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ORIGINAL PAPER

The high value of logged tropical forests: lessons from northern Borneo

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Abstract The carbon storage and conservation value of old-growth tropical forests is clear, but the value of logged forest is less certain. Here we analyse >100,000 observations of individuals from 11 taxonomic groups and >2,500 species, covering up to 19 years of post-logging regeneration, and quantify the impacts of logging on carbon storage and biodiversity within lowland dipterocarp forests of Sabah, Borneo. We estimate that forests lost ca. 53% of above-ground biomass as a result of logging but despite this high level of degradation, logged forest retained considerable conservation value: floral species richness was higher in logged forest than in primary forest and whilst faunal species richness was typically lower in logged forest, in most cases the difference between habitats was no greater than ca. 10%. Moreover, in most studies >90% of species recorded in primary forest were also present in logged forest, including species of conservation concern. During recovery, logged forest accumulated carbon at five times the rate of natural forest (1.4 and 0.28 Mg C ha^{-1} $year^{-1}$, respectively). We conclude that allowing the continued regeneration of extensive areas of Borneo's forest that have already been logged, and are at risk of conversion to other land uses, would provide a significant carbon store that is likely to increase over time. Protecting intact forest is critical for biodiversity conservation and

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climate change mitigation, but the contribution of logged forest to these twin goals should not be overlooked.

Keywords Biodiversity · Clean development mechanism · REDD · Tropical forestry · UNFCCC

Introduction

Forestry exports are a vital source of income to developing countries (worth > US$39 billion in 2006; Miles and Kapos 2008) and SE Asia has been prominent in this respect, with Indonesia, Malaysia and the Philippines together exporting more than 80% of all tropical timber during the latter decades of the twentieth century (Johns 1997; Table 5.2 in Gale 1998). In some regions, however, the economic benefits from forestry are now declining, because most forests outside protected areas have already been logged and are failing to recover sufficiently quickly. As a consequence, logged forests are coming under increasing pressure for conversion to other more profitable land uses (Laurance 2007).

One proposed mechanism to counter these economic incentives is to compensate developing countries for preserving carbon stores, through payments for Reduced Emissions from Deforestation and Degradation (REDD; Gullison et al. 2007; Canadell and Raupach 2008). This mechanism could also be widened to include biodiversity benefits of preserving forests intact, for instance by negotiating a premium for emissions reductions that reduce biodiversity losses, or through biodiversity agencies contributing funds to help develop REDD programs that best preserve biodiversity (Bekessy and Wintle 2008; Venter et al. 2009). However, the manner in which forests already degraded by logging should be included within such programs is uncertain (Neeff et al. 2006). Arguably, since protecting intact mature forests from destruction or degradation is the most effective way to both reduce carbon emissions and protect biodiversity (Venter et al. 2009), REDD funds should be used to expand protected areas containing mature forest rather than to preserve forest that has already been degraded (Putz and Redford 2009). Moreover there have been recent calls for a stricter definition of forests qualifying for credits (Sasaki and Putz 2009) and for more detailed ground-based information to allow funding to be targeted more effectively

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(Gibbs et al. 2007; Miles and Kapos 2008). Hence it is likely that protection of forests already degraded by logging will be given only a low priority by funding bodies and conservation agencies.

Within SE Asia, the island of Borneo is a centre of biodiversity and endemism (Woodruff 2010), where most remaining forests are within logging concessions (Meijaard and Sheil 2008) and timber extraction rates are among the highest globally (>150 m^3 ha^{-1} in some cases; Putz et al. 2001; Sodhi et al. 2004). By 2010 all forest outside of conservation areas is likely to have been logged at least once, leading to severe pressure for conversion to oil palm *Elaeis guinensis* plantations or other uses (Laurance 2007; Wilcove and Koh 2010). Here we quantify the residual value of logged forests in northern Borneo in terms of their capacity both to support biodiversity and to store and sequester carbon. We sampled in the vicinity of Danum Valley Field Centre (DVFC) in Sabah, Malaysian Borneo, which is adjacent to a 438 km^2 conservation area of unlogged forest surrounded by logged forest (Marsh and Greer 1992). Our sampling, together with published work from DVFC, includes >100,000 observations of individuals from 11 taxonomic groups and >2,500 species, covering up to 19 years of post-logging regeneration.

