increase market prices and access for legally produced timber while promoting more responsible forest management. Given that these regulations apply to the entire market chain from forest to consumer, even wood products processed in countries less scrupulous about their sources will need to carry assurances of legality if they are to be traded in markets in Europe and the USA. Such assurances are critical because, despite increasing scarcity of tropical forests, tropical timber prices have increased little in real terms over the past decades (http://www.itto.int/mis). This global market failure is greatly exacerbated by competition from illegally harvested wood (Seneca Creek Associates 2004; Lawson & MacFaul 2010).
2. Voluntary third party certification promotes responsible management by securing or even increasing market access and prices for forest products (Auld *et al.* 2008). The financial benefits of certification should be enhanced to render this mechanism more effective at stimulating

improvements in tropical forest management. Benefits can be increased by reducing certification costs through market and regulatory mechanisms. For example, certification might substitute for costly governmental regulation (e.g., Nittler & Nash 1999) or certified firms might be given preference in the allocation of new concessions (Blundell *et al*. 2011). Independent and critical evaluations of the biodiversity and carbon benefits of certification are now needed so that synergies with initiatives designed to enhance the retention of these values can be realized in cost-effective manners (van Kuijk *et al.* 2009).

3. The substantial carbon benefits from improvements in tropical forest management should be recognized and paid for by climate change mitigation programs designed to reduce emissions from deforestation and forest degradation and to enhance forest carbon stocks (REDD+; Angelsen *et al.* 2009). Improved forest management, as one land use included in systematic conservation planning (e.g., Wilson *et al.* 2010), figures prominently in REDD+ plans, both in voluntary schemes and as part of the new climate treaty being negotiated (Diaz *et al.* 2011). Where REDD+ payments are used to improve rather than halt timber harvesting, the costs of maintaining forest cover are reduced relative to strict protection and there is less risk of activity-shifting leakage due to loggers going elsewhere to harvest timber. Further advantages of using performance-based REDD+ payments to improve management derive from the fact that the forests must remain standing for the carbon contract's duration. These managed forests provide streams of social, economic, and environmental benefits while being more resistant to fire and resilient to climate change than conventionally logged forest.
4. Devolution of control over forests to indigenous and other rural communities together with other efforts to clarify forest tenure can serve the goals of improved tropical forest management as it reduces the likelihood of deforestation and contributes to human welfare (e.g., Chhatre & Agrawal 2008). But given the many challenges involved in running a forest industry, communities with decision-making authority should be provided long-term support on the full spectrum of activities from business practices and marketing to road engineering and tree felling. Often it is best to employ any of a variety of company-community partnerships, with which experience is accumulating (Vermeulen *et al.* 2008). But whatever form community participation takes, it should be with free, prior, and informed consent.

The "conservation through use" issue is politically charged and sustainability – a key point of reference – remains poorly defined. Financial losses and other tradeoffs among the goods and services to be sustained in managed tropical forests need to be understood and minimized. Rather than expecting timber yields from managed tropical forests to be sustained without any changes in species or log size and quality, emphasis should be on assuring that production forests remain standing in the best condition possible. To the extent that growing volumes of merchantable timber increase the value of forests and thereby decrease the likelihood of conversion, maintaining timber stocks should remain a priority. But even where sustaining timber yield is not the principal goal of management, it can serve as one indicator of the continued provision of other forest goods and services including carbon and biodiversity. And while it is possible to restore the capacities of forests to store carbon, produce timber, and support biodiversity after unnecessarily destructive logging, it is better to avoid degradation in the first place through responsible forest management.

Substantial and extensive improvements in tropical forest management are now more likely than ever if synergies can be secured between the naturally complementary efforts to control illegal logging, certify well-managed forests, maintain and enhance carbon stocks, and devolve rights and management responsibilities to local communities. One straightforward example that is already operational to some degree involves forest assessment teams that simultaneously audit for management certification, legality assurance, biodiversity impacts, and carbon emissions. The collaboration of rural communities in these assessments (e.g., Skutsch 2010) will strengthen the fourth pillar of responsible forest management. But even with these synergies fully developed, great care is warranted to avoid the pitfalls encountered by other interventions designed to reform tropical forestry such as the Tropical Forestry Action Plan (Pfaff *et al*. 2010).