Study area

The Danum Valley Conservation Area (DVCA; 5°N, 117°50′E) is an area of strictly protected dipterocarp forest within the 9,730 km^2 Yayasan Sabah Forest Management Area (YSFMA). Temperature (annual mean = 26.7°C) and rainfall (annual mean = 2,669 mm) in the area are typical of the moist tropics (Walsh and Newbery 1999). Most of the YSFMA, excluding the DVCA and two other large protected areas, has been logged with a modified uniform system (Whitmore 1984) in which stems of commercial species with a diameter > 60 cm were removed using high lead cable and tractor extraction methods.

Methods

Carbon accumulation

To estimate aboveground biomass (AGB) we used forest monitoring plots to measure tree diameters and an allometric equation to convert these to carbon stock values. We included the tissue density of each species' wood as this is the most important factor, beyond tree diameter, in accurately determining a tree's carbon content (Chave et al. 2005). We used data from 20 forest inventory plots divided between the DVCA and an adjacent area in the YSFMA that was logged in 1988 and 1989 (Fig. 1; plots sampled between June 2005 and July 2006; Berry et al. 2008). These data included trees $\geq$ 30 cm diameter surveyed over a total area of 20 ha, and trees $\geq$ 5 cm diameter surveyed over a total area of 2 ha. Plots were distributed throughout a 50 km^2 study area and included areas recovering from natural disturbance events such as tree falls, and so our estimate of mean above-ground biomass in intact forest is likely to be robust.

Estimates of wood density were obtained for 99.8% of trees sampled from an online database (ICRAF 2007) and published accounts (Köhler 1998; Suzuki 1999; Osunkoya et al. 2007). Species-level data were available for 59.8% of species. Where species-level data were not available, we used the mean for all Bornean species in the same genus (35.5% of trees) or family (5.3% of trees). Values that were reported as wood specific