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Supplemental Methods and Results

Methods

Simple meta-analysis

We performed simple (unweighted) meta-analyses (Osenberg et al. 1999) of published values for timber recuperation, carbon stocks, and species richness in selectively logged forests. While our review is extensive in terms of the coverage of relevant studies (>100 publications), most of the cited studies were pseudoreplicated (Hurlbert 1984). This implies that the standard deviations based on subplots should not be used to calculate effect sizes. Furthermore, in most studies the single unlogged control area was not immediately adjacent to the logged area, which casts doubt on their original similarity. For the data on timber yields, an unweighted meta-analysis is appropriate because the results are derived from one of a tremendous variety of simulation models. In addition to these shortcomings, the reviewed data were collected from forests subjected to unstated logging intensities that most likely varied over an order-of-magnitude. Logging practices (i.e., reduced-impact or conventional logging) and log extraction equipment (e.g., bulldozers or articulated skidders with rubber tires) were also mostly not described but undoubtedly varied. We note that these and other other deficiencies in experimental design were also characteristic of many of the studies used in a meta-analysis on forest management impacts on biodiversity in Europe (Paillet et al. 2010), as pointed out by Halme et al. (2010). Also, if in a publication reported the effects of logging on different taxa, these taxon-specific results are used as if they were independent even if the data were collected in the same plots

We limited our analyses to the calculation of averages, standard errors and simple statistical tests (one-sample and paired t-tests). We acknowledge the limitations of the results of our meta-analysis due to the shortcomings of the reviewed data, and interpret the results cautiously. Finally, we note that even if a more comprehensive and weighted meta-analysis were carried out, the results would likely have been biased by research preferences for certain taxa, sampling methods, regions, forest types, collaborating forest managers, management practices, and forest tenure regimes. In regards to the last mention factor, the majority of the studies used in our meta-analysis were carried out in lowland tropical logging concessions with just a few in community-managed or individually-owned forests. .

Recuperation of timber

We searched for publications containing information on projections of tropical timber yield based on empirical forest dynamics data but did not explicitly follow the Guidelines for Systematic Review in Environmental Management (Centre for Evidence-Based Conservation 2010). We searched for publications in refereed journals, refereed book chapters and PhD theses. In Web of Science (http://apps.isiknowledge.com) and Scopus (http://www.scopus.com), we used the following search term: timber AND tropical AND forest AND (projection OR simulation OR volume OR yield*)*. We selected those publications in which information (tables, figures, text) was provided on timber yield (volume, basal area; on an area basis) during various (at least two) logging events, based on model simulations that used empirical information on growth, survival and recruitment of tree populations or the entire tree community. Usually, the government-mandated minimum cutting cycle was applied in these simulations. To the initial selection, we added a number of journal publications and PhD studies which were known to contain useful information, but which were not revealed by the initial searches. The final selection contained 28 publications which reported on 59 studies.

Two sets of studies can be distinguished:

1. Same Species. Timber recuperation of the same species based on growth, survival, and recruitment data for that species only. Simulations were with tree-list models, population matrix models, and stand-models. We selected those studies that simulate logging following government regulations on intensity, harvest cycle, and minimum cutting diameter. This resulted in 35 studies on 27 species, reported in 12 publications (Table S1).

Values of timber recuperation in Table S1 show a wide variation caused by logging intensity and logging type (conventional vs. reduced-impact logging), but also by species characteristics such as diameter growth rates, mortality rates, and size distributions.

2. Same+ Species. Timber recuperation for a changing set of commercial tree species, allowing for changes in the proportion of exploited species and the addition of species expected to become commercial. Simulations were carried out using population matrix models, stand models, and individually based models. This resulted in 24 studies from 17 publications, see Table S2. This set of publications included studies in Asian forests, but lacked studies from Africa.

Retention of carbon

After retrieving relevant publications (both scientific papers and reports) from our own collections we searched the Web of Science (http://apps.isiknowledge.com) using the following search terms: tropical AND forest AND logging AND (carbon OR biomass). We selected those publications with data on tropical forest aboveground carbon stocks before and after one round of selective logging or in comparison with matched unlogged forests. Results of the 22 studies reported in 20 publications are included in Supplemental Table S3.