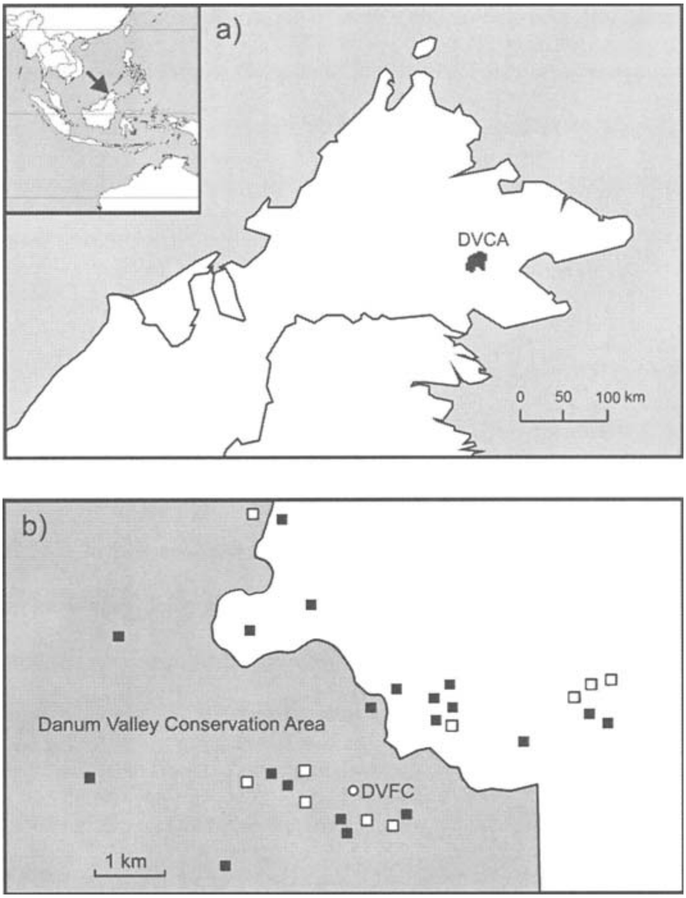

Fig. 1 Locations of **a** Danum Valley Conservation Area (DVCA) and **b** sampling plots in unlogged forest (*shaded*) and logged forest (*unshaded*) around the Danum valley Field Centre (DVFC). *Squares* represent 1 ha plots where biodiversity was sampled; filled squares indicate plots that were also used for forest inventory

gravity were converted with the following equation (adapted from Chave et al. 2006): *Wood Density* = 1.147 (*Wood Specific Gravity*).

We estimated AGB per hectare for logged and unlogged forest with the allometric equation recommended for moist forests by Chave et al. (2005):

$$\mathrm{AGB}\left(\mathrm{kg\ ha}^{-1}\right) = A^{-1}\sum \rho_i \times \exp\left(-1.499 + 2.148\ln(D_i) + 0.207(\ln(D_i))^2 - 0.0281(\ln(D_i))^3\right)$$

where A is the area of forest that was surveyed (ha), ρ_i is the wood density (kg m^{-3}) and D_i is the diameter at breast height of tree i (m). We then assumed that 50% of biomass is carbon (Kitayama and Aiba 2002; Putz et al. 2008).

Subtracting the carbon stocks in both the amount of timber removed and the trees killed in the process (necromass or coarse woody debris) from our estimate of carbon stored in unlogged forest gives an estimate of the carbon stocks in logged forest immediately following logging. The measured carbon stocks in logged forest minus estimated stocks immediately after logging, divided by the number of years since logging, provides our estimate of the annual increase in carbon storage in logged forest. Estimates of necromass production were taken from a previous study in the YSFMA (Pinard and Putz 1996), using data for plots where logging methods were the same as in our study. However, the volume of timber extracted (154 m^3 ha^{-1} on average) was about 60% higher than in our study and so we reduced the estimates accordingly, to estimate necromass resulting from logging in our study plots.

Biodiversity survey

We surveyed birds and ants over a 3-month period (February to April 2006) in 30 1-ha plots (Fig. 1), of which 15 were in unlogged forest and a further 15 in forest logged in 1988 or 1989. To survey birds, four 30-min point counts were carried out at each plot by one of the authors (DPE). Unknown bird vocalisations were recorded during point counts and were subsequently identified by comparison to recordings of known calls or by ornithological experts from the region. At each plot one count was carried out in early morning (06.15–09.00 h), one in late morning (09.30–12.30 h), one in late afternoon (15.30–17.00 h), and the fourth was assigned to one of the morning time-slots at random. Overflying birds and detections outside the plot were not recorded.

For ground-dwelling ants, ten 1 m^2 samples of leaf litter were collected from locations selected by stratified random sampling and separated by a minimum distance of 20 m within each plot. Sampling was carried out between 09.00 and 14.00 h, at least 24 h after any heavy rain. The litter was sieved (1 cm × 1 cm mesh) and placed in cloth bags for transportation to the laboratory where it was transferred to Winkler bags and left for 72 h to extract invertebrates (Bestelmeyer et al. 2000). Ants were identified to species where possible or assigned to morphospecies within genera by one of the authors (NBT). Voucher specimens are held at Universiti Malaysia Sabah and the California Academy of Sciences, USA.

In addition to these data, we obtained complimentary information from published papers together with data from PhD and MSc theses conducted at DVCA. This increased the range of taxa analysed while avoiding confounding factors related to studies comparing multiple sites, such as differences in the type of logging, sizes of forested areas or underlying biogeography. We examined 24 additional studies comparing primary forest in the DVCA with logged forest in the YSFMA, of which 12 studies presented information on species richness and abundances, whilst a further three studies provided autecological data on the abundances of individual species.