Retention of species richness (=species density)

After retrieving relevant publications from our own collections we made use of the reviews published by Sodhi *et al*. (2009), Berry *et al*. (2010), Edwards *et al.* (2011) and Schulze *et al.* (2004) and then searched the Web of Science (http://apps.isiknowledge.com) using the following search terms: tropical AND forest AND logging AND (biodiversity OR birds OR mammals OR plants OR vertebrates OR invertebrates OR insects OR dung beetles OR species). We selected those publications with data on tropical forest species richness before and after one round of selective logging or in comparison with matched unlogged forests. This resulted in a selection of 67 publications, reporting on 108 studies (see Supplemental Table S4).

Results of statistical tests

We used one-sample t-tests to evaluate whether the percentage of timber, carbon, and species richness in selectively logged forests significantly differed from 100% (the situation in unlogged forests). To compare timber volume recuperated at second and third harvest (as a percentage of volume at first harvest), we performed paired-sample t-tests for timber volume obtained from a changing set of species ('Changing Species'), as insufficient data were available on timber volume at third harvest if the same species is logged ('Same Species'). We stress that the output of these statistical tests need to be interpreted cautiously for reasons outlined above ('*Simple meta-analysis*'). We also note that when a single study presented the results for different taxa, we included them separately even when for all taxa the same (often remote) control area was used.**Supplemental Table S1.** Results of a simple meta-analysis on timber volume recuperation after selective logging of tropical forests for cases in which the same species were expected to be extracted during all harvests. Timber available at 2nd cut is presented as a percentage of logged volume or trees at first cut. CAR=Central African Republic; MCD=minimum cutting diameter; DBH=diameter at breast height; CL=conventional logging; * silvicultural treatments applied; RIL = reduced-impact logging; TLM=tree-list model; IBM=individual-based model; CH=cohort model; and, MM=matrix model.

Country	**Species**	**Cutting cycle (y) / MCD (cm DBH**	**Logging method**	**Logging intensity in m^3/ha or *trees/ha***	**Timber available at 2nd cut (%)**	**Model**	**Reference**
Bolivia	*Cedrela odorata*	20/60	RIL	2.2	28	TLM	Brienen & Zuidema 2006, 2007
Bolivia	*Amburana cearensis*	20/50	RIL	0.3	18	TLM	Brienen & Zuidema 2006, 2007
Bolivia	*Cedrelinga caeteniformis*	20/50	RIL	5.2	22	TLM	Brienen & Zuidema 2006, 2007
Bolivia	*Peltogyne sp*	20/50	RIL	0.4	51	TLM	Brienen & Zuidema 2006, 2007
Bolivia	*Cedrelinga caeteniformis*	20/60	RIL	11.0	20	TLM	Rozendaal et al. 2010
Bolivia	*Peltogyne heterophylla*	20/50	RIL	9.0	39	TLM	Rozendaal et al. 2010
Bolivia	*Clarisia racemosa*	20/45	RIL	2.0	22	TLM	Rozendaal et al. 2010
Brazil	*Swietenia macrophylla*	30/60	CL	0.7	42	TLM	Grogan et al. 2008
Brazil	*Swietenia macrophylla*	30/60	CL	1.2	27	TLM	Grogan et al. 2008
Brazil	*Swietenia macrophylla*	30/60	CL	2.5	9	TLM	Grogan et al. 2008
Brazil	*Bagassa guianensis*	35/45	CL*	*0.16*	32	IBM	Sebbenn et al. 2008
Brazil	*Hymenea courbaril*	35/55	CL*	*0.19*	35	IBM	Sebbenn et al. 2008
Brazil	*Manilkara huberi*	35/45	CL*	*1.71*	46	IBM	Sebbenn et al. 2008
Brazil	*Symphonia globulifera*	35/45	CL*	*0.08*	107	IBM	Sebbenn et al. 2008
Brazil	*Astronium lecointei*	30/50	RIL	1.6	37	CH	Schulze et al. 2008