Statistical analysis

For studies with more than one sample plot in each habitat, species abundances were pooled among plots to give total abundances for logged and unlogged forest. To ensure comparability among different studies, and to account for the large differences in abundance and species richness across the different taxa, all differences between the two habitats were converted to percentages of the total number of species or individuals in unlogged forest. When species abundance information was available, rarefied species richness was calculated based on the number of individuals in the habitat with the lowest abundance in that study. To determine the statistical significance of differences in species richness between the two habitat types, observed differences were then compared to the differences in 999 permutations of the species abundance data with individuals assigned to habitat types at random (Solow 1993). To investigate the possibility of local extinctions of species following logging, we also examined the proportion of species unique to unlogged forest. To avoid biases due to under-sampling (Dent and Wright 2009) we restricted this analysis to species with $\geq$10 individuals sampled in total. For the best-studied taxa (birds and butterflies) we also looked within these data for species that are known to be threatened (IUCN 2007) or that are endemic to Borneo or Sundaland.

Results

We estimate that intact forest stored 138 Mg C ha^{-1} in above-ground biomass (Table 1). Eighteen years after logging, nearby forest stored 89 Mg C ha^{-1}, 36% lower (Table 1). The initial reduction in above-ground biomass from the removal of timber and from logging-induced mortality is calculated to have been 53%. Thus the estimated rate of carbon sequestration in logged forest between 1989 and 2007 was 1.4 Mg C ha^{-1} year^{-1} (Table 1).

Across the 12 studies of nine taxa for which species abundance data were available, logging had opposite effects on flora and fauna (Fig. 2). Herbs and trees both showed a significant increase in rarified species richness in logged forest compared to unlogged forest whereas five of the seven animal taxa declined, with birds, ants, termites and butterflies all declining significantly in at least one study (Table 2). However, with the exception of termites (Donovan et al. 2007) and canopy-dwelling butterflies (Dumbrell and

Table 1 Carbon recovery in above-ground biomass of trees 18 years after logging dipterocarp forest in Sabah, Malaysia

	Biomass (Mg ha^{-1}) ± SE	Proportion of AGB in natural forest (%) ± SE
AGB of live trees in natural forest[a]	276.0 ± 29.0	–
Timber removed by logging[b]	58.3 ± 11.5	21.1 ± 4.2
Collateral damage[c]	89.3 ± 14.9	32.4 ± 5.4
Branches, stumps and butt roots of extracted trees	42.3 ± 3.1	15.3 ± 1.1
Additional trees uprooted and crushed	42.5 ± 14.4	15.4 ± 5.2
Damaged trees dead within 1 year post-logging	4.5 ± 2.2	1.6 ± 0.8
Estimated AGB after logging	128.4 ± 39.9	46.5 ± 14.5
AGB in logged forest after 18 years of regeneration[d]	177.0 ± 14.4	64.1 ± 5.2
AGB recovered in 18 years since logging	48.6 ± 42.4	17.6 ± 15.4
AGB recovered year^{-1}	2.7 ± 2.3	1.0 ± 0.8
Carbon recovered year^{-1}	1.4 ± 1.2	–

SE describes variation among plots and does not incorporate error in biomass equations

[a] Mean above-ground biomass (AGB) of live trees $\geq$ 5 cm dbh in ten 1 ha plots in primary forest

[b] Calculated assuming mean extraction volume of 97.2 m^3 ha^{-1} (Moura Costa and Karolus 1992) and wood density of dipterocarps (0.6 kg m^{-3}) in the study area

[c] Calculated using data on post-logging losses from Pinard and Putz (1996). Assuming a decay rate of around 32% per year (Yoneda et al. 1977) almost all necromass generated by logging is expected to have decayed after 18 years