Brazil	*Cordia goeldiana*	30/50	RIL	*22.0*	40	CH	Schulze et al. 2008
Brazil	*Hymenea courbaril*	30/50	RIL	2.3	27	CH	Schulze et al. 2008
Brazil	*Manilkara huberi*	30/50	CL	*97.0*	3	CH	Schulze 2003
Brazil	*Minquartia guianensis*	30/50	CL	*29.0*	0	CH	Schulze 2003
Brazil	*Parkia pendula*	30/50	RIL	0.6	51	CH	Schulze et al. 2008
Brazil	*Simarouba amara*	30/50	RIL	*16.0*	220	CH	Schulze et al. 2008
Brazil	*Tabebuia serratifolia*	30/50	RIL	1.1	15	CH	Schulze et al. 2008
CAR	*Entandrophragma cylindricum*	30/80	CL	24.3	16	MM	Karsenty & Gourlet-Fleury 2006
CAR	*Entandrophragma cylindricum*	30/80	CL	4.3	51	MM	Karsenty & Gourlet-Fleury 2006.
CAR	*Triplochiton scleroxylon*	30/80	CL	29.1	30	MM	Karsenty & Gourlet-Fleury 2006.
CAR	*Triplochiton scleroxylon*	30/80	CL	12.6	26	MM	Karsenty & Gourlet-Fleury 2006.
Fr Guiana	*Dicorynia guianensis*	42/60		*0.79*	53	IBM	Gourlet-Fleury et al 2005
Guyana	*Chlorocardium rodiei*	25/35	RIL	25.0	56	IBM	Arets 2005
Guyana	*Chlorocardium rodiei*	50/30	CL	*10.0*	40	MM	Zagt 1997
Panama	*Calophyllum longifolium*	30/60	CL	2.0	21	TLM	Condit et al. 1995
Panama	*Hura crepitans*	30/60	CL	42.2	5	TLM	Condit et al. 1995
Panama	*Platymiscium pinnatum*	30/60	CL	2.0	14	TLM	Condit et al. 1995
Panama	*Prioria copaifera*	30/60	CL	19.2	20	TLM	Condit et al. 1995
Panama	*Tabebuia guyacan*	30/60	CL	2.7	14	TLM	Condit et al. 1995
Panama	*Tabebuia rosea*	30/60	CL	1.5	11	TLM	Condit et al. 1995

Supplemental Table S2. Results of the simple meta-analysis on timber volume recuperation after selective logging of tropical forests for cases in which a changing set of species (Same+) is harvested. Timber available at 2nd and 3rd cut is presented as a percentage of logged volume at first cut. MCD=Minimum cutting diameter; DBH=diameter at breast height; CL=conventional logging; * silvicultural treatments applied; RIL = reduced-impact logging; IBM=individual-based model; CH=cohort model; MM=matrix model; and, NA= data not available. Note that practices described as "RIL" apparently vary a great deal between studies.

Country	**Cutting cycle (y) / MCD (cm DBH**	**Logging method**	**Logging intensity at 1st cut (m3/ha)**	**Timber available at 2nd cut (%)**	**Timber available at 3rd cut (%)**	**Model**	**Reference**
Australia	40/70	CL	19.2	81	85	CM	Vanclay 1994
Bolivia	25/50		11.8	21	NA	CM	Dauber et al. 2005
Bolivia	25/50		13.7	28	NA	CM	Dauber et al 2005
Bolivia	30/50	RIL	10.3	34	14	CM	Blate 2005a,b
Bolivia	30/50	RIL*	14.7	47	32	CM	Blate 2005a,b
Brazil	30/45		43.0	95	86	IBM	Phillips et al. 2004
Brazil	40/50	CL	30.0	50	55	MM	MacPherson et al. 2010
Brazil	40/50	RIL	30.0	67	73	MM	MacPherson et al. 2010
Brazil	30/45		75.0	72	NA	CM	Silva et al. 1995
Brazil	30/45	CL	39.0	74	38	CM	Valle et al. 2007
Brazil	30/45	RIL	36.0	89	56	CM	Valle et al. 2007
Brazil	30/45	CL	30.0	18	NA	CM	Valle et al. 2006
Brazil	30/45	RIL	37.0	0	NA	CM	Valle et al. 2006
Brazil	30/55	RIL	21.0	36	NA	CM	Sist & Ferreira 2007
Brazil	30/50	RIL	34.0	56	35	IBM	Van Gardingen et al. 2006
Brazil	30/55		57.0	75	23	CM	Keller et al. 2004; Alder & Silva 2002
Costa Rica	30/60	CL*	67.1	55	37	CM	Howard 1993

Guyana	25/35		32.5	79	81	IBM	Arets 2005
Indonesia	35/50	CL	80.0	44	49	IBM	Van Gardingen et al. 2003
Indonesia	35/50	RIL	80.0	43	53	IBM	Van Gardingen et al. 2003
Indonesia	35/50	RIL	60.0	56	59	IBM	Van Gardingen et al. 2003
Indonesia	35/50	RIL	50.0	86	90	IBM	Van Gardingen et al. 2003
Indonesia	35/50	CL	78.0	79	45	MM	Sist et al. 2003
Malaysia	20/60	CL	220.0	13	NA	IBM	Huth & Ditzer 2001

Supplemental Table S3. Results of a simple meta-analysis on retention of carbon stocks in aboveground biomass after selective logging of tropical forests. RIL = reduced-impact logging; and, NA= data not available. Note that practices described as "RIL" vary a great deal between studies.

Country	Harvest intensity (m^3/ha)	Above-ground C pre-logging (tC/ha)	C lost from logging (tC/ha)	C retained (%)	Notes	Reference
Bolivia	4.5	80	4	96		Brown et al. 2003
Brazil	NA	205	54	74		Mazzei et al. 2009
Brazil	23.2	127	48	63		Asner et al. 2005
Brazil	4.4	218	8	96		Pearson et al. 2006
Brazil	4.4	218	19	91	RIL	Keller et al. 2004
Brazil	30.0	186	22	88	RIL	Miller et al. 2011
Brazil	NA	168	30	82	RIL	Figuera et al, 2008
Brazil	NA	185*	54*	71		Huang & Asner 2010
Gabon	8.1	210	17	92	RIL	Medjibe et al, 2011
Gabon	11.4	194	12	94		Medjibe 2012
Gabon	5.7	190	6	97	RIL	Medjibe 2012
Guiana	32.5	210	85	59		Blanc et al. 2009
Indonesia	38.4	243	61	75		Griscom et al. 2010
Malaysia	97.2	138	73	47		Berry et al. 2010
Malaysia	154.0	166	80	52		Pinard & Putz 1996
Malaysia	104.0	164	45	72	RIL	Pinard & Putz 1996
Papua New Guinea	35.0	208	66	68		Stanley 2009
Papua New Guinea	10.7	96	23	76	RIL	Bryan et al. 2010
Papua New Guinea	10.7	126	47	63	RIL	Bryan et al. 2010
Papua New Guinea	NA	121	31	75	Logged vs. Unlogged	Fox et al. 2010
Phillipines	NA	193	100	52		Lasco et al. 2006
Republic of Congo	9.6	271	8	97		Brown et al. 2005

* C-stock in estimated total live biomass from remote sensing data.

Supplemental Table S4. Results of a simple meta-analysis on retention species richness (=species density) in of birds, invertebrates, mammals, and plants in selectively logged tropical forests or after selective logging. Gr=taxonomic group; B=birds; I=invertebrates; M=mammals; P=plants; #Spp unlogged=number of species in unlogged forest or pre-logging; Spp retained (%) = percentage of species richness retained in logged forest or after logging; RIL=reduced-impact logging. Data on harvest intensity and time since logging is missing for quite a number of studies because this information was not given or because the source could not be accessed (in case we used studies that were included in the meta-analyses by Berry *et al.* (2010) and Sodhi *et al.* (2009). Note that practices described as "RIL" apparently vary a great deal between studies.