[d] Mean AGB of live trees $\geq$ 5 cm dbh in ten 1 ha plots in logged forest

Fig. 2 Average percentage difference in rarefied species richness between logged and unlogged forest from studies that reported species abundance information (for a full list of studies included see Table 2). *Error bars* indicate the 95% confidence intervals from 999 randomisations with individuals assigned to logged or unlogged forest at random

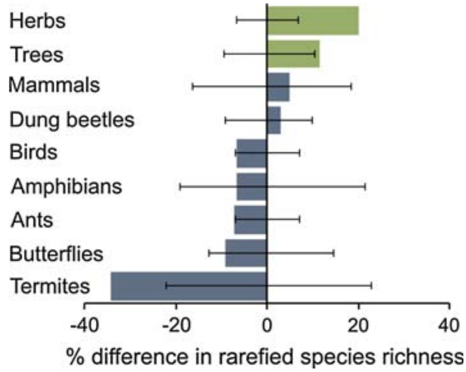

Table 2 Difference in species richness and abundance in logged and unlogged forest

Species group	N	S	Years since logging	% Difference in species richness		% Difference in abundance	% Species[a] unique to primary forest
				Observed	Rarefied		
Mammals[1]	872	44	12	−2.7	4.9	−32.3	5.0
Birds[2]	3,043	176	9	**−9.5**	**−11.4*****	9.9	10.6
Birds[3]	2,747	122	18	−9.1	−7.8	−8.2	0.0
Birds[4]	1,612	82	19	**−17.8****	**−15.2****	−7.1	0.0
Amphibians[5]	522	33	10	−15.4	−6.7	−35.9	18.2
Butterflies[6]	1,280	61	15	**−24.1****	**−21.9****	−10.1	7.7
Butterflies[7]	3,961	62	12	1.8	3.7	−8.1	0.0
Dung beetles[8]	18,162	64	2–9	18.0	3.1	120.1	2.4
Termites[9]	382	43	25	**−64.1****	**−34.3****	−81.8	33.3
Ants[3]	12,004	159	18	**−15.8****	**−7.1**	−38.1	5.3
Trees $\geq$ 30 cm dbh[10]	1,011	163	18	15.7*	**15.8*****	−0.2	5.0
Trees $\geq$ 10 cm dbh[1]	906	187	12	**25.0*****	**28.1*****	−6.0	7.4
Trees $\geq$ 2.5 cm dbh[10]	7,013	578	18	7.5*	6.0	3.9	1.4
Seedlings[11]	2,600	325	18	−3.9	1.0	−10.4	13.0
Herbs[12]	16,859	187	11	**14.2****	**20.2*****	−24.2	6.3

The total number of individuals (N) and species (S) in each study gives an indication of sampling effort. A negative difference indicates fewer species or individuals in logged forest

Bold type indicates observed values $\geq$ 97.5th percentile, or $\leq$2.5th percentile of 999 permutations with individuals randomly assigned to logged or unlogged forest. * $P < 0.05$, ** $P < 0.01$, *** $P = 0.001$.
[a] Analysis confined to species with $\geq$10 individuals sampled in total. *Sources*: [1] Ahmed (2001), [2] Lambert (1992), [3] this study, [4] Edwards et al. (2009), [5] Wong (2006), [6] Dumbrell and Hill (2005), [7] Hamer et al. (2003), [8] Davis et al. (2001), [9] Donovan et al. (2007), [10] Berry et al. (2008), [11] Delaney (2007), [12] Magintan (2000)

Hill 2005), declines in species richness following logging were typically no greater than ca 10% (Table 2). An average of 8% (range 0–33%) of species in primary forest were not recorded in logged forest but in the best-studied taxa (birds and butterflies) no restricted range or threatened species with n $\geq$ 10 in primary forest was absent from logged forest. Including studies without species abundance information increased our sample from nine to 11 taxa but produced qualitatively similar results, with recorded species richness being