Gr	**Country**	**Harvest intensity (m^3/ha, m^2/ha, or stems/ha)**	**Time since logging (y)**	**#Species unlogged**	**Species richness retained (%)**	**Notes**	**Reference**
B	Belize	0.5 stems	1	91	109		Whitman et al. 1998
B	Bolivia		1-4	133	99	RIL	Felton et al. 2008
B	Brazil	19 m^3	0.5	13	132	RIL	Azevedo et al. 2006
B	Brazil			92	92		Wunderle et al. 2006
B	Indonesia	3.92 m^2	22	14	79		Lammertink 2004
B	Indonesia	1.69 m^2	10	14	86		Lammertink 2004
B	Indonesia	5.23 m^2	10	14	93		Lammertink 2004
B	Indonesia	4.89 m^2	10	14	93		Lammertink 2004
B	Indonesia	3.28 m^2	3	14	93		Lammertink 2004
B	Indonesia		1	16	75		Marsden 1998
B	Indonesia		1	73	78		Marsden 1998
B	Indonesia		80	83	24		Sodhi et al. 2005a,b
B	Indonesia		4	83	31		Sodhi et al. 2005a,b
B	Indonesia		4	83	40		Sodhi et al. 2005a,b
B	Indonesia			17	67		Waltert et al. 2005
B	Malaysia			17	71		Johns 1986
B	Malaysia			49	76		Johns 1986
B	Malaysia			111	77		Johns 1986
B	Malaysia		1	193	70		Johns 1986
B	Malaysia		6	120	72		Johns 1989
B	Malaysia			120	83		Johns 1989
B	Malaysia	118 m^3	6	97	137		Johns 1996
B	Malaysia	118 m^3	12	97	151		Johns 1996
B	Malaysia			274	91		Lambert & Collar 2002
B	Malaysia	90 m^3	9	195	91		Lambert 1992
B	Malaysia		8	207	96		Lambert 1992
B	Malaysia			15	73		Styring & Ickes 2001
B	Malaysia		40	83	88		Wong 1986
B	Malaysia		18	122	91	Tractor and High Lead	Berry et al. 2010
B	Malaysia	80 m^3		73	82		Edwards et al. 2009
B	Malaysia	40-52 m^3	30	31	89		Yap et al. 2007
B	Thailand			63	85		Pattanavibool & Dearden 2002
B	Thailand			119	75		Pattanavibool & Dearden 2002
B	Thailand		5	110	61		Round & Brockelman 1998
B	Uganda	14-21m^3	30	95	108		Sekercioglu 2002
B	Venezuela			5	71		Thiollay 1997
I	Belize	6 stems	3	36	107		Lewis 2001
I	Brazil	19 m^3	0.5	28	127	RIL	Azevedo et al. 2006
I	Brazil	1-4 stems	6	37	81		Scheffler 2005
I	Brazil	8 stems	4. & 8.	97	105		Vasconcelos et al. 2000
I	Costa Rica	<5 m^3	1	11	100		Aguilar et al. 2007
I	Indonesia		2	202	105		Cleary 2003
I	Indonesia			202	111		Cleary 2003
I	Indonesia		5	37	78		Hill et al. 1995

I	Indonesia		13	34	68		Jones et al. 2003
I	Indonesia		24	16	94		Widodo et al. 2004
I	Indonesia		14	16	145		Widodo et al. 2004
I	Indonesia	5-20m^3		173	126		Cleary & Moers 2006
I	Malaysia			39	36		Donovan et al. 2007
I	Malaysia			7	110		Eltz 2004
I	Malaysia			13	66		Eltz 2004
I	Malaysia			2	158		Hassall et al. 2006
I	Malaysia			3	111		Hassall et al. 2006
I	Malaysia			43	58		Intachat et al. 1997
I	Malaysia		20	43	72		Intachat et al. 1997
I	Malaysia			43	105		Intachat et al. 1997
I	Malaysia			4	210		Wells et al. 2007
I	Malaysia			12	79		Wells et al. 2007
I	Malaysia			16.5	126		Wells et al. 2007
I	Malaysia		5	370	95		Willott 1999
I	Malaysia		5	835	68		Willott 1999
I	Malaysia	70 m^3	6	67	54		Willott et al. 2000
I	Malaysia	70 m^3	6	67	118		Willott et al. 2000
I	Malaysia	70 m^3	6	121	42		Willott et al. 2000
I	Malaysia	70 m^3	6	121	125		Willott et al. 2000
I	Malaysia	74 m^3	15	58	76		Dumbrell & Hill 2005
I	Malaysia				102		Hamer et al, 2003
I	Malaysia	87 m^3	4	45	127	RIL	Davis 2000
I	Malaysia	168 m^3	4	45	107	CL	Davis 2000
I	Malaysia	67 m^3	11	45	102	CL	Davis 2000
I	Malaysia				36		Donovan et al, 2007
I	Malaysia		18		84	Tractor and High Lead	Berry et al. 2010
I	Malaysia		3	31	92		Eggleton et al. 1997
I	Malaysia			45	112		Davis 2000
I	Malaysia	70 m^3	6	121	125		Willott 2000
I	Malaysia	72 m^3 (160 m^3)	1-8 (18-31)	100	88	Twice logged	Woodcock et al 2011
I	Sri Lanka			92	110		Gunawardene 2010
I	Thailand		5	39	95		Ghazoul 2002
I	Thailand		5	39	103		Ghazoul 2002
M	Brazil	19 m^3	0.5	21	96	RIL	Azevedo et al. 2006
M	Brazil	18 m^3	2-4	37	86	RIL	Castro et al. 2007
M	Brazil	19 m^3	2	32	65	RIL	Presley et al. 2008
M	Malaysia		18	17	65		Akbar & Ariffin 1997
M	Malaysia		22	17	94		Laidlaw 2000
M	Malaysia		7	20	110		Laidlaw 2000
M	Malaysia		27	22	91		Laidlaw 2000
M	Malaysia		3	23	109		Laidlaw 2000
M	Malaysia				97		Ahmed 2001; Berry et al. 2010
M	Malaysia		14 & 26	6	125		Bernard et al. 2009
M	Thailand			5	220		Pattanavibool & Dearden 2002
M	Thailand			19	47		Pattanavibool & Dearden 2002
M	Trinidad	2-4 stems	10-33	29	95		Clarke et al. 2005
M	Venezuela	4-7 m^3	4-7	18	117		Ochoa 2000
P	Indonesia		1-25	76	58		Silk et al. 2002
P	Singapore		100	53	47		Turner et al. 1997
P	Singapore		100	53	62		Turner et al. 1997

P	Malaysia	23-270 m^3	15-25		116	Tractor and High Lead	Berry et al. 2008
P	Malaysia				125		Ahmed 2001; Berry et al. 2010
P	Malaysia	23-270 m^3	15-25		108	Tractor and High Lead	Berry et al. 2008
P	Malaysia				96		Delaney 2007; Berry et al. 2010
P	Malaysia			187	114		Berry et al. 2010
P	Indonesia		8	18	76		Canon et al. 1998
P	Malaysia		3-33	50	80	RIL & CL	Akutsu et al. 2007
P	Malaysia			302	100		Bischoff et al. 2005
P	Malaysia	118 m^3	4-15	22	83	RIL & CL	Foody & Cutler 2003
P	Costa Rica	49 m^3	1-3	49	94	RIL	Webb & Peralta 1998
P	Argentina			55	127		Chediack 2008
P	Brazil	15-46 m^3	4-10	18	101		Costa & Magnusson 2002

Supplemental Table S5. Results of statistical tests for retention of timber, carbon and species richness in selectively logged forests. Variables as in Tables S1-S4. Tests were performed for unweighted data. One-sample t-tests compare percentages (of timber, carbon and species richness) retained in selectively logged forests to 100%. Paired sample t-tests were conducted to compare the retention of timber volume produced during the 2nd and the 3rd event with the initial harvest (100%).

One-sample t-tests	**Variable**	**t**	**p**	**n**
Timber				
Same species	Timber available at 2nd cut (%)	-10.05	<0.001	35
Changing set spp	Timber available at 2nd cut (%)	-8.55	<0.001	24
Changing set spp	Timber available at 3^{3d} cut (%)	-8.32	<0.001	17
Carbon	C retained (%)	-7.31	<0.001	22
Biodiversity				
Birds	Species richness retained (%)	-3.80	0.001	36
Invertebrates	Species richness retained (%)	-0.29	0.78	43
Mammals	Species richness retained (%)	0.11	0.91	14
Plants	Species richness retained (%)	-1.19	0.25	15

Paired-sample t-tests	**Variables**	**t**	**p**	**n**	**Mean difference (%)**
Timber					
Changing set spp	Timber available at 2nd cut (%) - Timber available at 3rd cut (%)	2.58	0.01	17	11.7

Supplemental references

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