Fig. 3 Percentage difference in species abundance between unlogged and logged forest, with error bars ± 1 SE of mean for taxa represented by more than one study (for a full list of studies see Table 2)

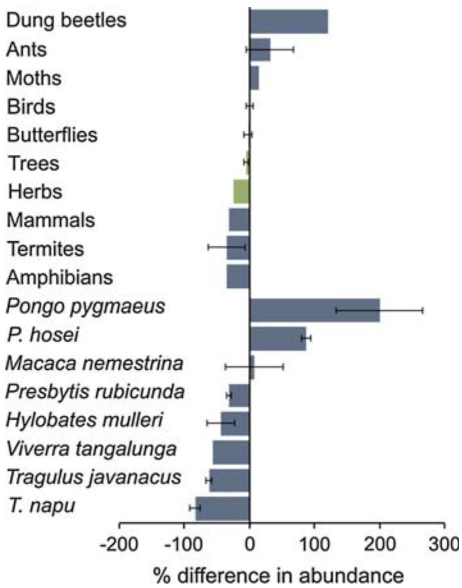

Table 3 Impacts of logging on the abundance of individual species of mammal

Species group	Years since logging	% difference in abundance
Mouse deer		
Tragulus javanicus[1]	2, 5, 12	−64.2, −68.1, −54.3
T. napu[1]	2, 5, 12	−89.1, −92.7, −67.2
Civets		
Viverra tangalunga[2]	8	−57.0
Primates		
Pongo pygmaeus[3]	6, 12	133.3, 266.7
Hylobates muelleri[3]	6, 12	−66.0, −22.6
Presbytis rubicunda[3]	6, 12	−27.9, −35.3
P. hosei[3]	6, 12	80.0, 95.0
Macaca nemestrina[3]	6, 12	−36.7, 51.9

Data for different intervals post-logging within a study are separated by commas. *Sources*: [1] Heydon and Bulloh (1997), [2] Colón (2002), [3] Johns (1992)

14% lower in logged forest than in primary forest for fish (Martin-Smith 1998) and 14–33% lower in logged forest for moths (Holloway et al. 1992; Willott 1999).

The impacts of logging on species' abundances varied among taxa (Fig. 3), with mammals, amphibians, ground-dwelling ants, termites and herbs all decreasing by ≥20%, whilst dung beetles and arboreal ants increased by ≥20% (Table 2). At species level, the responses of primates appeared idiosyncratic; for example, gibbons (*Hylobates muelleri*) were present in lower numbers but orang-utans (*Pongo pygmaeus*) were found at much higher abundance in logged forest, suggesting that they are well suited to the conditions in regenerating forest (Table 3).

Discussion

Our estimate of the aboveground biomass of live trees in unlogged forest around DVFC (276 ± 29 Mg ha^{-1}; Table 1) was similar to two previous estimates in the YSFMA (323 ± 20 and 317 ± 27 Mg ha^{-1}; calculated from Table 3 in Pinard and Putz 1996) but was much smaller than that estimated for dipterocarp forest in southwestern Borneo (430 Mg ha^{-1}; Paoli et al. 2008). However, the latter figure was only partly corrected for overestimation due to systematic avoidance of forest gaps, and was similar to the estimated total biomass, including belowground biomass, necromass and biomass of non-woody plants, in the YSFMA (426 Mg ha^{-1}; Table S2 in Putz et al. 2008).

We estimate that forests around DVFC lost 53% of AGB as a result of logging, which is consistent with losses indicated by other studies in Borneo (Pinard and Cropper 2000; Putz et al. 2008). Despite this high level of degradation, however, logged forest retained considerable residual value in terms of conserving biodiversity. Floral species richness was higher in logged forest than in unlogged forest, probably reflecting increased landscape-scale heterogeneity resulting from spatial variation in the intensity of disturbance due to logging (Hill and Hamer 2004; Berry et al. 2008). In contrast, faunal species richness was typically lower in logged forest, but in most cases the difference between habitats was no greater than ca 10%. This difference may be underestimated if canopy species not recorded in unlogged forest descend to lower heights in logged forest. In our study, however, there was little difference in the heights of the canopy in logged and unlogged forest (38 and 42 m, respectively in 1999–2000; Table 3 in Hamer et al. 2003) and so we are confident that this was not a problem. Species richness does not take account of changes in species composition but typically >90% of species recorded in primary forest were also present in logged forest, including species of conservation concern. In addition, there was no consistent pattern of changes in abundance following logging. These data accord with studies elsewhere indicating that whilst logged forest undoubtedly has lower conservation value than primary forest, logging has fewer adverse consequences for biodiversity than is often assumed (Dunn 2004; Meijaard et al. 2005; Dent and Wright 2009). A recent meta-analysis of SE Asian data indicated that the sensitivity of biodiversity to forest disturbance was moderately high (Sodhi et al. 2009). However, that analysis included clear-felling, fire and conversion to agriculture, all of which have much greater impacts than logging on biodiversity (Lawton et al. 1998; Barlow et al. 2007).

Following the initial loss of biomass due to logging, regenerating forests re-accumulated AGB at an average of 1.8% of this lost biomass each year (calculated from data in Table 1). Primary forests have also accumulated biomass over recent decades (Baker et al. 2004; Lewis et al. 2009) and in Borneo, AGB in Lambir Hills National Park increased by 0.2% year^{-1} between 1990 and 2000 (Chave et al. 2008). Against this background, the gain in AGB attributable to post-logging regeneration was about 2.4 Mg ha^{-1} year^{-1}, equivalent to 1.6% of AGB lost through logging. These data suggest that even if the rate of recovery remained constant, the carbon deficit due to logging of these forests would persist for around 60–65 years. In practice, however, the annual rate of growth is likely to decline as the forest matures, and our data are compatible with a time-span of 120 years suggested by Pinard and Cropper (2000) from a physiologically based model of forest gap dynamics.

We estimate that during recovery, logged forest accumulated carbon in AGB at five times the rate of natural forest (1.4 and 0.3 Mg C ha^{-1} year^{-1}, respectively). These are conservative estimates of total carbon accumulation because they do not include belowground biomass, which would increase these totals by around 37% (Phillips et al. 2008), or increases in soil carbon stocks within logged forest as it recovers. Allowing the continued regeneration of extensive areas of Borneo's forest that have already been logged, and are at risk of conversion to other land uses, would thus provide a significant carbon store that is likely to increase over time, providing a valuable contribution to meeting carbon dioxide mitigation targets. Moreover, this accumulation could be accelerated by management to rehabilitate logged forest, including planting of native tree species and cutting of climbers that retard tree regeneration and growth (Putz et al. 2001; Kettle 2010). Concern has been expressed that such carbon-based conservation could undermine the conservation of biodiversity (Putz and Redford 2009). However, recent evidence from our study area suggests that such rehabilitation can also benefit the recovery of biodiversity within logged forests (Edwards et al. 2009).

All IPCC emissions scenarios assume large reductions in carbon emissions from tropical deforestation over the coming decades (Nakicenovic et al. 2000). To achieve this aim, parties to the United Nations Framework Convention on Climate Change will need to design schemes that make the long-term protection of forests socially and economically attractive. The commitment by signatories to the Convention on Biodiversity to reduce the rate of biodiversity loss also requires concerted action to reduce tropical deforestation (Laurance 2007). Both these important policy objectives are more attainable through proper consideration of the full value of logged forest. We therefore urge that an emphasis on expanding the protection of intact forests should not result in the much more immediate threats to forests already degraded by logging being overlooked. In this respect we echo the sentiments of Meijaard and Sheil (2007) that a logged forest in Borneo is much better than no forest at all, and we urge that preventing logged forests being converted to oil palm or other crops should be a priority for policy makers and conservationists in Southeast Asia.

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